ARTIFICIAL RAINFALL

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Summary

In many regions of the world traditional sources and supplies of groundwater, rivers and reservoirs are either inadequate or under stress from increasing demands on water from changes in land use and growing population. The ability to influence and modify cloud microstructure in certain cloud systems has been demonstrated and verified in laboratory, modeling, and observational studies. Cloud seeding for precipitation enhancement has been used as a tool to help mitigate dwindling water resources. Weather modification activities to enhance water supplies have been conducted for a wide variety of users including water resource managers, hydroelectric power companies, and agriculture. Many operational programs have been ongoing and have increased in number in the past ten years. Despite this, there is still a need for continued and more intensive scientific studies to further develop the scientific basis for this technology.

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1. Introduction

When people speak of water resource development, it is generally understood as building dams and reservoirs, installing pipelines or concrete lining ditches or canals, or in some way storing or distributing water resources. There is only one way of increasing or developing new water supplies, however, and that is to develop atmospheric water. In many areas of the world there is a need for additional new water supplies, and, in many of these areas, the weather modification technology can be useful.

In many countries, water supplies frequently come under stress from droughts, resulting in shortages and an increase in the cost of potable water. Groundwater tables have been steadily falling in many areas around the world. To help offset these stresses and mitigate depletion of water resources, cloud seeding has been invoked for precipitation enhancement.

2. History

In 1881, the USA Government assigned funds for experiments to generate rain by explosions. Three types of means were tested: air balloons filled with a fire-damp gas, and bombs filled with dynamite, which were lifted by kites and exploded near the ground with great amounts of explosives containing potassium chloride. Heads of these expeditions reported on successful results, but meteorologists considered them as null. After 1882, these experiments were never repeated, but in 1909, similar attempts were tried in New Zealand. American experiments were based on the suggestion that particles from the explosions would act as condensation nuclei, and the sonic waves would make small cloud droplets merge and, thus, form rain drops.

In the USA, Prof. J. P. Espy had proposed in 1837 the idea of stimulating the development of convective clouds by heat energy release, e.g. by burning wood. Adopting the opposite tack, Prof. A. Macfarlane proposed to drop the cloud temperature instead of the raising it. Increasing the temperature vertical gradient to an unstable state of the medium causes vertical flows, and, finally, precipitation, and the amount obtained depends on the degree of the temperature drop in the upper layers. Macfarlane suggested reducing the air temperature at high levels by evaporation of liquid carbonic acid. However, both the above approaches, in stable atmosphere, required expenditures much greater than the value of the additional agricultural yield.

In the past, considerable attention was given to verification of the hypothesis that a change of the atmosphere electric state can influence precipitation. In 1893, A. Baudouin in France hoisted kites with a conducting rope to a height of 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 results in support of this method.

It was at the beginning of the twentieth century, that basic research by the great scientists A. Vegener, T. Bergeron and U. Findeisen created scientific bases for the development of weather modification methods.

In 1921, the Russian scientist V.I. Vitkevich conducted a series of laboratory experiments with charged sand particles to accelerate the collision of water droplets and tried to develop a seeding technique. A weather modification program to enhance precipitation was undertaken 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, with the main task to develop drought mitigation measures. At the institute, studies in the field of weather modification were headed by Prof. V.K Obolensky. In 1939, field experiments to seed clouds using charged sand particles were carried out. Regretfully, World War II, temporarily, broke off these studies.

Probably one of the first attempts at using an aircraft to seed clouds was made in 1922

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when a bi-plane was used for shoveling salt into clouds over the Karoo in South Africa.

The first field experiments to seed clouds by dry ice were carried out before World War II. In 1931, the Dutch physicist A. Feraart used dry ice (CO_2) as an ice nucleating agent to seed clouds from an aircraft.

