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Status and Trends of the Soviet Weather and Climate Modification Program

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STATUS AND TRENDS OF THE SOVIET WEATHER AND CLIMATE MODIFICATION PROGRAM

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Office of Scientific Intelligence

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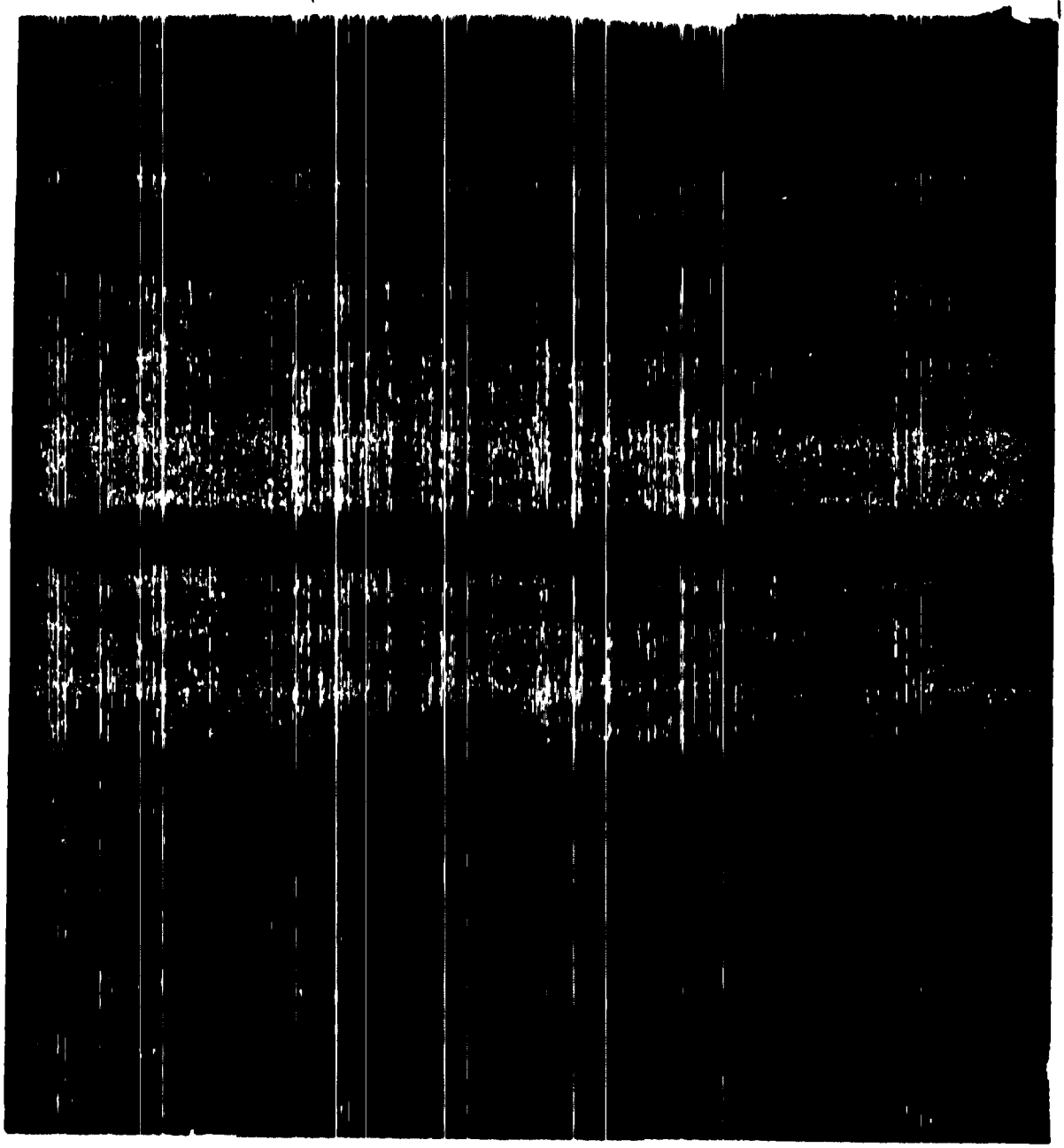

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STATUS AND TRENDS OF THE SOVIET WEATHER AND CLIMATE MODIFICATION PROGRAM

Project Officer

[redacted]

OSI-STIR/70-4
February 1970

CENTRAL INTELLIGENCE AGENCY
DIRECTORATE OF SCIENCE AND TECHNOLOGY
OFFICE OF SCIENTIFIC INTELLIGENCE

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PREFACE

Weather modification is directed toward changing meteorological phenomena for a short period of time usually over relatively small areas. Climate modification is directed toward changing meteorological phenomena over a long period of time usually over a large area. Almost all weather modification techniques can be applied to some type of military operation. Many have significant economic applications. Successful techniques to increase precipitation or to dissipate severe storms would benefit a country's economy considerably and could also support military operations. Techniques to dissipate or enhance fog and cloud could have important military applications, particularly for tactical operations. Even greater military and economic, as well as political, benefit could be derived from a successful method of modifying the climate.

This report discusses Soviet progress in weather and climate modification. Supporting basic research, such as cloud physics, is also considered [redacted]

This report, which updates an earlier study on weather and climate modification published in August 1965, has been prepared by the Office of Scientific Intelligence and coordinated with the Directorate of Intelligence. The cutoff date of information used is October 1969.

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CONTENTS

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STATUS AND TRENDS OF THE SOVIET WEATHER AND CLIMATE MODIFICATION PROGRAM

PROBLEM

To determine the status and trends of Soviet research and development in weather and climate modification.

