Crop duster-turned cloud seeder disperses salt powder milled to 2 to 5 microns for optimal hygroscopic seeding over the Galilee in northern Israel. Photo: D. Rosenfeld

Basic Cloud Seeding Concepts

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Cloud seeding is increasingly being used for both water supply enhancement and weather damage reduction. In the West, cloud seeding is performed with the goal of increasing the overall precipitation into a watershed. Elsewhere, particularly the High Plains of the United States and Canada, it is used for hail suppression to reduce damage to crops and urban areas.

Compelling evidence suggests that seeding supercooled orographic clouds, those formed by air lifting over mountains, can increase precipitation on the ground and cause significant increases in the snowpack. Although the amounts of precipitation increase are under debate, a 10 percent increase is conservatively estimated.

In the Colorado River Basin, we focus on glaciogenic seeding (using ice-forming materials) of winter orographic clouds because the strongest scientific evidence that seeding can increase precipitation comes from this method. In addition, western reservoirs are replenished primarily from snowmelt, derived largely from snowfall from winter orographic clouds, when conditions minimize losses to evaporation. In contrast, rainfall from summer convective clouds contributes much less to reservoirs, as it is largely absorbed locally by vegetation and lost via evaporation and evapotranspiration.

About Orographic Clouds

The figure at far right illustrates the formation of an orographic cloud as air is forced to lift in order to pass over mountains. Updraft velocities, which can be several meters per second, depend upon the speed and direction of the wind and the height of the barrier. Orographic clouds may be quite transitory, although with steady winds, they can last for hours. Precipitation can form in the time it takes the air parcel to move from the upwind lateral boundary to the downwind boundary, typically around 20 minutes. Because stable, wintertime orographic clouds have low liquid water content, usually less than 0.5 grams per kilogram, precipitation production requires efficient conversion of cloud droplets to precipitation.

The goal of seeding these clouds is to reduce the timescale of precipitation formation so that precipitation is optimized on the upwind side of the mountain crest. Orographic clouds offer several advantages over cumulus clouds for seeding: they are persistent and produce precipitation even in the absence of large-scale meteorological disturbances, and much of the precipitation is spatially confined to high mountainous regions, simplifying set-up of ground-based seeding and observational networks.

How Precipitation Forms

Warm cloud precipitation processes (above 0°C) involve larger-sized droplets settling through the cloud relative to smaller ones and colliding and coalescing to form still larger droplets. Precipitation growth proceeds very rapidly once droplets exceed 40 microns in diameter. The efficiency of the process depends on the time available for precipitation formation, the liquid water content of the cloud, and the concentration of cloud droplets that form.

Cloud droplets form on hygroscopic (salt and salt-like, including ammonium sulfate) particles in the atmosphere called cloud condensation nuclei (CCN). CCN concentrations are generally less than 100 per cubic centimeter over oceans, and range from a few hundred to 1,000 per cubic centimeter over remote land areas, up to several thousand per cubic centimeter in areas affected by human activities. Clouds with low CCN concentrations and high liquid water contents are most efficient at producing warm rain by collision and coalescence.

Ice phase precipitation processes (when most or all of the cloud is below 0°C) include vapor deposition growth of ice crystals, ice particles collecting cloud droplets (riming), and collision and coalescence of ice crystals (aggregation). Because the saturation vapor pressure over ice is less than that over water, ice crystals that form on ice nuclei (IN) in a water-saturated cloud of droplets are in a supersaturated environment and grow efficiently by vapor deposition. Riming involves ice particles settling through and colliding with cloud droplets, which then freeze onto the particles. Note that for a given liquid water content, the higher the CCN concentration (such as in polluted air), the smaller the cloud droplets and the lower the efficiency of this process. Ice crystal aggregation occurs most readily under conditions of high concentrations of ice crystals, relatively warm air (near 0°C), and with complex, dendritic ice crystal structures such that crystals can readily interlock.

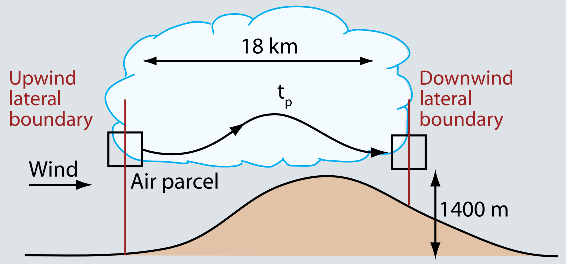
Concentrations of ice crystals do not always correspond to the concentrations of IN. Several mechanisms of ice multiplication have been proposed that explain many, but not all, differences between IN and ice crystal concentrations.

