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Report:

On the State of Cloud Seeding for Rain Enhancement

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Summary

As local synoptic and global climate change cause Cyprus and the eastern Mediterranean to become increasingly dry, interest in “weather modification” is growing. Cloud seeding, which has been used for rain enhancement for about 60 years, is receiving renewed attention.

Glaciogenic seeding and *hygroscopic seeding* are the two main types of cloud seeding. Glaciogenic seeding disperses ice-producing materials into a cloud containing water drops at a temperature below 0^0 C, stimulating precipitation. Hygroscopic seeding disperses large or “giant” hygroscopic particles (e.g. salt powders) into a cloud. Water vapor condenses, causing the particles to grow rapidly and produce collector drops.

S*tatic* or *broad scale seeding* and *target seeding* are the most commonly used seeding modes. The first uses glaciogenic seeding from airplanes beneath the clouds and/or from ground generators. Target seeding uses both airborne glaciogenic and hygroscopic techniques on clouds that have been identified as good candidates for rain enhancement.

An overview of existing research shows that, while cloud seeding affects microphysical processes in clouds, there is little evidence that it affects rain on the ground. Re-analysis of the data from many “successful” attempts fails to confirm that rainfall has increased.

Most of the early work hypothesized that clouds are often deficient in ice crystals. Experiments using silver iodide (AgI) particles as ice initiators (called ice nuclei) to increase crystal concentrations in clouds were expected to increase precipitation formation, since ice crystals grow faster than the drops around them. Unfortunately, due to large natural atmospheric variability, other processes and feedbacks overshadowed seeding effects.

Recently, a method previously used only in clouds with temperatures above freezing was tested in clouds containing ice. This method seeds clouds with hygroscopic particles (e.g. sea salt) that produce larger drops near the cloud base, accelerating precipitation growth by droplet collection. As they grow, the drops freeze and collect smaller droplets to form small hail (graupel) particles that descend, melt and fall as rain.

Although initial results in South Africa and Mexico were promising, later experiments failed to corroborate them. Nevertheless, results of these studies suggest that rain can sometimes be increased. However, future trials should be well designed based on the results of both physical experiments and statistical tests.

In response to global concern about water shortages, especially in the eastern Mediterranean region, other ideas for increasing rainfall have emerged. Unfortunately, some do not stand up to scientific scrutiny.

For example, there is no evidence that cloud ionization is effective. The World Meteorological Organization (WMO) warns against using methods that are not backed by solid science.

1. Introduction

Cloud seeding can increase precipitation formation in clouds that are already precipitating or are about to do so. It cannot be used to form new clouds or to convert small, non-precipitating, fair-weather clouds into rain clouds. Nevertheless, even small increases can be important for sub-tropical regions in which rain is scarce.

When cloud seeding is contemplated, it is important to evaluate the local conditions in the context of regional climatic conditions. For example, the Mediterranean region is connected to the large-scale atmospheric Hadley circulation, driven by deep tropical cumulonimbus clouds that are accompanied by descent in the subtropics. This is most pronounced during winter. The low level flow in the subtropics is characterized by vast anticyclones in which precipitation is suppressed. These occupy about 40% of the Earth's surface. During the eastern Mediterranean summer, a teleconnection with the Asian monsoon plays a key role (*Rodwell and Hoskins*, 1996). The monsoon convection acts as a remote dynamic that is enhanced by radiative cooling in the subsidence region, a positive feedback that adds to the drying.

The tropics are expanding (*Seidel et al.*, 2008) and the Asian monsoon may intensify under the influence of global warming. Robust climate modeling indicates that subsidence and dryness over the eastern Mediterranean will increase (*IPCC*, 2007). Concern about these trends fuels the discussion about using weather modification for artificial rain enhancement.

Deliberate cloud seeding, aimed at increasing precipitation by injecting specific types of particles into clouds, has been used since the mid-20th century. These efforts have improved our understanding about the processes that lead to cloud and precipitation formation and how seeding aerosols affect them. Unfortunately, there have been only a few large comprehensive projects that include both physical and statistical evaluations.