CONCLUSIONS

1. The Soviets have maintained a very large weather modification R&D program for a number of years but, despite the size of this program, they have contributed no significant or unique advances to the understanding of the phenomena involved. In certain instances the Soviets have been quicker than the United States to introduce new weather modification techniques into operational service. Their climate modification program is still in the conceptual or basic research stage as is the case in other countries.

2. The Soviet weather modification program is well organized and apparently has high-level centralized direction. The Soviets have concentrated their R&D efforts in subfields they judge to offer the most promise for military and economic purposes. In the 1950s this concentration was on supercooled fog and cloud dissipation techniques, which became operational about 1960. In the 1960s the Soviets concentrated their R&D efforts on hail suppression techniques.

3. The Soviets have conducted no known field experiments in climate modification. Conservatism is dictated by their inability to predict what effects such experiments might have in geographical areas outside the experimental area. The Soviets are working on mathematical models of the atmosphere to assist them in predicting these effects but their progress has been hindered by the inadequacy of their computers.

4. The concentrated Soviet effort of the past 10 years in hail suppression has progressed to the semi-operational stage and the benefit-to-cost ratio appears to be about 5 to 1. Some scientific resources used in this developmental effort probably will now be diverted to other weather modification subfields. The most likely subfields for new Soviet R&D appear to be warm fog and cloud modification and/or modification of larger weather systems. Some increase in the precipitation augmentation effort also seems possible.

5. Although most of the Soviet weather modification program appears to be unclassified, there is evidence of classified R&D in warm cloud and fog modification. Such modification techniques could have immediate military applications for offensive and defensive tactical operations.

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SUMMARY

The major Soviet weather modification effort in the 1950s was on supercooled fog and cloud dissipation. This effort culminated in the development of a technique for clearing airports of supercooled fog; a semioperational status was reached in the late 1950s, several years before the United States began a similar operational program.

After the fog dissipation project passed from the R&D to the operational stage, a large portion of the Soviet scientific resources was diverted to attacking the problem of suppressing the number of occurences and severity of hailstorms in the USSR. An experimental research area was established in a grape-growing section of the Caucasus in the mid-1950s and experiments began on a large scale about 1960. The motivation behind this program probably was to a large extent the potential economic benefits to agriculture, but a method for dissipating or preventing hailstorms could also have military applications, particularly for protecting vulnerable equipment such as aircraft and missiles.

The Soviet hail dissipation experiments have progressed systematically through the past 10 years. Since the Soviets first established the feasibility for modifying hailstorms, they have concentrated on conducting these experiments over different types of terrain, on developing a means for introducing reagents into the clouds, and on improving various related techniques. According to the Soviet theory, the time and place that the reagent is introduced into the cloud is critical. The use of aircraft was judged to be inadequate and antiaircraft artillery shells and rockets were developed for this purpose.

The Soviets claim that their hail suppression research program has been completely successful. The official Soviet estimate of the benefits versus cost ratio is about 5 to 1 and this estimate probably is accurate. In 1967 the Soviet government made the decision to expand these operations to all areas of the country subject to significant hail damage, and it now appears that they consider this program to be at least semioperational and no longer experimental.

Because the Soviets have emphasized supercooled fog and cloud dissipation and hail suppression over the past 15 to 20 years, they have put relatively less effort into other subfields of weather modification than has the United States. These subfields include precipitation augmentation and warm fog and cloud dissipation, both of which could have significant economic or military value if techniques are perfected. The Soviets maintain only one known sizable project (in the Ukraine) engaged in precipitation augmentation, but apparently it has produced no significant amounts of precipitation. Some increased activity in other geographical areas has been noted in the past year.

Based on open sources, it appears that Soviet experimental research on warm fog and cloud dissipation is in the initial stage, although there is evidence that at least one classified project was begun a few years ago. One unclassified project is an attempt to prevent fog from forming over the Kola Bay by covering the bay surface with a monomolecular film that reduces the rate of evaporation. A recent increase in Soviet basic research on hygroscopic nuclei may indicate that experimental research on warm fog and cloud dissipation using such nuclei will receive greater emphasis.

Soviet experimentation on severe storms and modification of large weather systems also is in its beginning stages and the Soviets have no known projects which compare in size or complexity with the US STORMFURY project to modify hurricanes. Current Soviet work on severe storms appears to be confined to experiments on individual cumulus clouds and thunderstorms. Some success has been reported in dissipating thunderstorms, but the Soviets need more data to make a final evaluation of the results. No information is available on recent Soviet experiments on large weather systems, but it appears that such work will be stepped up.

Soviet scientists and engineers have discussed the possibility of climate modification for many years, particularly the prospects of melting the Arctic ice. The well-known proposal by P. M. Borisov to dam the Bering Strait is directed to this end but Soviet scientists have warned that melting the Arctic ice could have harmful effects on the climate in other areas of the world. The uncertainty of these effects

probably has kept field experimentation to a minimum. Current basic Soviet research on the development of realistic mathematical models of the atmosphere could greatly assist in predicting effects over the entire Northern Hemisphere. The BESM-6, probably the best computer available for testing these models, is not adequate for performing the complex computations involved, although even the most advanced computers are not completely adequate for this job.

The Soviets are actively engaged in research on the microphysics of clouds and precipitation in support of weather modification. They are particularly active in laboratory studies involving cloud chambers. They also have been imaginative in applying radar to cloud research and precipitation studies. Soviet administrators of the weather modification program have stated that there is a need for intensifying these basic studies.

