Cambridge University Press
978-0-521-84086-6 - Human Impacts on Weather and Climate, Second Edition
William R. Cotton and Roger A. Pielke
Excerpt
More information

Part I

The rise and fall of the science of weather modification by cloud seeding

In Part I we examine human attempts at purposely modifying weather and climate. We also trace the history of the science of weather modification by cloud seeding describing its scientific basis and the rise and fall of funding of weather modification scientific programs, particularly in the United States.

1

The rise of the science of weather modification by cloud seeding

Throughout history and probably prehistory man has sought to modify weather by a variety of means. Many primitive tribes have employed witch doctors or medicine men to bring clouds and rainfall during periods of drought and to drive away rain clouds during flooding episodes. Numerous examples exist where modern man has shot cannons, fired rockets, rung bells, etc. in attempts to modify the weather (Changnon and Ivens, 1981).

It was Schaefer's (1948a) discovery in 1946 that the introduction of dry ice into a freezer containing cloud droplets cooled well below 0 °C (what we call supercooled droplets) resulted in the formation of ice crystals, that launched us into the modern age of the science of weather modification.[1] Working for the General Electric Research Laboratory under the direction of Irving Langmuir on a project investigating ways to combat aircraft icing, Schaefer learned to form a supercooled cloud by blowing moist air into a home freezer unit lined with black velvet. He noted that at temperatures as cold as −23 °C, ice crystals failed to form in the cloud. Introducing a variety of substances in the cloud failed to convert the cloud to ice crystals. It was only after a piece of dry ice was lowered into the cloud that thousands of twinkling ice crystals could be seen in the light beam passing through the chamber. He subsequently showed that only small grains of dry ice or even a needle cooled in liquid air could trigger the nucleation of millions of ice crystals.

Motivated by Schaefer's discovery, Vonnegut (1947), also a researcher at the General Electric Research Laboratory, began a systematic search through chemical tables for materials that have a crystallographic structure similar to ice. He hypothesized that such a material would serve as an artificial ice nucleus. It was well known at that time that under ordinary conditions, the formation (or nucleation) of ice crystals required the presence of a foreign substance called a

[1] A summary of this early work is given in Havens *et al.* (1978).

nucleus or mote that would promote their formation. For some time European researchers such as A. Wegener, T. Bergeron, and W. Findeisen had hypothesized that the presence of supercooled droplets in clouds indicated a scarcity of ice-forming nuclei in the atmosphere. It was believed that the dry ice in Schaefer's experiment cooled the air to such a low temperature that nucleation took place without an available nuclei; the process is referred to as *homogeneous nucleation.* Vonnegut's search through the chemical tables revealed three substances which had the desired crystallographic similarity to ice: lead iodide, silver iodide, and antimony. Dispersal of a powder of these substances in a cold box had little effect. Vonnegut then decided to produce a smoke of these substances by vaporizing the material, and as it condensed a smoke of very small crystals of the material was created. Vonnegut found that a smoke of silver iodide particles produced numerous ice crystals in the cold box at temperatures warmer than $-20\,°C$ similar to dry ice in Schaefer's experiment.

The stage was now set to attempt to introduce dry ice or silver iodide smoke into real supercooled clouds and observe the impact on those clouds. Again, the background of previous research by the Europeans (Wegener, Bergeron, and Findeisen) was important for this stage. They showed that ice crystals once formed in a supercooled cloud could grow very rapidly by deposition of vapor onto them at the expense of supercooled cloud droplets. This is due to the fact that the saturation vapor pressure with respect to ice is lower than the saturation vapor pressure with respect to water at temperatures colder than zero degrees centigrade. As shown in Fig. 1.1, the supersaturation with respect to ice increases linearly with decreasing temperature below 0 °C for a water-saturated cloud. Thus an ice crystal nucleated in a cloud that is water saturated finds itself in an environment which is supersaturated with respect to ice and can thereby grow rapidly by deposition of vapor. As vapor is deposited on the growing ice crystals the vapor in the cloud is depleted, and the cloud vapor pressure lowers to below water saturation. Thus cloud droplets evaporate providing a reservoir of water vapor for growing ice crystals. The ice crystals, therefore, grow at the expense of the cloud droplets.

It was thus hypothesized that the insertion of dry ice or silver iodide in a supercooled cloud would initiate the formation of ice crystals, which in turn would grow by vapor deposition into ice crystals. Precipitation could be artificially initiated in such clouds.