Definite proof of rain enhancement from cloud seeding projects would demonstrate that precipitation is at least partly connected to the type of aerosols that are injected into the clouds. The connection between aerosol and precipitation has been one of the poorly understood links in the long chain of processes leading from cloud initiation to precipitation on the ground (see *Levin and Cotton*, 2008). [1]

Rain enhancement by cloud seeding can be divided into two broad categories: *glaciogenic seeding* and *hygroscopic seeding*. The hypothesis behind *glaciogenic seeding* is that many clouds are deficient in natural ice nuclei and thus, cannot produce precipitation efficiently.

The process disperses ice-producing materials (e.g., dry ice (solid CO_2), silver iodide etc) into a cloud containing water drops at a temperature below 0^0 C. Subsequent ice particle growth stimulates precipitation. The underlying mechanism is that ice crystals surrounded by drops at the same temperature will grow faster by vapor diffusion than the drops around them[2]. This process, known as the Bergeron-Findeisen mechanism, is essential for precipitation formation in certain clouds, including winter clouds in the Mediterranean.

Hygroscopic seeding disperses large or “giant” hygroscopic particles (e.g., salt powders) into a cloud (generally at cloud base, although cloud top seeding has also been tested). Water vapor condensation causes them to grow rapidly and to produce collector drops. The goal of this type of seeding is to increase the concentration of collector drops that can grow into raindrops by collecting smaller droplets and to enhance the formation of frozen raindrops and graupel particles.

In the past, this type of seeding was used mainly for rain enhancement in warm clouds. However, more recent results have shown that it can also enhance the precipitation processes in mixed clouds.

Different modes of cloud seeding have been employed. *Static or broad scale* seeding and *target seeding* are the most common. The first mode uses airborne glaciogenic seeding from airplanes beneath the clouds and/or ground generators to seed all the clouds in the area, upwind of the target region. The second mode, target seeding, seeds clouds that have been identified as potentially good candidates for rain enhancement. It uses either airborne glaciogenic seeding or hygroscopic seeding.

Specific seeding techniques vary depending on the area and on the operators. Radar is often used to determine target and time of seeding. The seeding uses airplanes that disperse the nucleating particles from special generators or from flares attached to the airplane wings. Seeding is also done with rockets that explode upon reaching

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[1] For a more comprehensive assessment of the current status of cloud seeding research, the interested reader is referred to a number of available detailed weather modification assessments such as: *NRC* (2003), *Cotton and Pielke* (2007), *Silverman* (2001, 2003), *Garstang et al.* (2005), *WMO statements of weather modification (*2001 and 2007) and *Levin and Cotton* (2008).

[2] Since the saturation vapor pressure of liquid water exceeds that of ice, ice crystals will grow at the expense of the liquid water.

the right location in the cloud. In many countries, these methods are being used without objective statistical evaluation of their effectiveness.

2.Static Cloud Seeding

Static cloud seeding uses glaciogenic materials to modify the microstructures of super cooled clouds and precipitation. Airplanes that fly at cloud base seed the clouds along a trajectory that covers a large area. Often, seeding material that is dispersed from ground generators placed upwind of the target area is used exclusively or as a supplement to airborne seeding. The aim is to disperse the glaciogenic material into as many clouds as possible in the area upwind of the designated target area.

Over the past 50 years, there have been many attempts to develop strategies to increase precipitation by this method (several of which are still used). Most are classified as operational cloud seeding. Unfortunately, they have rarely provided sufficient information to determine if either the clouds or precipitation were modified.

Well-designed scientific experiments that include extensive measurements and model simulations are needed to determine whether artificial seeding can modify cloud structures and the effects of the seeding on precipitation when the seeding is randomized. Reports by the National Research Council (*NRC*, 2003) and the World Meteorological Organization (*WMO*, 2001) stress that for cloud seeding to be accepted as a viable procedure for enhancing rainfall, strong physical and statistical evidence of its effectiveness are required.