DISCUSSION

OVERALL WEATHER MODIFICATION PROGRAM

The Soviets have maintained a large weather modification program for about 20 years. In terms of numbers of personnel involved, it probably is the largest in the world. It appears that the Soviets maintain a much larger field experimental program than the United States but that their related basic research effort is smaller.[1] Consequently, the Soviets generally have been quicker to test weather modification techniques in the field than has the United States.

The Soviets appear to have a well-organized program.[2] High-level direction of the program is indicated by their apparent ability to channel efforts into particular subfields. Thus very intense work is carried out until a technique is perfected to the point that it can be used operationally or semioperationally. At that time, scientific resources are diverted to another subfield. As an example, a large Soviet effort in dissipating supercooled fogs and clouds was apparent in the middle and late 1950s. When this technique was developed to the point that it could be used operationally, the concentration of effort was shifted to hail suppression, where it has been since the early 1960s. The decision as to which subfield to concentrate the effort must be made at high levels and probably is based on a combination of factors, such as which areas appear to be the most promising and which have the most military and economic potential.

It is evident from the published literature that the overall weather modification program in the USSR underwent a considerable expansion in 1960-1964, with a steady but slower growth rate since then.[3] However, this expansion may have been more apparent than real because a general declassification of the program in the late 1950s may have resulted in an increase in published articles. Nevertheless, there is no question that the Soviet weather modification efforts have been increasing and they probably will continue to do so. Further, high-level Soviet officials have indicated that the future program probably will have a better balance between theoretical research and field experimentation.[4]

Hail suppression

The Soviets have continued to expand their activities in hail suppression over the past 5 years. This effort, which began in 1956 as a rather small experimental effort in the Caucasus Mountains near Mt. Elbrus, has now expanded to include areas of the republics of Georgia, Moldavia, Tadzhikistan, Ukraine, Armenia and Uzbekistan. Recently a cooperative hail suppression project has also been initiated with Bulgaria.[5] The long time period and the number of experiments conducted probably have given the Soviets more experience in this area of weather modification than any other country.

The Soviet government made the decision in 1967 to expand the hail suppression operations to include eventually all areas of the USSR that are subject to significant hail damage.[6] This decision leaves little doubt that Soviet officials are convinced that the method effectively reduces the amount of damaging hail which falls, but there appears to be some question as to the exact amount that hail damage is reduced. G. K. Sulakvelidze, who leads the hail sup-

pression effort in the Caucasus and who is one of the most enthusiastic proponents of the method, claims a benefit-to-cost ratio of about 17 to 1. The official Hydrometeorological Service estimate of the benefit-to-cost ratio appears to be about 5 to 1.[6] The more conservative estimate probably is closer to the true value. Part of the discrepancy between these figures probably is due to different methods of figuring the cost of the program. It is not entirely clear how the cost of such items as guns, rockets, ammunition, and radars are figured into the cost of the program since some of this equipment appears to be military surplus material.[6,7] The benefits of the program are calculated on the basis of insurance claims for the protected areas compared with claims for adjacent unprotected areas.[7]

The size of the hail suppression program in the USSR indicates that it has passed from a strictly experimental program into at least a semioperational program. It is not likely that the Soviet government would decide to expand a strictly experimental program into all hail-affected areas of the country. Nevertheless, the fact that a control area is almost invariably established alongside a protected area indicates that the Soviets do not consider the program to be entirely operational at present, and they are still interested in obtaining experimental data.

The principle behind the Soviet hail suppression efforts is that certain portions of well-developed convective clouds often have large accumulations of moisture in a liquid supercooled state. The ice particles which form as a result of the natural freezing of droplets falling through these areas grow rapidly and are transformed into hailstones. The Soviet theory states that by injecting a large number of artifical crystallization nuclei into the cloud, the nuclei can convert the region of high, supercooled water content into small ice crystals, thereby eliminating the large supply of supercooled water which is necessary for the formation of hailstones.[8]

According to the Soviet theory, the artificial nuclei must be injected into the portion of the cloud which has the high supercooled water content and they must be placed there before the hailstones can grow to a large size. Soviet observations and computations show that large hailstones can be formed in a matter of 5 to 10 minutes after the hail forming process begins.[8]

The Soviets rely heavily on radar to determine where they want to seed the clouds.[8,9] Their experience has shown that the radar reflectivity undergoes a perceptible change in the area of the cloud where the hail formation is beginning. Either rockets or 100-mm antiaircraft artillery are used to deliver the seeding agents to the cloud, and both delivery systems are tied into radar control points. Based on the military precision with which they operate, the gun crews appear to be either military personnel or civilians who have had extensive training with the guns.[8] The shells normally are loaded with a lead iodide reagent, and a timing device is used to explode the shell at a preselected point in the trajectory. The rockets are equipped with two timing devices: one to set the time of burning of the reagent and the other to set the time for parachute deployment.[8] Possible danger to the local population from antiaircraft shell fragments or from rockets landing in a populated area does not seem to concern the Soviets greatly. They claim that the shells fragment completely and that it is rare to find a piece as large as 1 gram on the ground.[8] The danger from the rockets is minimized by the use of parachutes, and the rocket sites are established in relatively unpopulated areas. Rocket firings must be coordinated with civil and military aircraft authorities, who have veto power over rocket firings.[10]