Langmuir (1953) calculated theoretically the number of ice crystals that would form from dry ice pellets of a given size. He also predicted that the latent heat released as the ice crystals grew by vapor deposition would warm the seeded part of the cloud, causing upward motion and turbulence which would disperse the

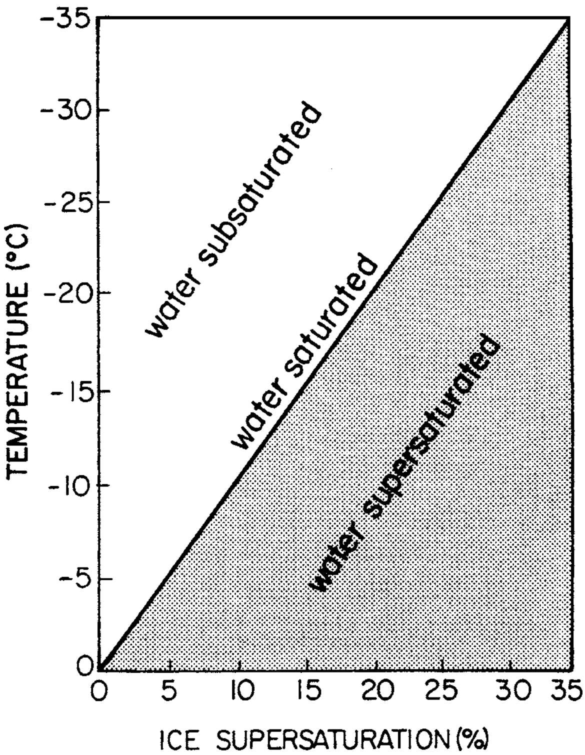

Figure 1.1 Supersaturation with respect to ice as a function of temperature for a water-saturated cloud. The shaded area represents a water-supersaturated cloud. From Cotton and Anthes (1989).

mist of ice crystals created by seeding over a large volume of the unseeded part of the cloud.

On November 13, 1946, Schaefer (1948b) dropped about 1.4 kg of dry ice pellets from an aircraft flying over a supercooled stratus cloud near Schenectady, New York. Similar to the laboratory cold box experiments, the cloud rapidly converted to ice crystals which fell out as snow beneath the stratus deck. This, as well as a number of other exploratory seeding experiments, led to the formation of Project Cirrus.

1.1 Project Cirrus

Under Project Cirrus, Langmuir and Schaefer performed a number of exploratory cloud seeding experiments including seeding of cirrus clouds, supercooled stratus clouds, cumulus clouds, and even hurricanes. Supercooled stratus clouds yielded the clearest response to seeding. A variety of aircraft patterns were flown over the stratus clouds while dropping dry ice. Patterns included L-shaped, race track, and Greek gammas. The response was the formation of holes in the clouds whose shape mirrored the aircraft flight pattern (see Fig. 1.2).

Seeding of supercooled cumulus clouds produced more controversial results. Dry ice and silver iodide seeding experiments were carried out at a variety of locations with the most comprehensive experiments being over New Mexico. Based on four seeding operations near Albuquerque, New Mexico, Langmuir claimed that seeding produced rainfall over a quarter of the area of the state of New Mexico. He concluded that "The odds in favor of this conclusion as compared to the rain was due to natural causes are millions to one." Langmuir was even more enthusiastic about the consequences of silver iodide seeding over New Mexico. The explosive growth of a cumulonimbus cloud and the heavy rainfall near Albuquerque and Santa Fe were attributed to the direct results of ground-based silver iodide seeding. In fact Langmuir concluded that nearly all the rainfall that occurred over New Mexico on the dry ice seeding day and the silver iodide seeding day were the result of seeding.