The experiments conducted at the General Electric Laboratories (USA) in 1946 and 1947 by Drs. Schaefer and Vonnegut demonstrated that certain materials were quite effective in converting supercooled liquid water droplets (droplets colder than freezing) into ice crystals. Schaefer demonstrated that dry ice (solid carbon dioxide), when dropped through a cloud of supercooled liquid water droplets, converted the droplets to ice crystals. The experiments conducted by Vonnegut showed that the most effective ice nucleants are silver and lead iodide (AgI and PbI). Schaefer and Vonnegut's discoveries ushered in the modern era of weather modification.

3. Scientific Basis

The technology of rain enhancement is based on the science of cloud physics with major ties reaching into mesoscale and boundary layer meteorology, weather forecasting, diffusion and turbulence, physical chemistry, aerosol physics, statistics and instrumentation. By combining field and laboratory experiments with theory and numerical modeling, cloud physicists are enlarging our understanding of clouds and precipitation processes. They have confirmed the usefulness of cloud seeding in certain meteorological conditions. Advancements in any of these fields will be required before the potential of weather modification can be thoroughly explored.

The scientific basis for cloud seeding to augment precipitation rests on the assumptions that natural cloud precipitating efficiency can be increased (static seeding) or that cloud development can be enhanced (dynamic seeding) to produce bigger clouds. Increasing precipitating efficiency of existing clouds assumes that at least some clouds are inefficient natural processors of cloud water for the formation of precipitation and that artificial treatments can be made that will increase the natural efficiency. Many clouds are naturally efficient and others are not. The assumption that cloud development might be enhanced implies that critical amounts of latent heat can be released by artificial seeding to substantially promote cloud growth in some marginal clouds. Man's tools for modifying the mechanisms that control cloud efficiency and enhanced development are very limited. Despite these limitations, there is a good scientific and an experimental basis for optimism that a sound cloud seeding technology can be developed for augmenting water supplies by at least small, but significant, amounts on certain occasions.

Precipitation efficiency can be defined as the percentage of condensed water within a cloud system that reaches the ground as precipitation. The remainder of the condensed water in the cloud is returned to vapor form through various processes. This loss back to vapor at the cloud edges constitutes a loss to the precipitation process. Precipitation augmentation can be realized if the precipitation efficiency is increased by cloud seeding. Seeding might also change the timing of various cloud processes and, thus, alter the precipitation location, but not change the precipitation efficiency or the amount

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of precipitation.

Very often, atmospheric water vapor present at surface temperatures and pressures is considerably less than that required for saturation. However, when lifting of the air takes place, the air expands and cools adiabatically. As this cooling takes place, the absolute amount of water in vapor form remains the same, but the capacity of the air to hold the water in vapor form decreases. Thus, when the lifting and cooling is sufficient, a temperature is ultimately reached for which the water vapor available is sufficient to produce water saturation at a new and colder temperature. Any further lifting and cooling results in temperatures at which the available water is greater than can be contained in vapor form in the air parcel, and the excess water is condensed out, generally, in the form of cloud droplets, but, on occasion, directly as ice crystals. It follows then that the amount of cloud water is controlled by the amount of water in an air mass being lifted. If all of this water ends up as precipitation, the precipitation efficiency is 100%. If none of it ends up as precipitation, the precipitation efficiency is 0%.

Once formed, cloud water can take various forms (small or large cloud droplets, rain drops, ice crystals, graupel, hail) and can be involved in a wide variety of cloud and precipitation particle interactions. One destination for the cloud water involves incorporation into the precipitation process and deposition on the ground as precipitation. Another destination involves transport of the condensate to the cloud boundary where evaporation takes place, and the cloud water is returned to the atmosphere in vapor form.

Cloud water is nearly always initially available in the form of small liquid droplets. This is true even though cloud temperatures may be well below freezing (0 °C) so that supercooled droplets are formed. As the cloud is formed, the small droplets, typically less than 10 μm in radius, are generally formed in concentrations of hundreds per cubic centimeter. The competition to the water vapor excess among the droplets is severe and further growth by condensate is severely restricted. Since the fall velocity of these small droplets is low (<0.3 cm/s), they essentially move with the air currents either horizontally or vertically within the visible cloud. The growth of the cloud droplets continues by condensation and stochastic coalescence between pairs of small droplets to form precipitation embryos (autoconversion), but this process in many cases is very slow.

