SCIENTIFIC WEATHER MODIFICATION

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Contents

Summary

In general, weather modification is any effort to alter artificially a natural phenomenon in the atmosphere. There are two main ways of the human impact upon the weather and climate, i.e. unintentional and intentional influence on the natural processes. Scientific weather modification usually means a technique to realize intentional change of the atmosphere state based on previously carefully investigated ways to control natural processes running in the atmosphere. Many damaging phenomena in the atmosphere such as wind breaks, thick fogs, strong frosts, hail and others can be an object of modification. After a long trial-and-error experience, people apply in practice only a few methods for the weather modification which are enhancement and redistribution of precipitation, hail suppression, fog dispersal, and a dispersal of super cooled low-level clouds and precipitation. Except the hail suppression method all the others are based on the understanding of the cloud microphysics. It can be achieved by either static or dynamic cloud seeding. Static cloud modification is realized by introducing a certain amount of artificial particles of silver iodide or solid carbon dioxide into subfreezing levels of a liquid water cloud in which natural ice nuclei are deficient. Precipitation results because ice crystals grow rapidly in a subfreezing liquid water environment. Dynamic cloud seeding involves the massive injection of silver iodide into a subfreezing layer of a growing cumulus cloud composed of water droplets. The hail suppression is based on the concept

that damage can be reduced if the hailstone sizes are reduced. Nowadays, effective techniques for intentional modification of clouds and fogs have been developed, which allow successful prevention of losses from hazardous weather phenomena, detrimental to economy, such as insufficient or redundant atmospheric precipitation, fogs at airports, etc. Physical bases and main principles of the cloud modification along with the technical means are described in this article.

1. Introduction

Mankind has always dreamed of becoming independent of hazardous weather conditions, and attempts to fight droughts had been undertaken at the very dawn of civilization. The same refers to other phenomena, such as hail, thunderstorm and lightning. So, for thousands of years, people sought ways to modify weather and climate so that to augment water resources and mitigate severe weather. However, lack of the necessary understanding of the atmosphere physics and weather-forming processes together with poor technology prevented solving that problem.

Human impact upon the weather and climate follows the whole history of our civilization since even cutting a part of forests by first human tribes had a certain effect upon the environment. This impact may proceed by both unintentional and intentional ways. Unintentional impact plays an important role but for a long-lasting period, and, thus, can not be noticed by just one generation. So, this article presents so-called **intentional weather modification.**

In the majority of cases the term "artificial weather modification" still refers to seeding clouds and fogs, aimed at either destroying or dispersing them, or starting or redistributing precipitation. That is so, because the processes forming both weather and climate, command enormous energies, so that their direct changes by the available technical means are still out of the question. It is only in cloud formations that the atmosphere appears to be in a state of unstable equilibrium, so that expending comparatively low energies one is capable of significantly changing the course of the natural processes.

Based on the results of long-term theoretical and experimental investigations in the field of artificial weather modification, conducted by numerous research institutions throughout the World, effective techniques for intentional modification of clouds and fogs have been developed, which permit successful prevention of losses from hazardous weather phenomena, detrimental to economy, such as insufficient or redundant atmospheric precipitation, fogs at airports, etc.

2. History of the Problem

It is clear that mankind always tried to improve their environment whatever and wherever people lived. In antique times, attempts to change weather were expressed in superstition-religious form. In ancient Greece (*Naturales quaestiones* by Seneca), performance of religious duties, needed to prevent losses because of hail, was entrusted to special responsible persons appointed by the state. As a fee, they received from population a live-stock and meal. Hail watchmen must have sent hail-bearing clouds in a safe direction, i.e. to the sea or mountains. When they failed a punishment was inevitable.