There is a certain degree of rivalry between the groups using guns and those using rockets, but there is no evidence that the Soviet decision makers have any intention of adopting only one delivery method. The rockets used in the program have undergone continued improvement through the years and the Soviets presently are using a multiple rocket launcher capable of firing four rockets simultaneously. These rockets are approximately 5 ft. long and have a range of about 8 km. The new larger Alazani rocket is now in its final test phase. It has a launcher capable of simultaneously launching several rockets in different directions.[8]

Each delivery system has certain advantages and disadvantages. The antiaircraft artillery can deliver a shell to a particular spot in the cloud with relatively good accuracy. When the shell explodes, a large number of nuclei are then released in a relatively small volume. A large storm would require a large number of firings to seed it completely. In one operation observed by Western scientists, about 200 rounds were fired to seed one storm.[8] The rockets

apparently also achieve good accuracy and they have the ability to deliver the nuclei over a considerable volume of the cloud. The number of nuclei delivered per unit volume is not as high as in the case of the shells, but the rockets are somewhat more versatile in that they can be set to eject the nuclei either in a horizontal trajectory through the cloud or vertically as the rocket descends through the cloud by parachute.[7]

The hail suppression expedition located near Kormeshta in Moldavia appears to be the most scientifically oriented group of its kind in the USSR. The Moldavian expedition is under the leadership of I. I. Gayvoronskiy of the Central Aerological Observatory. Although all the hail suppression groups study the result their efforts have on crop damage by hail, only the Moldavian expedition apparently has made any study of the effects their operations have had on precipitation in the area of operations. Gayvoronskiy's statistics, based on 10 years of observation, tend to show that his operations have had little effect on precipitation in the area.[11]

The overall Soviet hail suppression program is a large, impressive effort which seems to dominate the entire Soviet weather modification program.[8] The Soviets have developed effective delivery systems and have a well-coordinated program. The primary benefit of hail modification is, as the Soviets have stated, for the protection of crops. However, the ability to dissipate hail storms could also be used by the military to protect personnel and certain valuable equipment. The Soviet use of lead iodide as a seeding agent may be somewhat less efficient than silver iodide, but is not a serious limitation to the program.

Precipitation augmentation

Precipitation augmentation, a subfield of weather modification popularly referred to as rain-making, has received a large percentage of the total weather modification budget in the United States. In the USSR, however, this subfield has received considerably less effort than that of hail suppression, and there is some indication that it is not receiving unqualified support at the top administrative levels. One reason may be the belief, expressed by some Soviet officials, that the increase in precipitation produced by cloud seeding has not been great enough to make it economically feasible on a large scale.[8] Another possible explanation is that the Soviets may have decided to concentrate their resources on hail suppression because the economic benefits were more clear cut. Some Soviet scientific resources allotted to hail suppression could be diverted to other areas of weather modification, such as precipitation augmentation, as the hail suppression operations become less experimental and more operational. In any case, there is little doubt that the Soviets recognize that even a small increase in precipitation at the right time and place can have considerable economic benefits. Military benefits from precipitation augmentation are less clear cut but certain tactical operations could derive some marginal benefits from such a program.

The largest Soviet weather modification effort to increase precipitation is a joint effort between the Ukrainian Hydrometeorological Research Institute at Kiev and the Main Geophysical Observatory at Leningrad.[8] This project was established in 1958 and cloud seeding with dry ice has been carried out continuously since 1959.[8,13] The Ukrainian experiments have been conducted using two IL-14 aircraft for dispensing dry ice into the clouds.

In setting up this operation, the Soviets established two areas of equal size (3,750 km²) separated by a distance of 30 km. All the cloud seeding experiments have been conducted in the eastern area, and the western area has been used as a control area. Operating in this manner, the Soviets are able to avoid contaminating the control area with seeding nuclei because of the prevailing westerly winds in the area. The Soviets set up a dense network of rain guages in the two areas (one per every 10-12 km²) to make fine-scale measurements of natural precipitation in the control area and of that from cloud seeding in the operating area. The experimental area is also instrumented with two radar installations to observe areas of precipitation and to track and control the aircraft doing the seeding.[12]

The Soviets have seeded stratus and stratocumulus air mass clouds as well as frontal-type clouds in the Ukrainian operations. They have reported about a 10 percent increase in precipitation amounts when operating on winter air mass clouds. However, the scientists involved do not consider this a very significant increase because the total water content of these clouds is very small in the first place.[1] They claim to have been more successful when operating

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on frontal-type clouds, with some claiming as much as a 20 to 25 percent increase while others, only about 15 percent.[11 12] If this magnitude of precipitation augmentation could be achieved for all frontal cloud situations, it could be quite significant. However, the Soviets have determined that only about 50 percent of the winter frontal-type clouds are favorable for seeding.[13]

Since 1960 the Ukrainian expedition has also systematically seeded summer cumulus clouds. From 1960 to 1966 the Soviets seeded when possible all clouds which exceed 2.2 km in depth and whose temperature at cloud top was lower than −5° C. These parameters had been established, through previous Soviet investigations, as being necessary for favorable seeding conditions. The amount of precipitation which fell over the operational area was then compared with the amount which fell over the control area to determine the effectiveness of the experiments. The results showed some increase in the seeded area, but the increase was not large enough to rule out the possibility that it could have been a chance occurrence.[13]

