The Double-Sided Sensitivity of Clouds to

Air Pollution & Intentional Seeding

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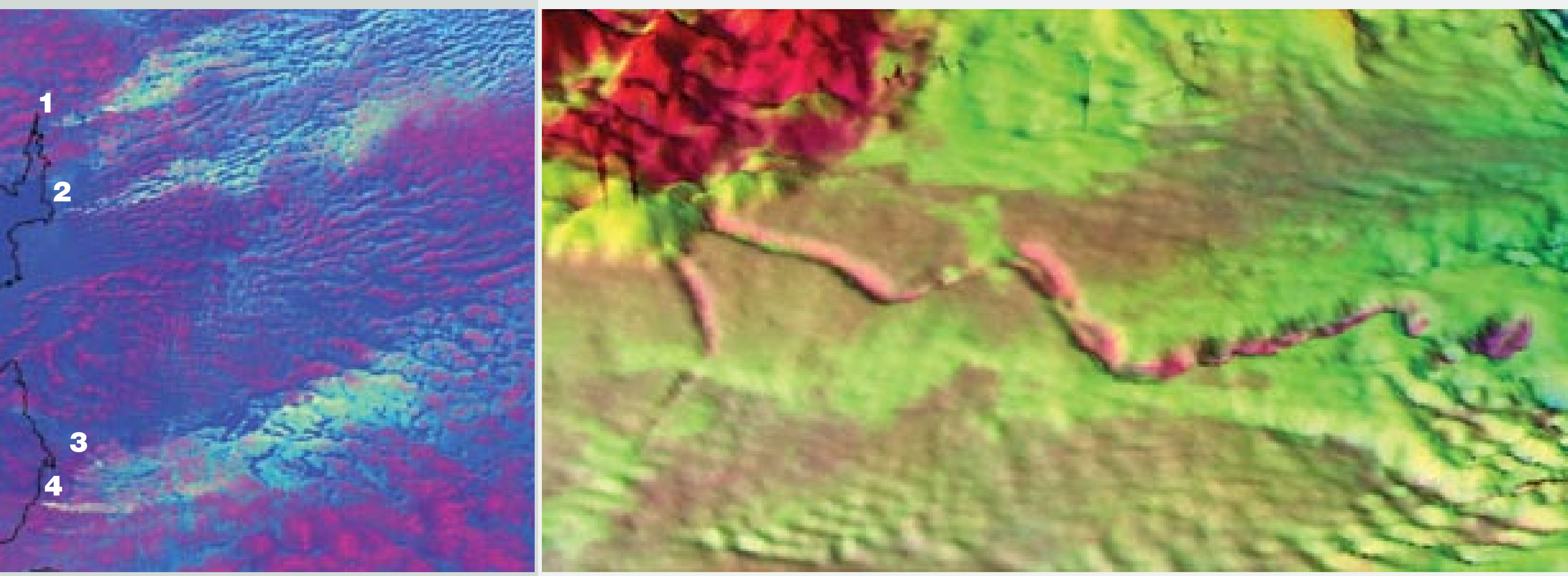
Similar to how dewdrops form on cooled surfaces on the ground, cloud drops form on pre-existing aerosol particles in cooled ascending air streams. Polluted air provides many of these cloud drop condensation nuclei (CCN). Cloud water is comprised of many water drops 10-20 microns in size that are small relative to the range of droplet size in a cloud, float in the air, and are too small to combine into raindrops. Rain might be enhanced by seeding such clouds with two- to five-micron hygroscopic particles (relatively large compared to many aerosols) that nucleate large cloud drops, and then can become embryos of rain drops.

Small drops are also slower to freeze into ice crystals and are less efficiently collected by the ice crystals that do form,



Satellite visualization of NOAA/AVHRR images illustrate the opposite effects of air pollution (left) and cloud seeding (right). At left, shown in yellow are small cloud drops that are not conducive to precipitation; clouds composed of large drops are purple, and snow clouds are red (see Rosenfeld and Lensky, 1998). The image, covering 350 x 450 km, shows pollution tracks manifested as reduced cloud drops over South Australia, originating from the Port Augusta coal power plant (1), Port Pirie lead smelter (2), Adelaide city (3) and oil refineries (4). The image at right shows a silver iodide icy seeding track in clouds composed of small super-cooled liquid water drops over central China. The ~300-km long track appears red because the cloud drops froze and converted to snow that fell from the cloud top and left behind a channel the size of the Grand Canyon. Left image from Rosenfeld, 2000; right image from Rosenfeld and others, 2005.

so they produce less snow. Therefore, cloud seeding to augment precipitation is most effective in “super-cooled” water clouds, clouds that are composed of small water drops that remain liquid at subfreezing temperatures. Because super-cooled clouds of small drops are slow to freeze, precipitation can also be enhanced by seeding with ice nuclei, such as silver iodide, that initiate the ice crystals that subsequently collect the remaining cloud water into snowflakes.