Since prayers of saint fathers were not successful, already the very first Rome Code «Twelve Tables» prohibited using of the superstitious ways of a fight against hail. However, helpless people watching destruction of fields and gardens attempted to try any available means. For many years people set all the bells ringing and exhibited tables with prayers. In 789, Charles (Karl) the Great forbade to ring the bells and to expose the tables. Initial shooting to clouds with arrows was later replaced by gun and riffle shots and firing from guns and mortars after the gunpowder was invented. In 1789, Austrian empress Maria Terezia, receiving many complaints for evil-minded direction of hail clouds, ordered to find out if any use was received from similar fights against hail. Answers from different regions of the Empire were contradictory but they mostly contained requests for permission to continue the shooting and ringing. Despite that, in 1750, the shooting was strictly prohibited throughout the whole Austrian Empire, but even stern measures did not stop attempts to suppress hails far away from the capital, and the shooting was going on. Since in other countries of the Central and South Europe no veto existed, people there continued to shoot the hail clouds.

It is clear that these measures had no scientific bases, and the science of XVIII century was not able to create any basis for the weather modification.

It may be thought that a real history of the weather modification began in 1772 when the Bavarian Academy of Sciences declared a prize for any successful way to change weather according to a human need.

In 1886, the Austrian Empire started scientific experiments for anti-hail shooting at the large scale. At that time, over the whole Europe (Austria, North Italy, Switzerland, France) the anti-hail shooting from big mortars up to 4 m long was spread. Already in 1900, the shooting from 10 000 mortars was done just in Italy alone. During the period from 1899 to 1920, six international congresses were held to discuss problems of the anti-hail struggle. At the congress of 1902, the decision was made to ask governments of Italy and Austria to assign funds for long-lasting and decisive experiments. They were completed in 1906, and the results were considered negative in Italy and Austria, although the experiments carried out did not give definite answer in France.

At the same time, other possible mechanisms (mechanical, sonic, electric) to suppress hail by bombs and rockets were discussed in details. Chemical effects of the bombs and rockets were considered too, and it was estimated how the explosion products may become nuclei of condensation.

Fighting against a hail logically suggested a possibility to fight against an adverse weather in general, and, in particular, against droughts. American general Pauers in his book «War and Weather» described 137 great battles after which in one or two days a rain occurred. Although statistics estimated the data presented in Pauers' book as failing to prove, in 1981, the USA government assigned funds for experiments to generate a rain by explosions. Three types of means were tested which are: air balloons filled with a fire-damp gas; bombs filled with dynamite which were lifted by kites and exploded near the ground with great amount of explosives containing the potassium chloride. Heads of the expeditions reported on successful results, but meteorologists considered them as the nullity. After 1982, these experiments were never repeated, and only in 1909, similar attempts were tried in New Zealand.

Certainly, experiments aimed at a solution of the problem of artificial rain generation were connected with one or other idea on a nature of the atmospheric precipitation. American experiments were based upon the suggestion that particles from the explosions are nuclei of condensation, and the sonic waves make small cloud droplets to merge and, thus, to form rain drops.

Perhaps, American scientists underestimated the air warming caused by intensive explosions. Still in 1837, the American meteorologist Prof. J. P. Espy proposed the idea of a possibility to stimulate development of the convective clouds by a heat energy release, e.g., by burning a wood. On the contrary, Prof. A. Macfarlane proposed to drop the cloud temperature instead of its rising. Increase of the temperature vertical gradient up to unstable state of the medium causes vertical flows, and, finally, precipitation, and the amount obtained depends on a degree of the temperature drop in upper layers. A. Macfarlane proposed to reduce the air temperature at high levels by evaporation of liquid carbonic acid. However, both above approaches in the stable atmosphere required expenditures much greater than a cost of additional yield achieved.

In the past, considerable attention was given to verification of the hypothesis that a change of the atmosphere electric state can make effect on precipitation and a hail generation. At the end of XVIII and beginning of XIX centuries, a wide spreading of lightning rods in Europe was followed by repeated attempts to use the rods as hail rods. Different types of the hail rods were proposed, but using of them to fight against a hail proved to be useless. In 1893, famous physicist F. Arrago suggested to reduce a difference of the potentials by means of lifting kites or balloons with conducting wires. In 1893, A. Baudouin hoisted kites with conducting rope up to height 1200 m and asserted that in such cases a fog was generated and rain drops precipitated. However, numerous experiments in other countries could not obtain convincing arguments in support of this method.