2.1. Seeding Cumulus Clouds With Glaciogenic Material

The static (broad scale) seeding concept has been applied to supercooled cumulus clouds and tested in various regions. The peer-reviewed literature describes two such experiments carried out in Israel (Israel I and Israel II) (e.g. Gagin and Neumann, 1981). These experiments were originally viewed as successful and as evidence that under the appropriate conditions, cloud seeding can increase precipitation (e.g., NRC, 1973; Sax et al., 1975; Tukey et al., 1978a,b; Simpson, 1979; Dennis, 1980; Mason, 1980,1982; Kerr, 1982; Silverman, 1986; Braham, 1986; Cotton, 1986a,b;).

Years later, Rangno and Hobbs (1993) reanalyzed the results. They concluded that the apparent increase in rainfall in the Israel I experiment was due to “lucky draws” or a Type I statistical error. They also argued that during Israel II, the apparent precipitation increase in the north target areas was due to natural heavy rainfall over a wide region. Levin et al. (manuscript to be submitted to J. Applied Meteorology) found that similar increases in precipitation without seeding occurred during the same period in the center of Israel.

A comprehensive analysis by Kessler et al. (2007, in Hebrew) and a subsequent summary by Sharon et al. (2008) concluded that seeding enhanced the amount of precipitation by about 30 % in storms that produced less that 5 mm per day in Israel. However, seeding storms that produced more than 15 mm per day produced no effect or even reduced precipitation by about 10%. Since most of the water from precipitation in Israel comes from storms producing more than 15 mm per day, seeding all storms may not have a net effect and may even cause rainfall to decrease.

The lack of rain enhancement in Israel was partly due to the fact that much of the seeding material did not reach the proper heights in the clouds at the right time for it to be effective (see Levin et al, 1997). The results are consistent with the conclusion that the convective clouds in the eastern Mediterranean (e.g. Cyprus, Lebanon, Israel etc) are not really continental (containing high concentrations of cloud drops having similar sizes), as was originally thought, but are often more microphysically maritime in nature. This appears to be due mainly to the natural hygroscopic seeding by sea spray or mineral dust particles coated with soluble material (Levin et al., 1996, 2005; Rosenfeld et al, 2002) that enhance the warm precipitation as well as promote the formation of more ice hydrometeors (by a process called ice multiplication, see Hallett and Mossop, 1974).

Results of a project in Tasmania that seeded clouds along the coastline, upwind of a hilly area, lend support to these suggestions. Ryan and King (1997) analyzed the results of this project and concluded that seeding in Tasmania enhanced precipitation from the stratiform orographic clouds, but not from the convective clouds. This is also consistent with Rangno and Hobbs' (1993) conclusion that cloud seeding, as done in Israel, could not have caused the documented rain enhancement from the convective clouds.

A randomized rain enhancement experiment was carried out during 1988–94 in the area of Bari and Canosa, Italy, on the Adriatic coast. Its purpose was to study rain-producing weather systems in southern Italy, establish similarities with Israel, and transfer Israeli technology. The experiment was a cross-over design with two alternating target areas, a buffer in between, and two additional control areas (see List et al., 1999, for a summary of the project). Aircraft flying near the cloud bases along predetermined tracks upwind of the target area injected them with silver iodide.

Rain gauge data was used to estimate, at a significance level of 0.05 and 90%probability, that 303 rainy days were required to establish a 15% rain increase. The experiment was terminated after 260 days when the statistical analysis showed no discernable seeding effect. This clearly indicated that cloud seeding technology cannot be transferred from one location to another without prior study of the local meteorology and (micro) physical properties of the storms.

Another key experiment was carried out in the U.S., the High Plains Experiment (HIPLEX-1, see Smith et al., 1984). Analysis of this experiment (Mielke et al., 1984; Cooper and Lawson, 1984; Isaac et al., 1982; Schemenauer and Tsonis, 1985) showed that cloud lifetimes in the HIPLEX domain were too short for seeding to have been effective (i.e., the clouds with tops warmer than –12ºC). Since the window of opportunity for seeding is narrow (see Reisin et al., 1996) and since the ice particle density in cold-based continental clouds with tops warmer than –25ºC is very high (e.g. Hobbs and Rangno, 1985), seeding them to create additional ice particles is ineffective.