Pollutant Seeds Have Opposite Effect

Cloud seeding for enhancing precipitation is the opposite of inadvertent suppression of precipitation caused by small CCN aerosols from smoke and urban particulate air pollution. We “seed” the clouds negatively with pollution aerosols on a much grander scale than we do positively with silver iodide and large hygroscopic particles. Thus, we can learn much about how to intentionally enhance rain by observing how we inadvertently suppress it.

The recently acquired ability to detect the composition of clouds from weather satellites revealed tracks of super-cooled small drops in clouds downwind of major urban and industrial areas over many parts of the world (see image opposite, left). The same satellite technique was used to show how cloud seeding with silver iodide has the opposite effect of converting the small super-cooled cloud drops into falling snow (see image opposite, right).

The western United States is particularly vulnerable to the effects of pollution, because much of its water comes from pristine oceanic air masses that become polluted by the major urban areas during

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their trek inland. When the polluted air ascends the mountain ranges it forms new clouds with reduced drop size, which dissipate when they pass the ridge line and are forced to descend on the lee side. The short lifetimes of clouds mean that pollution-induced slowing of the conversion of cloud drops to precipitation translates to a net loss of water on the ground. Consequently, we would expect urbanization and the resulting added aerosols during the last century to have caused a reduction in mountain precipitation with respect to coastal and upwind lowland precipitation, defined here as the orographic enhancement factor, Ro.

The Evidence

This hypothesis was validated, as reductions of 10 to 25 percent in Ro were recorded during the past decades in much of the mountain ranges of the western United States, including the California Sierra Nevada, the Cascades east of Seattle, the Wasatch Mountains east of Salt Lake City, the Sandias east of Albuquerque, and parts of the Rocky Mountains west of Denver and Colorado Springs (see Givati and Rosenfeld, 2004 and Rosenfeld and Givati, 2006). The estimated loss of precipitation at the central Sierra Nevada alone is estimated at 4×10^9 cubic meters per year (3.2 million acre-feet per year [afy]). A new study by Rosenfeld documented similar effects over Israel, with losses of usable water to the Lake of Galilee amounting to about 1×10^8 m^3 per year (81,000 afy), approximately six percent of the overall water potential of Israel.

These alarming findings prompted the California Energy Commission to support cloud physics aircraft measurements of pollution aerosols and their interactions with the potential rain clouds over California. These measurements, which took place during the latter part of the winters of 2005 and 2006, confirmed that urban aerosols are ingested into potential rain clouds and suppress their precipitation (Rosenfeld, 2006). Model simulations of these processes provide additional support and insights.

Testing Ro Sensitivity

Cloud seeding for precipitation enhancement is being conducted extensively in the western United States, but assessment of its efficacy requires a randomized seeding scheme, yet to be conducted here in a scientific manner that benefits these new insights. Experimental randomized cloud seeding with silver iodide in northern Israel, which was reported to enhance rainfall there by 13 to 16 percent, has continued operationally since 1975. Givati and Rosenfeld (2005) analyzed the orographic enhancement factor over the hills of northern Israel for the whole period of 1950 to 2002, during which time Ro decreased by 15 percent despite the reported positive seeding effect over the hills there. When separating the time series to seeded and

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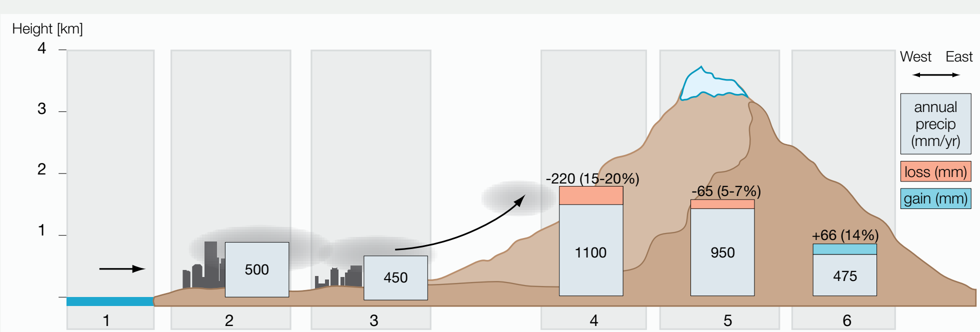