Two different mechanisms can lead to larger cloud particles, which, in turn, have greater fall velocities and can fall out as precipitation. One mechanism involves direct collisions and coalescence among the drops, so that successively large water drops form. When a few large cloud droplets co-exist with smaller ones, the larger droplets have a slight, but significantly greater, fall velocity and can grow much more quickly by the collision process. The presence of larger droplets is generally associated with maritime (in contrast to continental) air masses, since these air masses contain hygroscopic (water attracting) salt particles, upon which large cloud droplets can condense. The efficiency with which collisions will occur is highly dependent on the relative sizes of the large and small droplets. Collisions sequentially become more frequent and lead to large drops with sufficient fall velocities to reach the ground as

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precipitation. This process occurs primarily in maritime clouds whose tops are at elevations where the temperature is near or slightly less than freezing. In deep clouds extending well above the freezing level, ice processes will typically dominate this process for the development of precipitation. Nevertheless, large collision-coalescence droplets entering the updraft in large clouds may, and in many cases do, play a vital role in initiating the ice process.

The second mechanism that leads to precipitation involves the interaction between supercooled cloud droplets and ice crystals. This process proceeds rapidly when ice particles are present and almost immediately provides a means for the growth of large ice particles with significant fall velocities. Since the vapor pressure over ice is less than that over water, ice crystals in the presence of cloud water droplets are in an environment that is highly supersaturated with respect to the saturation vapor pressure at their ice surface. Consequently, ice crystals grow rapidly from vapor transfer to their surface. Surrounding water droplets will tend to decrease in size to maintain a saturated vapor environment with respect to water.

While collision and ice processes are the primary ones responsible for cloud colloidal and phase instability, resulting in the formation of precipitation, there are important interdependent aspects between these two mechanisms that are very important. For instance, collision growth can provide large water droplets that will freeze more readily. It has also been shown that when some larger droplets are present in the cloud in a temperature range from about -3 °C to -7 °C, they can lead to a very great multiplication of existing ice particles. These can then grow in portions of the cloud where ice crystal concentrations from primary ice nuclei are deficient. Since this process can enhance ice crystal formation by three to four or more orders above backgrounds, this can be a significant mechanism in the formation of precipitation in clouds. Experimental evidence has shown that this ice process is most likely to occur in maritime air masses where large water droplets are available. The process is likely to be a minor factor in many continental clouds where very few large droplets in a -5 °C to -7 °C temperature range are available to initiate the process.

Another major interaction of the ice and collision processes involves direct removal of cloud droplets through their accretion to falling ice crystals. The smallest cloud droplets will generally be evaporated to compensate for the large vapor deficiency being created by rapidly growing ice crystals. The larger ones (but still very small), however, can survive this vapor deficiency for the short time involved and can be collected directly by the ice crystals. These droplets rime the ice crystals, and this process removes substantial quantities of cloud liquid water. Intensive riming of crystals leads to graupel and hail. Additional interactions among ice crystals themselves and between ice particles and water droplets can lead to the aggregation of ice crystals. This can also enhance the utilization of cloud water in the form of precipitation.

Clouds that have significant cloud water, but do not have appropriate mechanisms for particle growth, can be considered to have potential for weather modification.

In the case of the collision-coalescence mechanism, opportunities sometimes exist for artificially providing large, hygroscopic nuclei to promote initial droplet growth.