In 1910, at a meeting of the International Association for Science Development in Shephild (Great Britain), when a problem regarding the electrization influence upon a weather was discussed, well-known physicist J. J. Thomson reported that, according to his calculations a moderate amount of electricity is sufficient to modify the weather over a large area. Now, we know that, in the past, great scientists sometimes made mistakes in their estimates and forecasts. Many years of theoretical and experimental work were taken to create nowadays notions of the atmospheric electricity and to estimate realistically its influence upon the weather and climate. And only at the beginning of XX century, basic researches of great scientists A. Vegener, T. Bergeron and U. Findeisen created scientific basis for development of the weather modification methods. First field experiments for cloud seeding were carried out as early as in the 1930s.

Since the beginning of XX century, problems of weather modification were actively discussed and developed in Europe, and a number of symposiums were hold. But, it was only during the last 40 or 50 years, that developing of techniques for intentional artificial modification of weather processes has become one of important branches of sciences on the atmosphere.

Different means for active weather modification (WM) were suggested to modify clouds and fogs via artificial enlargement of cloud particles up to the precipitable sizes. Attempts to introduce water droplets or some hygroscopic particles into clouds were also undertaken. The means finding the widest use are those when certain reactants (agents) are introduced into super cooled areas of clouds to produce their crystallization. Experiments in which some crystallizing agents were introduced into a cloud demonstrated the most successful results. Below, the physical basis of this technique is outlined. It should be noted that the very first successful experiments in active modification of natural clouds were undertaken in 1931 by the Dutch physicist A. Feraart, who used dry carbon dioxide (CO_2) as the icing agent.

Quite a long background of studies is known to search ways for active cloud modification in the former USSR. In 1921, V.I. Vitchevich conducted a series of laboratory experiments in enlarging fine water droplets by charged sand and tried to develop a theory to substantiate this technique. A technique for artificial cloud modification was created in a specially founded Moscow Institute of Artificial Rain, headed by S.L. Bastamov. In 1931, a department of that Institute was later transformed into the Leningrad Institute of Experimental Meteorology (LIEM), its main goal was to develop preventive means against droughts. In this institute, studies on problems of the artificial weather modification were headed by Professor V.K Obolenskii, an eminent scientist of that time. Regretfully, the Second World War had temporarily broken off these studies.

Figure 1: Flying laboratory “Ilyushin-18” equipped with different sensors for measurements of atmospheric parameters and tools for cloud seeding. It was used in various research and operational projects for weather modification

In 1946, V. Sheffer and E. Langmuir conducted successful experiments in the USA in dispersing a fog in a freezing camera. They introduced particles of solid CO_2 into it, thus actually repeating the Feraart experiments for a cloud dispersal. B. Vonneghut (1946) suggested the use of silver iodide (AgI) as such agent, its particles playing the role of crystallizing centers, or nuclei, serving a center for further growth of the ice crystals. Starting from the end of the 1940s, development a new technique for active cloud modification, as one of the means for intentional control of atmospheric processes, found increasingly wide support in the former USSR, the US, Israel, and some other countries. WM was first primarily aimed at dispersal of fogs, stratiform clouds and stimulating a precipitation. In 1958, experts from Central Aerological Observatory (CAO) of the Russian Hydrometeorological Service together with those from the Institute of Geophysics of the Academy of Sciences of the former Georgian SSR started developing the hail-suppression techniques. These studies resulted in a practically feasible technique for hail suppression, aimed at protection of valuable agricultural crops. As a result, it became possible to start systematic hail suppression programs in the former USSR for protection of various crops, grapevines, first of all. Initiated in 1961, such service is still operating in various regions (Fig. 1) of the Caucasus, the Crimea, Moldavia, Central Asia countries, and the South of the European Russia (former USSR). Such operations are carried out also in some countries of South America, and others.