Because of this uncertainty in the results, the Soviets changed their approach in 1966 and began the random selection of the clouds to be seeded. The evaluation of these randomized experiments involves the comparison of the amount of precipitation from the seeded clouds with the amount from the unseeded clouds. These experiments have not been under way long enough for them to make a definite conclusion about the effectiveness of the experiments; however, preliminary results have not been particularly encouraging.[12] Perhaps the most significant aspect of these experiments is that this is the first time the Soviets have been known to use this technique. One of the criticisms of the Soviet weather modification experiments in the past has been the lack of statistical controls for evaluation purposes. Randomization is a technique commonly used by Western scientists to establish such controls, and recent information indicates that the Soviets will be using it more in the future.[13]

Scientists involved in the Ukrainian experiments have subjected their data to analysis to determine whether or not the cloud seeding operations resulted in any decrease in precipitation downwind from the operating area.[14] Several specialists in the field have postulated that such a decrease might occur, but the researchers in the Ukraine turned up no detectable decrease. However, they have reported that a secondary maximum in precipitation downwind from the operating area seems to be indicated. This secondary maximum, if real, is quite small and probably will have little significance on the overall precipitation pattern produced by the cloud seeding operations.

The only other known sizable Soviet effort to augment precipitation is a project in northern Kazakhstan under the control of the Kazakh Scientific and Experimental Hydrometeorological Institute.[15] This effort apparently has been under way since about 1963, but little else is known about it. The fact that practically nothing has been published concerning this effort is unusual; it could indicate that certain aspects of the project are classified, or it might indicate that the operations there are being conducted with little scientific analysis of the results of the experiments. A recent press report has mentioned another operation designed to augment precipitation in the Yakutia ASSR. According to the report, an experiment was conducted to produce rain in the area of a forest fire; however, it is not clear from the report whether this was part of an established weather modification program or was carried out on an *ad hoc* basis.[16]

Cloud and fog dissipation

Much of the early effort by the Soviets in weather modification apparently was devoted to the dissipation of supercooled fog and clouds, which has particular application for military and civil air operations. This work proved the feasibility of using cloud seeding techniques. After the feasibility was established, the major remaining problem was to develop reliable and economical techniques for dispersing the seeding agents. As early as 1958 the Soviets claimed that they were using dry ice on at least a semi-operational basis to dissipate supercooled fogs over airports in the USSR. At present the Soviets operationally clear supercooled fogs at 10 to 12 airports using ground equipment that blows flakes of CO_2 to a height of 20 meters. These flakes are produced from tanks each containing 25 kg of liquid CO_2; four tanks are used to seed at 6.5 kg per minute.[3] In the early 1960s the Soviets reported experiments on clearing large areas (up to 20,000 km²) of supercooled clouds. Successful operations of this type could have considerable military potential for tac-

tical air, land, and sea operations, and are of considerable scientific interest because the energy involved approaches that required to cause a measurable perturbation in atmospheric circulation. No recent reference has been found to any further operations involving large areas, although at a recent meeting, Ye. K. Fedorov, chief of the Main Administration of the Hydrometeorological Service (GUGMS), stated that more work should be done on large cloud systems.[9]

Work still continues in the USSR on supercooled cloud and fog dispersal, but the major effort of Soviet scientists in this subfield has been diverted to the much more perplexing problem of dissipating warm clouds and fogs.[9] Warm clouds and fogs are much more prevalent than supercooled types, and they are much less susceptible to modification.[7] The Soviet warm cloud and fog effort is led by the Main Geophysical Observatory in Leningrad with the cooperation of the Central Aerological Observatory in Dolgoprudnaya, the Institute of Experimental Meteorology in Obninsk, and the Ukrainian Scientific Research Hydrometeorological Institute in Kiev.[17] Any successful techniques developed in warm cloud and fog dispersal would have considerable military, civil, and scientific significance.

The Soviet program for modifying warm clouds and fogs generally has proceeded along lines similar to those of Western countries that are active in the field. The major Soviet effort has been devoted to determining the feasibility of using heat sources and of seeding with hygroscopic or surfactant materials.*[9 17] The available information indicates that the Soviets have not yet settled on any one technique but that they are still searching for a workable method.[9 10]

Heat sources have been used at least since World War II when the British developed the fog investigation dispersal operations (FIDO) system to dissipate warm fogs over runways. The principle behind this method is that the addition of heat will result in the evaporation of the fog. The heat may be applied from below, as with the FIDO system, or from above. The addition of heat from above is a commonly observed natural phenomenon when ground fog is dissipated after the sun rises in the morning. In principle, this process can be assisted and speeded up by adding a heat absorbing material, such as carbon black, to the top of the fog deck thus increasing the absorption of the solar radiation. The addition of heat to evaporate a warm fog is a proven technique; however, US studies to date have determined that it is only marginally cost effective. Nevertheless, at some locations where fog is very prevalent this method may prove to be worthwhile. The French have made the decision to install jet aircraft engines underground alongside the runways at Orly Airfield to provide the necessary heat to dissipate warm fogs.

There is some evidence that the Soviets currently consider the heat source technique to be the most practical, at least for situations where there is a requirement for rapid fog dissipation as might be required for aircraft operations. Gayvoronskiy of the Central Aerological Observatory cites these figures from theoretical calculations: for a warm fog 50 m thick with a water content of 0.1 gm/m³, 149 cal/m³ of heat are required to disperse the fog in 0.5 minute. To perform the same rate of clearing with hygroscopic particles, hundreds of kilograms of seeding material per second would be required. Gayvoronskiy further points out that the heating method contributes little pollution to the atmosphere, is fast acting, and is not dependent on the varying microphysical characteristics of fogs. He concludes from this that thermal methods of warm fog dispersal should be given preference over others.[10]

Although there has been some laboratory work reported by the Soviets on hygroscopic and surfactant materials, there has been surprisingly little reported in the way of actual field experimentation. [redacted] However, one Soviet scientist has stated that his laboratory work in this field which formerly was unclassified has now been classified by the Soviet military.[18] This indicates that the pub-

*Hygroscopic materials have the property of increasing the condensation of water vapor, and such materials as NaCl and $CaCl_2$ are commonly used as hygroscopic seeding agents. Surfactant materials reduce the surface tension of the cloud or fog droplets, which results in a more rapid coalescent rate of the droplets. When the droplets grow large enough through this process, they fall out as rain or mist and the cloud or fog should dissipate provided the efficiency is great enough.

