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Invited review article

Hail prevention by ground-based silver iodide generators: Results of historical and modern field projects

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A B S T R A C T

The science of hail suppression by silver iodide (AgI) cloud seeding was developed during the second half of the 20th century in laboratory and tested in several research or operational projects using three delivery methods for the ice forming particles: ground generators, aircraft, and rockets. The randomization process for the seeding was often considered as the imperative method for a better evaluation but failed to give firm results, mostly because the projects did not last long enough considering the hazardous occurrence of severe hailfalls, and also probably due to the use of improper hail parameters. At the same time and until now, a continuous long-term research and operational field project (1952–2015) using ground generator networks has been conducted in France under the leadership of the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques (ANELFA), with a control initially based on annual insurance loss-to-risk ratios, then on hailpad data. More recently (2000–2009), a companion ground seeding project was developed in the north of Spain, with control mostly based on microphysical and hailpad data. The present paper, which focuses on hail suppression by ground seeding, reviews the production of the AgI nuclei, their dispersion and measurement in the atmosphere, as well as their observed or simulated effects in clouds. The paper summarizes the results of the main historical projects in Switzerland, Argentina, and North America, and finally concentrates on the current French and Spanish projects, with a review of already published results, complemented by new ones recently collected in Spain. The conclusion, at least for France and Spain, is that if ground seeding is performed starting 3 hours before the hail falls at the ground with a 10-km mesh AgI generator network located in the developing hailstorm areas, each generator burning about 9 g of AgI per hour, the hailfall energy of the most severe hail days is decreased by about 50%.

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1. Introduction

In several countries of the world, hail is one of the most costly atmospheric plagues for crops, vegetation, cars, and other types of property. People experiencing damaging hailfalls often ask scientists about reducing hail damage by weather modification and sometimes even develop prevention projects without scientific basis and control. The question has recently been exacerbated by climate warming and the risk of increasing hail it induces. This review is aimed at giving accurate information about hail prevention by silver iodide nuclei ground seeding.

The scientific attempts to mitigate or suppress hailfalls began in the 1950s, a few years after Schaefer (1946) and Vonnegut (1947) discovered the means to increase the ice crystal concentration in clouds by using dry ice or silver iodide (AgI) particles, and consequently to interfere with the natural precipitation processes. At that time, the scientific concept behind hail suppression was that adding artificial ice forming nuclei (IFN) to the natural ones induces a competition in the hailstone growth processes preventing the development of large pieces of ice. The first commercial and scientific projects were using silver iodide smoke generators, operated from aircraft or from the ground, in order to increase the IFN concentration in the convective clouds or in the boundary layer feeding them (Dessens, 1953; Krick, 1954). The use of rockets to carry the active substance inside the hailstorm core was developed a decade later by Russian scientists (Sulakvelidze et al., 1974).

Review of the first hail suppression projects can be found in Changnon (1977) for the United States, Federer (1977) for Europe and the former USSR, and Dennis (1980) for the rest of the world. More recently, the American Society of Civil Engineers published a standard on hail suppression projects (ASCE, 2003) reporting on the historical perspective, the scientific basis, the seeding agent delivery methods, and the evaluation processes. The ASCE manual reviews in detail the three delivery methods with ground-based generators, rockets, and aircraft, gives an appreciation on the physical validity of the methods, but does not provide a quantitative assessment of their success. A few years later, the World Meteorological Organization also published a summary of the ASCE standard but it did not contain an assessment of the hail suppression experiments either (WMO, 2006). Very recently, an up-to-date version of the ASCE standard was published, still without an assessment (ASCE, 2015).