3. Physical Basis for Artificial Modification of Clouds and Precipitation

Water in clouds may be found in three different phases: the vapor (gas phase), the liquid (water), and the solid phase (ice crystals, soft and hard hail). For precipitation to fall down from clouds in mid-latitudes both super cooled droplets (this implies that the temperature of the medium is below 0°C), and ice crystals should be presented in the clouds, i.e. they should be clouds of mixed type. In this case, the ice particles begin to grow due to pumping of water vapor from droplets to crystals. Such pumping is possible due to the fact that the saturating pressure of the water vapor above the surface of ice crystals is lower than that above the water droplets. If a cloud consists of super cooled water droplets only, which do not differ too much in their size, (and that is the most typical for fogs and stratiform clouds of the cold season), no precipitation would fall down from a cloud, since there is no efficient mechanism for a quick enlargement of cloud particles, and hence - for formation of precipitation particles. If the temperature inside the cloud is positive, precipitation would fall out only in the case when the vertical extension of the cloud itself is very large, and droplets strongly differ from one another in their diameter (mass), so that they fall with different vertical speeds. Large particles then catch up with the fine ones, and may merge with them upon a collision. Such a process is called gravitational coagulation. Apparently, gravitational coagulation may only result in forming large enough particles in extremely developed purely water droplet clouds (which are the most typical for the tropics). Note that if a cloud temperature exceeds 0°C, only one droplet of every million may grow to the size of a rain droplet in it.

As for the middle latitudes, a precipitation from a purely water droplet cloud (or a fog), remains so weak and fine, that it reaches the ground as drizzle only. No noticeable precipitation falls out of purely crystal clouds either.

A most important result from studies of the processes of the precipitation formation consisted in a conclusion that a certain optimal amount of ice crystals had to be contained in a cloud for a heavy rain (snow) to fall from it. In a case the concentration of such crystals is low; additional crystals have to be introduced into such clouds to stimulate formation of precipitation.

Ice crystals in the cloud can be artificially formed if particles of solid carbon dioxide are introduced into it or some "ice-forming" aerosols are dispersed within the cloud. Solid carbon dioxide (the dry ice) and ice-forming aerosols are called agents for the purpose of weather modification practices. Introduction of such agents into the cloud is called seeding. The action of such a freezing agent, such as carbon dioxide, for example, consists in sharply decreasing the local air temperature during evaporation of its particles in a super cooled water droplet cloud (solid carbon dioxide evaporates at -79 °C), so that the air becomes heavily supersaturated with water vapor around such particles. Thus, an enormous number of fine ice crystals is produced, and they stimulate water vapor pumping from water droplets to ice particles.

Assuming that all the cold productivity of solid CO_2 introduced into the cloud is spent on cooling of ambient air down to some critical temperature (t_{cr}) and on forming fine ice crystals, one may estimate the maximum possible number of such newly formed crystals, $N_{\max}$, from:

$$N_{\max} = \frac{Q\left(q_t - q_{t_{\mathrm{cr}}}\right)}{4/3\pi\rho_{\mathrm{i}} r_{\mathrm{cr}}^3 c\left(t - t_{\mathrm{cr}}\right) + L\left(q_t - q_{t_{\mathrm{cr}}}\right)} \qquad (1)$$

where $Q = 638.7\ \mathrm{J\,kg^{-1}}$ is the cold productivity of solid carbon dioxide; q_t and $q_{t_{\mathrm{cr}}}$ are the amounts of water vapor per unit mass of air at temperatures t and t_{cr}, respectively (per mille); ρ_{i} is the density of ice (g $\mathrm{m^{-3}}$); r_{cr} is the critical radius of an ice particle (m); c is air heat capacity (J $(\mathrm{kg\,K})^{-1}$); L is latent heat of formation of ice particles (J $\mathrm{kg^{-1}}$).

Both calculations and experimental measurements demonstrated that on evaporating of 1 g of a cooling agent in a cloud medium at temperatures below -5°C, 10^{11} - 10^{12} ice crystals could be formed.

Introduction of crystallizing aerosols into a super cooled cloud may be done by sublimating the necessary substances in special generators, or burning special pyrotechnic mixtures, containing the active aerosol of silver iodide (AgI). Its action is based on the crystallographic similarity between the ice and AgI crystals. After their introduction into a cloud, the particles of AgI serve as artificial crystallization nuclei. Due to pumping of water vapor from cloud droplets to ice crystals or due to freezing of cloud droplets upon collision with those crystals ice particles grow to turn into precipitable particles. Crystallizing aerosols are characterized by their threshold and limit activity levels.