Topographic cross section showing the effects of urban air pollution on precipitation as the clouds move from the California coast east to the Sierra Nevada Mountains. Maritime air (zone 1) is polluted over the coastal and Central Valley urban areas (zones 2, 3): no precipitation decrease occurs. The polluted air rises over mountains and forms new polluted clouds (zone 4): decreases occur in the precipitation ratio of the western slopes to the coastal and plains areas. The clouds reach the high mountains (zone 5) where all precipitation is snow: slight decreases occur in the ratio of the summits to the plains areas. The clouds move to the high eastern slopes (zone 6): some unprecipitated water from the western slop falls there and increases the ratio of the eastern slopes to the plains. Figure modified from Givati and Rosenfeld, 2004.

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unseeded conditions they found that the trend line of Ro shifted upward by 12 to 14 percent for the seeded rain time series compared to the unseeded time series. The sensitivity of Ro to both seeding and pollution effects was greatest in the hilly areas with the greatest natural orographic enhancement factor and practically non-existent in the low-lying areas where no orographic enhancement occurs.

The double-sided sensitivity of clouds to the damaging effects of pollution aerosols and potential corrective effects of cloud seeding provides another powerful tool for assessing the potential for enhancement of orographic precipitation. Areas that have experienced significant reductions in the trends of the orographic enhancement factor are likely manifesting the sensitivity of the clouds to aerosols, and hence could benefit from cloud seeding.

Satellites Offer Great Opportunities

The multispectral capabilities of recently commissioned satellites have provided new insights into the impacts of aerosols in reducing cloud drop size and in slowing the process of precipitation formation. These satellite capabilities can provide further insights into the efficacy of cloud seeding for rain enhancement. They also can be used to direct seeding operations to the clouds that likely will be most responsive to the process. Given the severe shortage of water in the southwestern United States, the time is right to start a new generation of cloud seeding research so the region can benefit from the new methodologies and insights it will produce.

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Yet, changing levels of background aerosols associated with inadvertent weather modification in a region can influence or change the potential for deliberate weather modification and render previous cloud seeding results inapplicable. This finding and other recent work has raised critical questions about the microphysical processes leading to precipitation, the transport and dispersion of seeding material in the cloud volume, the effects of seeding on the dynamical growth of clouds, and the logistics of translating storm-scale effects into an area-wide precipitation effect. Questions such as the transferability of seeding techniques or whether seeding in one location can "steal" rain from other locations can only be addressed through sustained research on the underlying science combined with carefully crafted hypotheses and physical and statistical experiments.

Significant and exciting advances in observational, computational, and statistical technologies have occurred over the past two to three decades. These include capabilities to: 1) detect and quantify relevant variables on temporal and spatial scales not previously possible; 2) acquire, store, and process vast quantities of data; and 3) account for sources of uncertainty and incorporate complex spatial and temporal relationships. Increased computing power has enabled the development of models that range in scale from a single cloud to the global atmosphere. However, because of lack of funding, few of these tools have been applied in any collective and concerted fashion to resolve critical uncertainties in weather modification activities.

Future Directions

Capitalizing on these advances and especially adding new remote and in situ observational tools to existing or new experiments could yield substantial new insights and at last simultaneously provide the necessary physical and statistical data on the efficacy of cloud seeding to enhance precipitation or mitigate hail. Some especially promising areas include:

- *Hygroscopic seeding to enhance rainfall*. The small-scale experiments and larger-scale coordinated field efforts proposed by the WMO (2000) could serve as a starting point for such efforts.
- *Orographic cloud seeding to enhance precipitation*. A randomized program that includes strong modeling and observational components and employs advanced computational and observational tools could substantially enhance our understanding of seeding effects and winter orographic precipitation.
- *Studies of specific seeding effects*. These could include studies of initial droplet broadening, the formation of drizzle and rain associated with natural hygroscopic seeding, and anthropogenic sources of particles.
- *Improving modeling*. Special focus is needed on modeling cloud microphysical processes.

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