From 1979 to 1981, the WMO organized an experimental study to evaluate the potential for rain augmentation by glaciogenic cloud seeding in Valladolid, Spain (called PEP, Precipitation Enhancement Project). The first phase of the experiment, which included no cloud seeding operations, involved extensive measurements of cloud properties and environmental conditions by aircraft, radar and satellite. WMO concluded that the potential for significant rain enhancement in the region during the winter months was insufficient to warrant a full-scale seeding operation. Despite the disappointing conclusions, the study was useful because it prevented the start of a cloud seeding experiment that would probably have failed. Much more importantly, set an example of logical and non-political planning of weather modification efforts.

2.2 Seeding Winter Orographic Clouds

Static cloud seeding has also been applied to orographic clouds, i.e. clouds that are formed over hills or mountains due to the forced upward flow of moist air. Since these clouds are persistent features that produce precipitation even in the absence of large-scale meteorological disturbances, enhancing precipitation by seeding them has several advantages over seeding cumulus clouds.

The window of opportunity for seeding orographic clouds depends on the time it takes for air parcels to reach the mountain top. If winds are weak, there may be sufficient time for natural precipitation processes to occur efficiently. Stronger winds, however, may prevent precipitation from forming on the upwind side of the mountain by blowing the clouds over to the lee side. In such cases, seeding may help speed up precipitation formation on the upwind side of the mountain.

In a recent modeling simulation, *Muehlbauer and Lohmann* (2009) showed that the distribution of orographic precipitation strongly depends on the composition and size of the background aerosols. If they lack sufficient giant cloud condensation nuclei (GCCN) or efficient ice nuclei, precipitation develops slowly and a higher fraction of the precipitation is moved by the winds to the lee side of the mountain. In such a case, seeding can increase the efficiency of precipitation formation on the upwind side of the mountain.

On the other hand, when the background aerosols contain sufficient concentrations of GCCN and ice nuclei, clouds produce rain without seeding and a larger fraction of the rain falls on the upwind side of the mountain. Thus, seeding is ineffective. In some cases, seeding such clouds could freeze most of the cloud drops, thus limiting the growth of the small ice crystals by the Bergeron-Findeisen mechanism and reducing total precipitation. Clearly, it is essential to understand the nature of the background aerosols before considering such seeding operations

In spite of these difficulties, many experiments have reported some significant enhancement in precipitation. For example, the seeding experiments near Fremont Pass, Colorado (referred to as *Climax I* and *Climax II,* reported by *Grant and Mielke,* 1967, and *Mielke et al,* 1970; 1971) claimed a 50% increase in precipitation. *Hobbs* *and Rangno* (1979) and *Rangno and Hobbs* (1987, 1993) challenged these results, raising questions about the validity of the statistical techniques and the quality of data collection. They concluded that the *Climax II* experiment failed to confirm that precipitation can be increased by cloud seeding.

Super and Heimbach (1983, 1988) reported some success from randomized seeding experiments in the California Sierra Mountains, e.g. the Lake Almanor Experiment (*Mooney and Lunn,* 1969) and the Bridger Range Experiment (BRE) (*Super and Heimbach,* 1983; *Super,* 1986). *Ryan and King* (1997) reviewed more than 14 cloud seeding experiments in Australia, including the island of Tasmania. They concluded that, while static seeding of convective clouds over the plains of Australia is not effective, seeding orographic stratiform clouds with cloud top temperatures between –10 to –12°C caused precipitation increases over Tasmania.

Over the years, there have been a few reports of numerical model simulations of seeding effects. Many of these simulations examined the effects of seeding on single clouds. Unfortunately, only a few attempted to simulate the effects of seeding on a large scale, mimicking real conditions. Recently, *Cotton et al.* (2006) applied the Colorado State University Regional Atmospheric Modeling System (RAMS) to simulate operational cloud seeding in the central Colorado Mountains in the 2003–2004 winter season. Their results showed no increase in precipitation and also pointed to the critical dependence of the results on the background level of cloud condensation nuclei (CCN).