One of the most controversial experiments performed during Project Cirrus was the periodic seeding experiment. In this experiment a ground-based silver iodide generator was operated on a 7-day periodic schedule with the generator

Figure 1.2 Race track pattern approximately 20 miles long produced by dropping crushed dry ice from an airplane. The safety-pin-like loop at the near end of the pattern resulted when the dry ice dispenser was inadvertently left running as the airplane began climbing to attain altitude from which to photograph results. From Havens *et al.* (1978). Photo courtesy of Dr. Vincent Schaefer.

being operated 8 hours a day on Tuesday, Wednesday, and Thursday and turned off the rest of the week. A total of 1000 g of silver iodide was used per week and the experiment was carried out from December 1949 to the middle of 1951. The analysis of precipitation and other weather records over the Ohio River basin and other regions to the east of New Mexico revealed a highly significant 7-day periodicity. Langmuir and his colleagues were convinced that this periodicity in the rainfall records was a direct result of their seeding in New Mexico. Other scientists were not so convinced (Lewis, 1951; Wahl, 1951; Wexler, 1951; Brier, 1955; Byers, 1974). They showed that large-amplitude 7-day periodicities in rainfall and other meteorological variables, though not common, had occurred during the period 1899–1951. Thus they felt the rainfall periodicity was due to *natural variability* rather than to a direct consequence of cloud seeding.

Convinced that cloud seeding was a miraculous cure to all of nature's evils, Langmuir and his colleagues carried out a trial seeding experiment of a hurricane with the hope of altering the course of the storm or reducing its intensity. On October 10, 1947, a hurricane was seeded off the east coast of the United States. About 102 kg of dry ice was dropped in clouds in the storm. Due to logistical reasons, the eyewall region and the dominate spiral band were not seeded. Observers interpreted visual observations of snow showers as evidence that seeding had some effect on cloud structure. Following seeding, the hurricane changed direction from a northeasterly to a westerly course, crossing the coast into Georgia. The change in course may have been a result of the storm's interaction with the larger-scale flow field. Nonetheless, General Electric Corporation became the target of lawsuits for damage claims associated with the hurricane.

While the main focus of research during Project Cirrus was the dry ice and silver iodide seeding of supercooled clouds, some theoretical and experimental effort was directed toward stimulated rain formation in non-freezing clouds or what we will refer to as warm clouds. In 1948, Langmuir (1948) published his theoretical study of rain formation by chain reaction. According to his theory, once a few raindrops grew by colliding and coalescing with smaller drops to such a size that they would break up, the fragments they produced would serve as embryos for further growth by collection. The smaller-sized embryos would then ascend in the cloud updrafts while growing by collection and also break up creating more raindrop embryos. Langmuir hypothesized that insertion of only a few raindrops in a cloud could infect the cloud with raindrops through the chain-reaction process. Some attempts were made to initiate rain in warm clouds by water-drop seeding in Puerto Rico, though no suitable clouds were found. Subsequently Braham *et al.* (1957) and others at the University of Chicago demonstrated that one could initiate rainfall by water-drop seeding. This experiment will be discussed more fully in a later section.

In summary, Project Cirrus launched the United States and much of the world into the age of cloud seeding. The impact of this project on the science of cloud seeding, cloud physics research, and the entire field of atmospheric science was similar to the effects of the launching of Sputnik on the United States aerospace industry.

2

The glory years of weather modification

2.1 Introduction

The exploratory cloud seeding experiments performed by Langmuir, Schaefer, and Project Cirrus personnel fueled a new era in weather modification research as well as basic research in the microphysics of precipitation processes, cloud dynamics, and small-scale weather systems, in general. At the same time commercial cloud seeding companies sprung up worldwide practicing the art of cloud seeding to enhance and suppress rainfall, dissipate fog, and decrease hail damage. Armed with only rudimentary knowledge of the physics of clouds and the meteorology of small-scale weather systems, these weather modification practitioners sought to alleviate all the symptoms of undesirable weather by prescribing cloud seeding medication. The prevailing view was "cloud seeding is good!"

Scientists were now faced with the major challenge of proving that cloud seeding did indeed result in the enhancement of precipitation or produce some other desired response, as well as unravel the intricate web of physical processes responsible for both natural and artificially stimulated rainfall. We, therefore, entered the era where scientists had to get down in the trenches and sift through every little piece of physical evidence to unravel the mysteries of cloud microphysics and precipitation processes.

As the science of weather modification developed, two schools of cloud seeding methodology emerged. One school embraced what is called the *static mode* of seeding while the other is called the *dynamic mode* of seeding. In the next few sections, we will review these two approaches including the application of cloud seeding to hail suppression, hurricane modification, and precipitation enhancement in warm clouds.

2.2 The static mode of cloud seeding

We have seen that the pioneering experiments of Schaefer and Langmuir suggested that the introduction of dry ice or silver iodide into supercooled clouds could initiate a precipitation process. The underlying concept behind the *static mode* of cloud seeding is that natural clouds are deficient in ice nuclei. (For an excellent, more technical review of static seeding, see Silverman (1986).)