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Opportunities for altering the collision-coalescence mechanism exist, on occasions, in continental air masses when there are low densities of natural concentrations of larger hygroscopic nuclei for producing a few large cloud droplets for broadening the cloud droplet size distribution. Such clouds may respond to seeding with appropriately sized hygroscopic materials. In contrast, it seems likely that clouds in maritime air mass nearly always meet the conditions for broad droplet size distributions that can already efficiently lead to precipitation. This does not indicate frequent opportunities for seeding with hygroscopic materials in these maritime air masses.

In the case of the ice mechanism, opportunities sometimes exist for artificially producing ice nuclei, which can provide more ice crystals that can grow and utilize cloud water for precipitation in the time frame available. Ice particles form by ice nucleation (conversion of water vapor to liquid or ice) or by multiplication processes from ice particles already formed. The nucleation of ice from water substance, either liquid water or water vapor, is highly temperature dependent. Greater numbers of atmospheric aerosols are effective as ice nuclei as temperatures below freezing become progressively colder until, at about -40 °C, where spontaneous, or homogeneous, nucleation occurs and all liquid water freezes. In natural clouds, concentrations of ice nuclei that can produce ice crystals at a temperature of -12 °C are typically around 1/100 L of air. The concentrations of naturally active ice nuclei at -20 °C are typically around l/L, and, at -28 °C, the concentrations of naturally active ice nuclei are typically around 100/L. Since 10 to 100 ice crystals per liter are generally required for the most effective utilization of cloud water by the ice process, the natural concentrations of naturally active ice nuclei that produce ice crystals are typically less than the concentrations required to use all cloud water when cloud temperatures are warmer than about -25 °C. Cloud seeding constitutes a procedure for providing artificial ice nuclei that can nucleate the additional ice crystals needed in these cases.

The opportunity for enhancing cloud development by seeding results from opportunities to increase cloud temperature with respect to that of the cloud environment and, consequently, enhance the cloud buoyancy. With cumulus clouds, in-cloud temperature increases of a few tenths of a degree centigrade can sometimes cause great differences in cloud growth. The basic concept for enhancing the development of individual convective clouds is quite complex. A simple consideration involves the rapid conversion of large amounts of supercooled cloud water to ice particles. This adds heat to the cloud with respect to the cloud environment by the release of the latent heat of fusion (approx. 250 kJ/kg). In "wet" clouds with substantial amounts of supercooled water, this can involve a substantial amount of added heat to the cloud. Increases in cloud temperature of 0.5 ~ 1.0 °C can result in modest-sized clouds. In cases where all of the liquid water has been utilized for ice particle growth, another 0.5 - 1.0 °C temperature rise might result from ice particle growth from vapor as the humidity decreases from that at water vapor saturation to that at ice saturation. Since the heated cloud air is then less dense than the cooler surrounding air, it will rise and have more buoyancy than it would have without the additional heating. This can lead to greater cloud development. If the air mass in which the cloud is embedded is quite stable, the additional heating and buoyancy might have little effect. There are cases, however, where the atmosphere is only conditionally stable. In these cases, the slight temperature increase is sufficient to create and maintain, through a substantial vertical depth, a

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temperature excess in the cloud above that in the surrounding environmental air. In these cases, the increased buoyancy can permit cloud growth to elevations much higher than those that would occur without the additional heating increment. Field experiments have verified that when such clouds have been seeded for promoting such a dynamic effect, greatly enhanced cloud growth does occur. This process can be most effective in clouds with large amounts of supercooled liquid water in the form of large droplets. Large droplets provide a large amount of liquid water from which the latent heat can be released for each ice nucleus provided.

While dynamic seeding can produce large percentage effects from individual cumulus towers, the overall impact on regional and seasonal precipitation is limited. Considerably more significant impacts can result if dynamically enhanced convective towers can promote or intensify other cloud towers in multicell cloud complexes or create added mesoscale cloud development. While evidence exists that this can happen and has resulted from treatment, the understanding of the linkages is insufficient

The insight into such seeding enhancement processes is weak due to our lack of understanding of the linkage between individual cumulus cloud systems and mesoscale processes

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Biographical Sketch

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.

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