In summary, in some cases, the “static” mode of cloud seeding has caused the expected alterations in cloud microstructure. These include increased concentrations of ice crystals, reduced supercooled liquid water content, and more rapid production of precipitation elements in both cumuli and orographic clouds. There is very little documentation of precipitation increases on the ground due to static seeding of cumuli, however. The evidence that glaciogenic seeding of orographic clouds can cause significant increases in snowpack is more compelling, particularly in the more continental and cold-based orographic clouds.

3. Dynamic Seeding With Glaciogenic Material

While the objective of *static seeding* is to modify the microstructures of clouds to increase precipitation, there is another glaciogenic seeding hypothesis called dynamic cloud seeding that enhances cloud-scale dynamics of a cloud by stimulating buoyancy and upward motions of air. Individual clouds are seeded (target seeding) to glaciate a large fraction of the cloud water, thus invigorating the updrafts due to the release of latent heat of freezing. This can be particularly effective if the unstable lower atmosphere is capped by an inversion, with another unstable layer aloft. In such cases, the growth of the clouds is restricted by a shallow stable layer induced by the temperature inversion.

The objective of dynamic seeding is to cause a sudden release of a large quantity of latent heat, providing the buoyancy needed to push the top of the cloud through the inversion layer and into the unstable region above. The cloud can then rise up to much greater heights, leading to glaciation and precipitation.

A number of dynamic seeding experiments were carried out in Florida in 1968 and 1970–1973 (the Florida Area Cumulus Experiment, FACE). *Simpson and Woodley (*1975; *Woodley et al.,* 1982) initially reported that precipitation (measured by radar) from seeded isolated cumulus clouds ~5 km in diameter was about twice that from the unseeded control clouds. Although the rain rate from the seeded clouds did not increase, the clouds became bigger and lasted longer, and the total precipitation was significantly greater. Following the apparent success of FACE I, a new confirmatory experiment (FACE II) was initiated. Unfortunately, the overall results of FACE II failed to confirm the results of FACE I (*Flueck et al.,* 1981; *Nickerson,* 1979, 1981).

More recently, the dynamic seeding strategy was tested in Thailand and West Texas. *Rosenfeld and Woodley* (1989, 1993) reported results for exploratory dynamic seeding experiments, showing that the seeded clouds increased in height by about 7% and in area by 43%. Although the rain intensity did not increase, the duration increased by 36% and the total rainfall by 130%. Although these results are encouraging, the small increase in height following seeding seems inconsistent with the hypothesis of dynamic seeding or with the earlier exploratory seeding experiments.

In summary, the experimental results indicate that modifying the dynamics of the cloud to increase precipitation is much more complex than originally envisioned. It requires better understanding of the behavior of cumulus clouds and their interaction with each other, the boundary layer and the larger-scale weather systems.

4. Cloud Seeding With Hygroscopic Material

Hygroscopic seeding disperses giant soluble particles into the clouds to enhance drop growth by coalescence. In the past, this method was used only in warm clouds; more recently, it has been tried in mixed phase clouds. Numerical model simulations and in-clouds observations show that the ice crystal concentration increases in the presence of large cloud drops. Therefore, the hypothesis is that seeding of mixed-phase clouds with such GCCN will affect both drop growth and ice formation, probably through the efficient formation of graupel particles. Seeding has used appropriately sized salt particles, water droplets from sprays of either water or saline solution (e.g. *Silverman and Sukarnjanasat,* 2000) and hygroscopic flares (*Mather et al.,* 1997).

Mather (1991 observed that large drops appeared in the cloud whenever the effluent from a paper mill reached the cloud. Ensuing statistical results, observations and modeling results have indicated that under certain conditions and with optimal size of seeding material, precipitation may be enhanced (*Reisin et al.,* 1996c; *Yin et al.,* 2000a,b). The seeding method was improved, using new hygroscopic flares with particle size that corresponded with theoretical calculations.

The initial seeding of single clouds, and subsequent single (target) cloud analyses (*Mather et al.,* 1997; *Bigg,* 1997; *Silverman,* 2003), provided statistical evidence that seeding increases rainfall. According to simulations using models with a detailed treatment of cloud microphysics,this is because the increased concentration of larger drops generates an increase in graupel numbers and masses (*Yin et al.* 2000a, b). Such increases could cause more rain, although it remains unclear how the clouds are affected for the extended length of time that is suggested by some of the measurements (e.g. *Silverman,* 2003).