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lished Soviet literatur [redacted] probably do not give a true picture of the actual situation, and field experimentation on the dissipation of warm clouds and fogs very likely is under way in the USSR.

The reason such R&D has been classified by the Soviets is not entirely obvious. There is no question that the development of a successful method to dissipate warm clouds and fog would have important military implications, but other types of weather modification, which they do not classify, also have such implications. Warm cloud and fog dissipation has the obvious potential for aircraft operations and many ground and sea battle situations. Other reasons for the classification could be that the Soviets have discovered a technique which they believe to be superior to techniques under development by other countries or that its potential is greater than other subfields of weather modification.

In contrast to the general lack of information on Soviet field experiments on warm cloud and fog dissipation, one field project to disperse fog over Kola Bay has been reported rather freely. This project is under the direction of the Ukranian Scientific Research Hydrometeorological Institute, and personnel from Kiev State University and the Murmansk Administration of the Hydrometeorological Service also are involved.[20] These experiments were started in the winter of 1964-1965 to determine the feasibility of dispersing warm fogs over the bay by covering the water surface with a monomolecular film of higher fatty alcohols. In theory, such a film should reduce the evaporation from the water surface thereby cutting off the moisture supply which is responsible for the formation of the fog. Although the Soviets have claimed some success with this technique, no spectacular results are apparent.[8] One interesting result the Soviets have reported from these experiments is that when the winds are stronger than 7 m/sec (about 15 mph) the film is destroyed.[8] Nevertheless, the Soviets have been successful in dissipating warm fog using these techniques when the proper conditions have existed. However, they have found that very large quantities of reagents are needed to clear large areas. Presently they are using kerosene as a solvent for the fatty alcohol reagent, and this presents a problem when large quantities are involved. Consequently, the Soviets are searching for other solvents which could be used for spreading an effective film on the water.[20]

One laboratory experiment has been reported which has interesting possibilities if it proves to be successful. It was an attempt to coat the fog droplets rather than the sea surface with a monomolecular film of higher alcohols.[21] If this technique were successful, it should reduce evaporation within the fog or cloud and thereby prolong rather than reduce the lifetime of the fog or cloud. The capability to prolong cloud or fog lifetime could be used in many tactical military situations, but there are few obvious situations where such a technique would have an economic application. This experiment was reported at a 1966 conference in the Soviet Union and no further information has appeared. This could indicate that the Soviets have found the technique to be infeasible under natural conditions as opposed to the laboratory conditions under which it was first tested with some reported success. On the other hand, it could also indicate that work has continued but has been classified because of military implications.

Severe storm modification

The Soviets have reported no experiments to modify large severe storms comparable with the US STORMFURY project, which is designed to study the effects of modification techniques on hurricanes. However, the Soviets have conducted numerous experiments on individual cumulus clouds and some on fully developed thunderstorms. These experiments in general have been designed to stop the growth of the cumulus clouds before they reach the thunderstorm stage or, in the case of the experiments on cumulonimbus clouds, to reduce the effects after the thunderstorm stage has been reached. In one set of experiments, the Soviets have attempted to produce the opposite effect; that is, to induce the growth of small cumulus clouds into mature cumulonimbus clouds. Such experiments, if successful, would have application both for military and civil operations. The ability to prevent severe thunderstorms would be useful for protecting vulnerable military equipment such as aircraft or missiles and for protecting exposed personnel. The ability to produce thunderstorms could be used as an offensive weapon in tactical situations.

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A group of scientists under the leadership of the Central Aerological Observatory is conducting an experimental field program in the Georgian SSR to dissipate rapidly growing cumulus and cumulonimbus clouds. This project is designed to destory the ascending currents within the cloud and to change them to descending currents. The downward motion stops the vertical growth of the cloud and, if it continues long enough, will result eventually in the destruction of the cloud.[32 33] In these experiments the Soviets have seeded the growing cumulus clouds with insoluable particles of 5 to 50 microns. Different seeding agents have been tested but clay and cement have been the most commonly used. In some of the later experiments a CuO powder also has been tested. The seeding agent is dispensed in fairly large quantities (up to 50 kg have been used) from an IL-28 jet aircraft. The material is ejected into the cloud where upward motion is the greatest; tests have been conducted on clouds of up to 10 km in vertical extent.[33] According to recent information, the Soviets have conducted experiments of this type on 500 cumulus clouds and on 65 cumulonimbus clouds which had reached the thunderstorm stage.[34] The Soviets claim that effects from the seeding were observable on 62 of the 65 experiments on cumulonimbus clouds, and almost all of the cumulus clouds showed an effect.[35]

The first effect usually observed after seeding was a noticeable darkening of the cloud followed by lamination and evaporation. Precipitation often was noted falling from the cloud following the seeding, but this usually was very light and in many cases evaporated before reaching the ground. In the majority of cases reported, complete dissipation of the cumulus cloud occurred in 20 to 30 minutes, although remnants of middle or high level clouds often persisted.[33] To minimize the possibilities that these effects could have occurred naturally, the Soviets have conducted all the experiments between 1300 and 1600 hrs local time when convection normally is at its greatest. They also have observed the behavior of untreated clouds in the vicinity of operations to determine whether any of these dissipated naturally. Visual and instrumented observations of the results of these experiments have been carried out from an IL-14 aircraft and by ground-based radars.[36] Apparently no attempt has been made up to the present to randomize the experiments, and it is therefore difficult to judge the true efficacy of the work. However, the results reported are rather impressive and indicate that the Soviets have been able to dissipate at least some cumulus and cumulonimbus clouds under proper conditions.