As a result many clouds contain an abundance of supercooled liquid water which represents an underutilized water resource. Supercooled clouds are thus viewed to be inefficient in precipitation formation, where precipitation efficiency is defined as the ratio of the rainfall rate or flux of rainfall on the ground to the flux of water substance entering the base of a cloud. The major focus of the static mode of cloud seeding is to increase the precipitation efficiency of a cloud or cloud system.

In its simplest form the static mode of cloud seeding was based on the Bergeron–Findeisen concept in which ice crystals nucleated either naturally or through seeding in a water-saturated supercooled cloud will grow by vapor deposition at the expense of cloud droplets. Figure 2.1 illustrates schematically the Bergeron–Findeisen process. Seeding therefore can convert a naturally inefficient cloud containing supercooled cloud droplets into a precipitating cloud in which the precipitation is in the form of vapor-grown ice crystals or raindrops formed from melted ice crystals. The "seedability" of a cloud is thus primarily a function of the availability of supercooled water. Because laboratory cloud chambers predicted that natural ice nuclei concentrations increased exponentially with the degree of supercooling (i.e., degrees colder than 0 °C) and because the amount of water vapor available for condensation increases with temperature, it was generally believed that the availability of supercooled water was greatest at warm temperatures, or between 0 °C and −20 °C.

Cloud seeding experiments and research on the basic physics of clouds during the 1950s through the early 1980s revealed that this simple concept of static

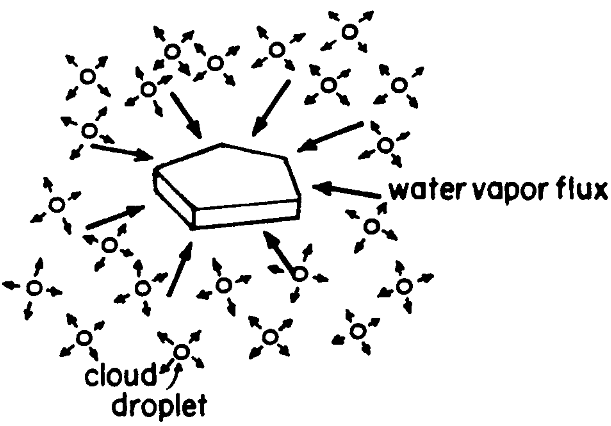

Figure 2.1 Schematic illustration of the Bergeron–Findeisen process.

seeding is only applicable to a limited range of clouds. It was found that in many supercooled clouds, the primary natural precipitation process was not growth of ice crystals by vapor deposition but growth of precipitation by collision and coalescence, or collection (see Fig. 2.2). It was found that clouds containing relatively low concentrations of cloud condensation nuclei (CCN) were more likely to produce rain by collision and coalescence among cloud droplets than clouds containing high concentrations of CCN. If a cloud condenses a given amount of supercooled liquid water, then a cloud containing low CCN concentrations will produce fewer cloud droplets than a cloud containing high CCN concentrations. As a result, in a cloud containing fewer cloud droplets, the droplets will be bigger on the average and fall faster than a cloud containing numerous, slowly settling cloud droplets. Because some of the bigger cloud droplets will settle through a population of smaller droplets more readily in a cloud containing low CCN concentrations, a cloud containing low CCN concentrations is more likely to initiate a precipitation process by collision and coalescence among cloud droplets than a cloud with a high CCN concentration. Generally clouds forming in a maritime airmass have lower concentrations of CCN than clouds forming in continental regions, often differing by an order of magnitude or more, and in polluted air masses the CCN concentrations can be 40 times that found in a clean maritime airmass.

It was also found that clouds having relatively warm cloud base temperatures were richer in liquid water content than clouds having cold cloud base temperatures. This is because the saturation vapor pressure increases exponentially with temperature. As a result clouds with warm cloud base temperatures have much more water vapor entering cloud base available to be condensed in the upper

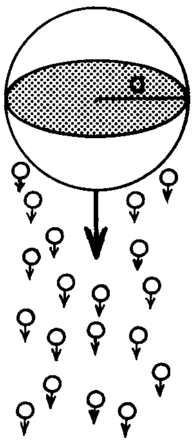

Figure 2.2 Illustration of growth of a drop by colliding and coalescing with smaller, slower-settling cloud droplets. From Cotton (1990).