The principle of enhancing the coalescence process via hygroscopic seeding depends on the following parameters: the chemical composition (hygroscopicity), size and concentration of both the seeded particles (CCN) and the natural background particles. For example, clouds with maritime characteristics (having a low droplet concentration and a wide size spectrum) do not respond to hygroscopic cloud seeding, because the clouds are already very effective precipitation producers. Flare seeding produces effective GCCN (usually sodium chloride, potassium chloride, or calcium chloride) that are larger than those in the natural environment.

Modeling studies by *Cooper et al.* (1997) and *Reisin et al*. (1996) showed that the flares used in the South African experiment (*Mather et al.,* 1997) provided large CCN (>0.3 μm diameter, although *Reisin et al*., 1996, argued that particles larger than 1 μm should be used) to a growing cloud, influencing the initial condensation process and allowing fewer CCN to activate to cloud droplets. If the CCN dispersed into the cloud from the flare are larger than the natural CCN, the seeded particles will activate preferentially and prevent nucleation of drops on the smaller natural CCN. Thus, the seeded particles form fewer but larger cloud drops and change the character of the cloud drop size distribution to favor the collision-coalescence process and rain formation. Cloud droplets grow to larger sizes, and within less than 10 min, can start growing by collecting other cloud droplets, initiating rain in about 30 min.

Model simulations (*Reisin et al.,* 1996c; *Yin et al.,* 2000a, b; *Caro et al.,* 2002; *Segal et al*., 2004) suggest that there is a narrow window of opportunity within which seeding can be successful. This window is longer for hygroscopic than for glaciogenic seeding. Thus, in addition to the size of the hygroscopic particles, the timing of seeding is crucial. Seeding too early could lead to reduced rain amounts, too late could cause the seeding to fail.

The first hygroscopic seeding experiment in mixed phase cloud took place in South Africa (*Mather et al.,* 1997). Hygroscopic flares were applied to convective cloud systems in limited physical and statistical experiments. Aircraft microphysical measurements were made to monitor some of the processes. Radars with a cell-tracking algorithm (Titan) measured condensed water volumes produced by the convective complexes and analyzed various storm and track properties.

Later, a similar experiment was conducted in Mexico. These two sets of experiments produced remarkably similar results in terms of the difference between the seeded and non-seeded groups in radar-estimated rainfall (*WMO*, 2000). In both cases, the presence of condensed perceptible water mass aloft remained for much longer than the unseeded cloud, suggesting a precipitation increase. The reason for the significant increase in the lifetime of the seeded clouds remains unclear, although it appeared in both experiments in the two continental environments.

Subsequently, *Bigg* (1997) and *Silverman* (2000) independently reevaluated the South African data. Both found statistically significant evidence of an increase in *radar-estimated* rainfall from seeded convective cloud systems.

Mather et al. (1997), *Bigg* (1997), and *Silverman* (2000) all suggested that dynamical effects of the seeded clouds could explain the increased lifetime of the rain. They speculated that seeding affects duration of rainfall by affecting the dynamics through the relation between precipitation loading and evaporation, and the characteristics of the downdraft that is generated, and between the downdraft and the storm organization, evolution and lifetime.

It is also possible that seeding reduces the rain drop size, thus increasing the evaporation below cloud base and altering cold-pool and downdraft effects, leading to enhanced interactions and updrafts in neighboring clouds. If seeding shifts the raindrop spectrum to larger drops, the opposite response would be expected (*Yin et al.,* 2001).

In summary, it seems that continental clouds (clouds with high concentrations and narrow size spectra of cloud drops), such as the ones in South Africa and Mexico, are much more responsive to hygroscopic seeding. Both experiments showed very strong signals in terms of increased storm lifetime in seeded storms, increases in reflectivity aloft, and increases in storm densities. Thus, they suggest that it is possible, under appropriate conditions, to produce large differences in cloud properties by dispersing hygroscopic particles into cloud bases.