Another project, similar in principle but smaller in magnitude and using different techniques, is being carried out by personnel from the Institute of Experimental Meteorology. This project also is directed toward the dissipation of cumulus clouds by creating artificial downdrafts, but aircraft jets are used instead of cloud seeding agents.[34] Jet aircraft are flown through the clouds at high pitch angles, thereby directing their jet downward through the cloud. Nine experiments of this type have been reported, and in all cases some effect was noted. According to the Soviet report, the clouds either completely dissipated, broke into parts, or ceased their vertical growth. The operations were carried out on cumulus clouds ranging from 5 to 6 km in vertical extent.[34] Although positive results were reported from these experiments, the necessity of flying the aircraft through the clouds probably will limit the usefulness of this technique to a considerable degree.

The same experimenters together with personnel from the State Scientific Research Institute of Civil Aviation have tested the feasibility of using jet aircraft engines on the ground to create artificial updrafts in an attempt to stimulate the growth of cumulus clouds into cumulonimbus clouds. During dry weather in the summer, cumulus clouds often will form but will be prevented from developing into cumulonimbus clouds by a temperature inversion at some level in the free atmosphere. In theory, if an ascending current could be produced that could penetrate this inversion, the cloud might continue to grow and eventually to produce rain. An analysis of several years' data showed that 75 percent of the summer inversions over Moscow could be penetrated in this manner, and in 1967 an experimental apparatus was set up near Borispol. Four jet engines were joined so that their exhaust jets all fed into one vertically directed vent. Twenty experiments were carried out to test the technique. In most cases the Soviets reported that small cumulus clouds were formed over the jets. In the case where natural clouds were already present, they generally became larger in size. In a few cases the clouds darkened at the base and occasionally produced rain. According to Soviet reports,

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they plan to continue these experiments and increase the number of jet engines used from four to ten.[20] These results reported thus far by the Soviets do not appear to be very significant. The use of additional engines might produce better results, but the fuel consumption is likely to make this technique marginal at best with regard to cost effectiveness. However, cost may not be a factor for a military system, and the Soviets might continue R&D on this technique if further testing indicates that it may be militarily useful.

Related research

Despite the relatively large weather modification research effort that has been carried out over a number of years, there are still several questions relating to the basic physics of clouds and precipitation that are still not completely understood. One of the unresolved microphysical problems of cloud and precipitation processes concerns the initial stages of rain formation through coalescence of water droplets. A requirement for relatively simple, reliable field instrumentation for measuring the concentrations of atmospheric ice nuclei still has to be met. Further, much work needs to be done on measuring and reproducing in mathematical models the atmospheric motions in and around clouds.[20]

The Soviets have recognized the unsolved problems in basic cloud and precipitation physics, and they have conducted an active research program for many years in these areas. In general, however, it appears that the Soviets lag the United States in these theoretical aspects of their research.[1] The Soviets have acknowledged that they are weaker in the basic research than in the experimental work, and Ye. K. Fedorov has stated that one of his objectives is to strengthen that portion of the program to increase the understanding of the physics of what really happens.[1,21]

The Soviets have relied heavily on cloud chambers to collect basic data for their microphysical studies on clouds. The Institute of Experimental Meteorology at Obninsk has at its disposal three large cloud chambers, two with a volume of 100 m^3 and one with a volume of 3,200 m^3.[1,21] The latter chamber is one of the largest in the world, and one of its advantages is that it allows larger volumes of clouds to be studied. The 18-m height of this chamber also allows the Soviets to study the effects of seeding nuclei on the water droplets as the nuclei fall down through the artificial cloud. A distinct disadvantage of the chamber is that the temperature can be regulated only between 15° and 20°C, and the pressure can be regulated only between 1.0 and 1.5 atm.[21] Although these restrictions are not very serious for the study of low-level clouds, they are unreal for higher level clouds. This chamber is highly instrumented to collect microphysical data from the artificial clouds contained in it. One impressive instrument used on this chamber is a photoelectric sensor which measures the drop size distribution in the air that is funneled past the counter. This instrument can be set to measure particles in increments of 4-micron steps, the smallest being 8 microns.[21]

The two smaller cloud chambers at the Institute of Experimental Meteorology are much more versatile than the larger chamber. These cloud chambers are designed so that the temperature can be regulated between −50° and 20°C, and the pressure can be regulated from 0.05 to 2.0 atm.[20] Thus these chambers provide for a more nearly real atmosphere than the larger facility and for most research they may be more useful. The Soviets are building a 200 m^3 cloud chamber at the Institute of Geophysics under the Georgian Academy of Sciences.[5] This chamber will have the capability of reaching temperatures as low as −40°C but its pressure capability is not known. Present plans are to instrument this facility with optical lasers and a 1-cm radar to measure the moisture content of the clouds which are produced. It appears that this will be an excellent research facility when completed, but it is somewhat questionable whether the staff at the Institute will be capable of utilizing it to its fullest extent.[11]

The Soviets have also been actively investigating the microphysical properties of clouds using instrumented aircraft and radar. These types of investigations are necessary to supplement the cloud chamber studies because, no matter how sophisticated a cloud chamber is, it is impossible to duplicate all the processes and interactions found in the real atmosphere. Instrumented aircraft, which traditionally have been widely used for collecting microphysical data, are still used, but modern radars are now making it possible to collect much of this data indirectly. Aircraft measurements suffer from several

limitations among which are the difficulties in flying through convective-type clouds and problems in developing instruments that will make accurate measurements of the necessary parameters.