The ambient temperature at which the particles of AgI become active as ice forming crystals is -5...-6 °C. The output of active nuclei depends on the temperature of the cloud medium and on the sublimation technique used. For example, the number of active nuclei produced during sublimation of 1 g of AgI varies from 10^{12} to 10^{16} at ambient temperature within -10...-20 °C.

The change of the phase composition of clouds or of the ratio between the solid and the liquid phases in such clouds by introducing active ice forming agents into them (such as CO_2 and AgI) is the principal technique used for artificial modification of clouds. It serves to disperse super cooled clouds and fogs, to produce precipitation, to suppress hail, and is also one of the possible techniques in thunderstorm suppressing operations.

To introduce the agent into the cloud, special anti-hail rockets and cannon shells are designed, used to introduce the agent into the cloud from below. When seeding clouds from above, from board aircraft both pyrotechnical compositions and solid carbon dioxide are used. Ground-based aerosol generators may be used in mountainous areas.

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Biographical Sketches

Albert A. Chernikov, professor, Dr.Sc. in Physics and mathematics, was born on January 4, 1936 near Moscow (Soviet Union). In 1959, he had been graduated from Moscow Physical and Technical Institute which was the best in the country high school in field of physics and mathematics. A citizen of Russia, he is now one of leading Russian scientists in the field of the atmosphere physics and, particularly to cloud physics and radar meteorology. Since 1959, he works in Central Aerological Observatory of Russian Federal Service for Hydrometeorology and Environmental monitoring. Starting with young scientist, he is now the director of this research institute. For many years he was active member of Commission for Basic Systems of the World Meteorological Organization and reporter of WMO on weather modification issues. He participated many times in important international meetings and assemblies such as ICSY, IAMAP, etc.

Yury V. Melnichuk, PhD in physics and mathematics, was born on April 26, 1937 in Moscow (soviet Union). In 1960, he had been graduated from Moscow Physical and Technical Institute which was the best in the country high school in field of physics and mathematics. A citizen of Russia, he is now one of leading specialists in the world on the atmosphere physics and, especially in the filed of radar meteorology and weather modification. Since 1960, he worked in Central Aerological Observatory. Starting with young scientist, he is now the head of Department on Weather Radar Meteorology. In1970s, he participated in several important international experiments such as GARP Atlantic Tropical Experiment (1974) and International Experiment on Precipitation Enhancement (Spain, 1976). For several last winter seasons he headed experiments for precipitation enhancement in Syria and Iran. Many times he participated in the international symposiums on cloud physics and weather modification.

Nina A. Zaitseva, Dr.Sc. in Geography, was born on August 30, 1940 in Moscow (Soviet Union). In 1962, she had been graduated from the Lomonosov Moscow State University as a geographer-climatologist. A citizen of Russia, she is now one of leading Russian scientists in the field of the atmosphere physics, radiation processes, and upper-air techniques. For about thirty years she dealt with the radiometersonde observations, which were organized on a special radiometersounding network on the USSR territory, weather ships, and in the Antarctica. Her PhD (1971) and Dr.Sc. theses were devoted to study of spatial and temporal variability of terrestrial (long-wave) radiation in the free atmosphere based on the radiometersounding method. She was active participant of a number of large international experiments in framework of the Global Atmosphere Research Program, twice participated in Soviet Antarctic Expedition. In 1976-1984, N.A. Zaitseva had been twice elected a member of the IAMAP (International Association of Meteorology and Atmospheric Physics) Radiation Commission. She participated with reports in several quadrennial International Radiation Symposiums, rather well experienced in international co-operation. She is the author of over 100 published works and the textbook on aerology.

In 1962-1997, she served as young, then senior scientist and secretary in Central Aerological Observatory of Russian Federal Service of Hydrometeorology and Environmental Monitoring. Since 1997, she is leading scientist of Department of Earth Sciences in Presidium of Russian Academy of Sciences.