Types of Cloud Seeding

Hygroscopic seeding is used in warm or mixed-phase clouds. Large hydroscopic particles (salt powders and hygroscopic flare-produced particles; see image below) are injected into a cloud to increase the concentration of "collector drops" that can grow into raindrops by collecting smaller droplets and enhancing the formation of frozen raindrops and graupel (snow-like ice) particles. This method of seeding may also be effective in wintertime orographic clouds because it may counteract the negative influences on precipitation of high concentrations of CCN in polluted airmasses.

Glaciogenic seeding involves the injection of ice-producing materials into a supercooled cloud to stimulate precipitation by ice particle growth. The objective of glaciogenic seeding is to introduce seeding material that will produce the optimum concentration of ice crystals for precipitation formation. That concentration depends on particular features of the clouds and background aerosol concentrations. Recent experiments and basic physical modeling suggest that the window of opportunity for precipitation enhancement by glaciogenic cloud seeding is limited to:

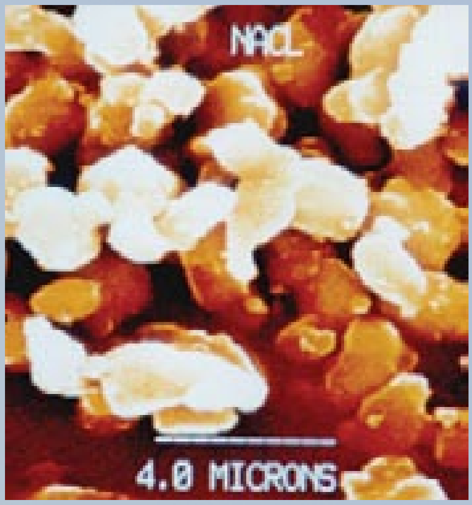
- clouds that are relatively cold-based and continental;
- clouds having top temperatures in the range of -10°C to -25°C;
- the time available for precipitation formation, as illustrated at right.



Schematic of a stable orographic cloud showing the trajectory of an air parcel through the cloud, which determines the Lagrangian time scale (t_p) for the development of precipitable particles.

The temperature window is critical: at cloud temperatures colder than -25°C, natural ice crystal concentrations can be high, and seeding could produce too many small ice crystals, resulting in an "overseeded" cloud. Alternatively, seeding materials are less effective in nucleating crystals above -10°C.

Timing is also important. If winds are weak, sufficient time may exist for natural precipitation processes to occur efficiently. Stronger winds may prohibit efficient natural precipitation, so seeding could speed up precipitation formation. But if the wind is too strong, seeded ice crystals will not have enough time to grow to precipitation before they are blown over the mountain crest and evaporate in the sinking subsaturated air on the lee side. Normally National Weather Service model forecasts and synoptic analyses of winds and temperatures are used to determine if conditions are optimum for seeding clouds.



Scanning electron microscope image of experimental hygroscopic powder milled to the optimal size of 2 to 5 microns, used in a seeding experiment conducted in parallel in Israel and Texas (from D. Rosenfeld).

The Seeding Process

Most cloud-seeding operations use silver iodide (AgI), which has a crystalline structure similar to ice. Its ice-nucleating ability depends on the mode of generation, which typically is by acetone generators in which AgI is suspended in acetone. The acetone is burned, producing a smoke of IN. This method allows generators to be located on the ground where they can use natural turbulence to carry IN into the cloud.

Seeding with liquid propane generators is also possible, relatively inexpensive, and suitable for remote computer-controlled generation. However, the generators must be located within the cloud to be effective; not all supercooled clouds reach the surface. Moreover, placement of generators at the tops of mountains is not feasible in designated wilderness areas.

Looking Ahead

The application of glaciogenic cloud seeding to orographic clouds has been shown to increase concentrations of ice crystals in clouds, reduce supercooled liquid water content, and rapidly promote precipitation. However, further refinement of modeling and forecasting abilities would help optimize the cloud seeding process. One model currently being evaluated by the author is the RAMS high-resolution mesoscale model, which can predict wind speeds, cloud water contents, natural precipitation amounts, transport and dispersion, activation of seeding material, and the amount of precipitation enhancement by seeding. In addition, the role of background aerosol concentrations on precipitation formation will be an important area of investigation.

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