Soviet development of radars for these purposes generally has kept pace with Western developments. They have done a great deal of work with dual frequency radars: 3- and 10-cm radars are used extensively in the hail suppression program to discriminate between hail and nonhail clouds. Information from the two radars is fed into one radar console, which then directly presents the difference between the reflectivity of the cloud in the two wavelengths on both the plan position indicator and the A-scope.[3] The Soviets claim that this differencing technique is very accurate in discriminating between those clouds which produce hail and those which do not. They also use the dual frequency technique to determine the intensity of precipitation. In this case they use wavelengths of 0.86 and 3.2 cm. By measuring the differences in reflectivity and absorption in these two wavelengths, the Soviets claim that they are able to overcome the problems of variable drop sizes in the cloud, which make such measurements on single frequency radars difficult.[33] The Soviet capabilities for processing the dual frequency radar information in real time are impressive, and it appears that this technique should be useful for studies of clouds and precipitation.[34] The Soviets also use radar methods for other microphysical measurements of clouds, and it appears that their use of radar and radar processing equipment for these studies will be expanded.[3]

The Soviets also are actively engaged in seeding-nuclei research. At the present time they seem to favor the use of lead iodide, probably because it is readily available to them.[3,34] The United States favors the use of silver iodide over lead iodide because US techniques for crystallization have not worked well with lead iodide. However, it appears to work satisfactorily with Soviet pyrotechnic methods.[3] The Soviets have expressed some concern about the toxic effects of lead iodide and they have tested many other substances in the laboratory and some in the field. They seem to favor copper sulfide at the present time to replace lead iodide as the primary seeding nuclei. They claim to have developed a powdered form of copper sulfide that can produce about 10^{15} nuclei per gram, which is very good. They have also indicated that they have enough confidence in copper sulfide as a seeding nuclei to begin using it in their hail suppression program.[3] This could be quite significant if successful because copper sulfide is a much cheaper product than silver iodide. Organic materials, hygroscopic nuclei, and various insoluble materials are also being investigated intensively, particularly for use on nonsupercooled clouds and fogs.

CLIMATE MODIFICATION

The Soviets have shown an interest in climate modification for many years. This interest probably is partly due to the unfavorable climate which prevails over much of the USSR. In addition a successful climate modification technique could have considerable significance for both tactical and strategic military operations. Many schemes have been proposed in the Soviet Union for melting the Arctic ice and thus moderating the average temperatures of the northern areas of the country. One of the oldest and best known proposals is that of P. M. Borisov, who has advocated damming the Bering Strait. Borisov's concept is to pump water from the Arctic Ocean through a dam into the Pacific Ocean. This, in turn, would draw the warmer water from the Atlantic Ocean through the Arctic Ocean and eventually melt the ice.[36] Borisov claims that the ice in the Arctic Ocean would be completely melted in three years, and that once melted, it would not return. Borisov, an engineer, claims that this project is technically feasible, and scientific studies at the Main Geophysical Observatory tend to support his claim that the ice would not re-form once it was melted. However, M. I. Budyko, director of the Main Geophysical Observatory, has pointed out that his studies show that melting the Arctic ice could have adverse effects on the climate of the temperate zone of the USSR.[37] Despite this warning, Borisov periodically revives his proposal for damming the Bering Strait.

Although the Soviets have apparently approached the proposal for large-scale melting of the ice in the Arctic with caution, they have developed and used other techniques for melting ice on a smaller scale. One technique which they have used for many years is to blacken the surface of the ice to increase the amount of solar energy absorbed by the surface. The Soviets apparently have concluded that this technique is feasible, although some tech-

nical difficulties have been encountered with the use of carbon black as the blackening agent. During recent years the Soviets apparently have been using coal dust rather than carbon black as the blackening agent, and this seems to have eliminated some of the early problems.[28] Personnel from the Arctic and Antarctic Scientific Research Institute developed this technique. They claim that, using coal particles 3-4 millimeters in size, they can melt a volume of ice of about 3 km² in area and 2 meters thick. Approximately 500 tons of coal dust applied at frequent intervals are required to melt this volume of ice.[29] It can be seen from these figures that a very large logistic effort would be required to melt the large areas of ice in the Arctic Ocean using this technique, but Ye. K. Fedorov has stated that it could be done.[30]

The lack of quantitative data on what effects large-scale climate modification in the Arctic would have on other areas of the country probably has been the governing factor against proceeding with experiments of this type. Quantitative data of this type probably will not be available until satisfactory mathematical models of the atmospheric circulation can be developed. A group at the Computing Center of the Siberian Division of the Academy of Sciences is very active in the development of such models. However, the best computer available to this group is the BESM 6, which is not adequate for testing the very sophisticated models required in the field of climate modification. Until new and improved computers become available and realistic atmospheric models are developed, large-scale climate modification experiments probably will not be field tested by the Soviets.

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