As with the other weather modification activities, the main difficulty in a hail suppression project is the assessment of the results. Aircraft seeding has shown strong positive indications of efficiency in South Dakota (Dennis et al., 1981), North Dakota (Smith et al., 1992, 1997), Greece (Rudolph et al., 1994), Canada and Argentina (Krauss, 2003). Rocket seeding has been reported as very successful in USSR (Burtsev, 1985; Abshaev and Malkarova, 2003; Tlisov and Khuchunaev, 2003), and successful in other countries (Mesinger and Mesinger, 1992; Simeonov, 1996). The efficiency of ground seeding has also been assessed as significant in various countries: France (Dessens et al., 1970; Dessens, 1986b, 1998), Argentina in cold front situations (Iribarne and Grandoso, 1965), and Spain (Balasch et al., 2004). However, the beneficial results of the three methods have also been critically discussed by other scientists because two costly randomized projects using either aircraft (Knight et al., 1979) or rockets (Federer et al., 1986), operated in the US and in Switzerland, ended without conclusive results. Different explanations have been proposed for this apparent dichotomy, among which the hypothesis that experimental results obtained with small target areas may not be a reliable indication to what one can expect over larger areas (Smith et al., 1992), or that the results achieved under one set of conditions or in one part of the world are not necessarily transferable to other conditions or meteorological regimes (Atlas, 1977). It is also now generally accepted that the two randomized experiments cited above ended after too few hail seasons to obtain significant conclusions simply because the most severe hailstorms, which really constitute the core of the problem, occur very rarely in a given region (Berthet et al., 2013).

The aim of our paper is not to duplicate the relevant ASCE document but to examine the scientific and practical results for the delivery method using ground-based silver iodide generators. The concept of seeding hailstorms from ground generators is presented in Section 2, which reviews the process of emission of silver iodide nuclei by burning a silver iodide compound, the dispersion of the nuclei in the boundary layer, the possible decrease in the nucleating power of silver iodide under solar radiation, and the ingestion of the particles by convective clouds. The changes in the microphysical processes induced by the artificial IFNs are examined in Section 3, with a review of the modern hail suppression conceptual models and numerical simulations. The main historical projects of hail suppression with ground generators are summarized in Section 4. Section 5 presents the scientific project in operation in France and Spain, with assessment of the physical results. Finally, Section 6 summarizes the practical results of hail suppression with ground seeding and suggests possible improvements for the future.

2. Monitoring of silver iodide nuclei from ground generators to cloud bases

The possibility to mitigate hailfall intensity by using small burners at the ground needs to be carefully explained to the general public, if not to some meteorologists. The purpose of this section is to summarize the scientific results concerning the migration of the artificial IFNs from the ground to the cloud bases, and to survey their efficiency in changing the microphysical processes inside the clouds. Many papers relative to this section have been published in the *Journal of Weather Modification* (J. Wea. Modif.), and in the *Bulletin de l'Observatoire du Puy de Dôme* (Bull. Obs. P.d.D.) or its successors, the *Journal de Recherches Atmosphériques* (J. Rech. Atmos) then *Atmospheric Research* (Atmos. Res.).

2.1. AgI nuclei production

A silver iodide nuclei generator must produce as many "effective" IFNs as possible with a given quantity of silver iodide, "effective" meaning that the particles are able to produce ice crystals in a supercooled cloud at a given temperature. Experiments show that the largest AgI particles meet their nucleating efficiency at −5 °C, while for the smaller ones, the efficiency is observed at colder temperatures. The performance of a generator burning a silver iodide compound must then be specified at different temperatures, but, for the sake of simplification, and as there are strong correlations between the numbers of nuclei active at different temperatures, one frequently gives the production number at −15 °C, an intermediate temperature at which the saturation water vapor pressure difference above water and ice is maximum (Mason, 1971), suggesting that the seeding effect is probably the highest.

As reported in the ASCE (2015) standard, AgI aerosols can be generated by burning silver iodide with various chemical solutions or pyrotechnics. When burning an AgI-NaI acetonic solution, Dessens (1961) has shown that the use of an auxiliary solid fuel, like charcoal, or of a combustible gas, like kerosene or propane, is not recommended, the thermodynamic calculations showing that there are enough calories