On the other hand, no effect is expected when hygroscopic seeding is carried out in clouds having a more maritime type drop spectra (*Reisin et al,* 1996a,b,c; *Cooper et al,* 1997; *Yin et al,* 2000a,b; *Caro et al,* 2002 and *Segal et al,* 2004). Model calculations show that clouds with natural CCN concentrations <500 cm^{-3} do not respond to hygroscopic seeding. Clearly, it is essential to understand the climatology of the cloud microphysics in an area designated for seeding before the seeding starts.

In spite of the reported success, there are a few unanswered questions regarding the hygroscopic seeding method. The *NRC* (2003) pointed out that although the South African and Mexican experiments showed how clouds respond to treatment in accordance with the understanding of the chain of physical reactions leading to precipitation, the effects on rainfall on the ground are still not clear. This is because the experiment showed the effects of seeding on the radar signature at 6 km. It is not obvious how this translates into rainfall on the ground. Finally, though the South African, Mexican, and Thailand experiments found that the rainy period was prolonged by 1- 6h following the cessation of seeding, we do not understand the processes that led to this.

5. Rain enhancement by cloud ionization

The lack of water in many parts of the world has prompted numerous suggestions for enhancing precipitation. Some of these are unrealistic and not physically feasible. A recent suggestion was to introduce ions from the surface artificially so clouds would form and precipitation increase. The hypothesis is that the ions enhance the formation of CCN, producing more drops and thus, more rain.

This hypothesis has not been proven; even the initial impact on the formation of cloud drops has not been shown. The problems with this proposed method are numerous:

1) The ions that are produced have a short lifetime because they attach rapidly to ambient aerosols already present in the atmosphere.
2) The extra charge on the aerosols due to the attachment of the ions is partly neutralized by atmospheric ions that are produced by cosmic radiation and radioactivity from the ground.
3) While advocates of this method claim to be able to produce clouds on clear days and even on summer days in the eastern Mediterranean, this is not possible. Even if cloud drops are nucleated near the surface, the released latent heat could not produce updrafts strong enough to overcome the inversion aloft.
4) Even if the artificially added ions could produce cloud condensation nuclei at cloud base, this would increase concentrations of cloud drops that compete for the available water vapor, leading to the formation of smaller drops. Precipitation would **decrease** because the collection process would be less effective.
5) While it is possible that increased concentrations of smaller drops would be lifted to higher altitudes, thus forming more ice, this would cause many very small ice crystals to form. Lack of water vapor would prevent them from growing to large sizes (most drops would be frozen). Small ice crystals would not fall rapidly enough to overcome the cloud updrafts and would be dispersed laterally by the stronger horizontal winds aloft. This would lead to the formation of larger thin anvils **and to a decrease,** not increase, in precipitation.

This method is promoted, even though it contradicts the laws of nature, under the cover of commercial secrecy. This is a good example of why any new method of rain enhancement must be supported by scientific results that are published and made available for the scrutiny of the atmospheric science community before it is accepted. In its statement on weather modification, the WMO stresses that methods such as these are not proven and are thus not recommended[3].

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[3] The proponents of this method have approached several countries. They guarantee that the method will increase rainfall and promise to return the payments if unsuccessful. The difficulty is to prove that the rain has increased (or decreased) because of the operations. Until a plausible scientific explanation that can be reviewed by the science community is shown, the method should be viewed with caution.

6. Concluding remarks

Rain enhancement by cloud seeding has been tried for almost 60 years. Many of the experiments initially seemed successful until subsequent re-analyses raised questions and doubts. Some experiments were operational rather than scientific, providing very little added insight into the mechanisms of the effects of the seeding material on the precipitation processes or statistical results to give confidence in the outcome of the operations.

Glaciogenic cloud seeding by the static mode of some orographic clouds has shown some potential for success. However, more studies with robust statistical experiments are needed to increase the confidence in these operations.

Hygroscopic seeding also has shown potential. Although the confirmatory experiments failed to reproduce the results of the first experiments, more research using this method is required.

Finally, one central lesson that is learned from all these experiments is that before undertaking a cloud seeding experiment, preliminary studies of the local meteorology and cloud microphysics are essential. In other words, the technology of cloud seeding is not yet a transferable technology.

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