

THE DOUBLE-SIDED SENSITIVITY OF CLOUDS TO AIR POLLUTION AND ADVERTENT SEEDING

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1. DOES ACCELERATING PRECIPITATION FORMING PROCESSES ADD RAINFALL?

Deliberate cloud seeding for rain enhancement by glaciogenic IN (Ice Nuclei) and hygroscopic large CCN (Cloud Condensation Nuclei) is the counterpart of inadvertent precipitation suppression by small CCN aerosols from smoke (Rosenfeld, 1999) and urban (Rosenfeld, 2000) particulate air pollution. We "seed" the clouds negatively by pollution aerosols on a much

grand scale than we do positively by IN and large CCN. Being the two sides of the same coin, we can learn much about how to enhance rain advertently by observing how we suppress rain inadvertently.

The traditional perception has been that microphysically maritime clouds (i.e., clouds that form in clean air with small number concentrations of CCN and large drops that are fast to coalesce), which possess much faster conversion of their cloud water to precipitation than microphysically continental clouds,

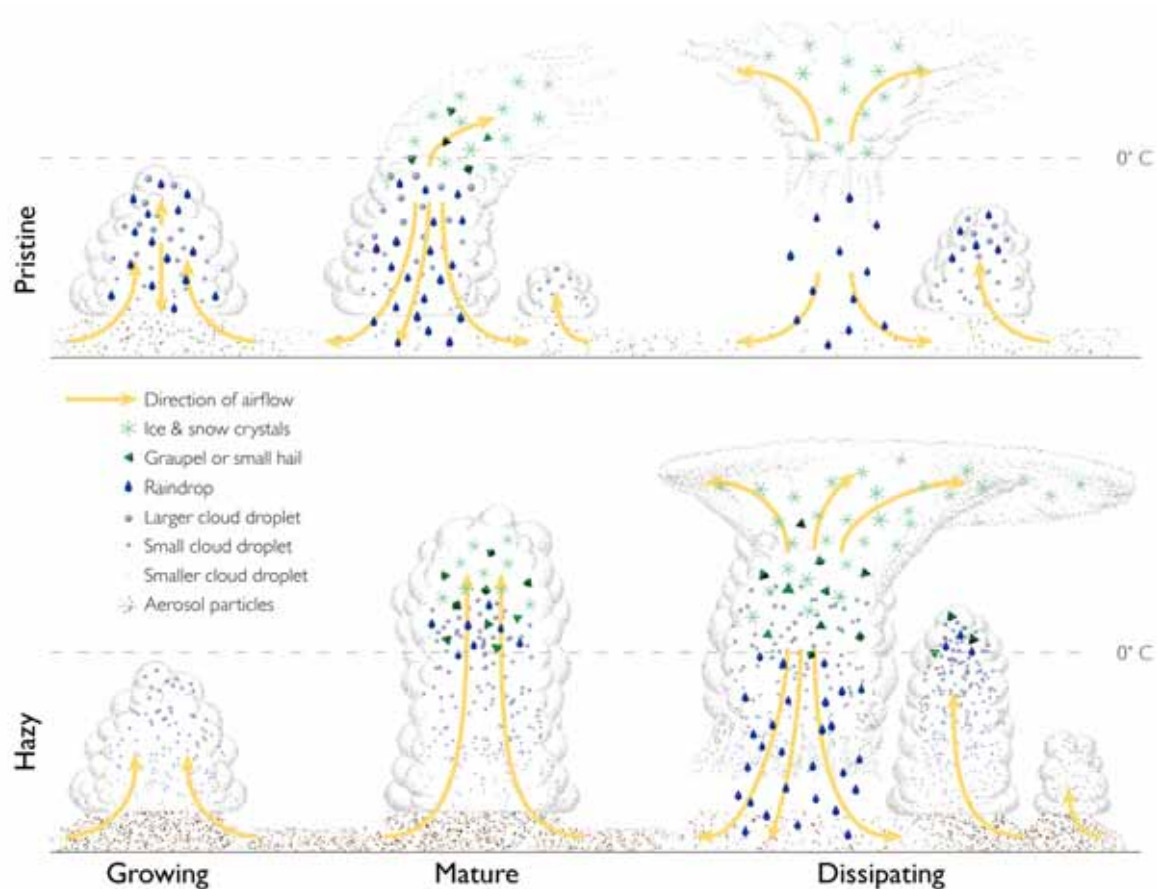


Figure 1: The conceptual model for pollution aerosols invigorating warm-base convective clouds. The early rain formation in the pristine case invokes early downdraft and prevents the lifting of much water to the supercooled levels, so that the cloud dies early with a moderate amount of rainfall. In the polluted case the rain is delayed, so that much supercooled water is accumulated in the mature stage that produces hail, strong precipitation and downdraft in the dissipating stage. The gust front can be sufficiently strong to trigger the next generation of convective clouds and so on, leading to the formation and propagation of a squall line.

also generally produce overall more rainfall. This perception was challenged by the author of this paper in observational (Andrea et al., 2004; Williams et al., 2002) and simulation (Khain et al., 2005) studies, where he suggested that in very clean air, the fast formation of precipitation would cause early rainout from the lower levels of the clouds and so deprive the water and the respective latent heat of freezing from the upper portions of the clouds.

Early rain formation also replaces the updrafts, which feed the clouds with heat and moisture, with downdrafts. This process leads to early maturation and dissipation of clouds, and it explains how aerosols affect cloud lifetime and cover mainly as a response to the dynamic feedbacks of the cloud to the aerosol-induced changes in the precipitation forming processes. The other side of the same coin is observed in CCN-rich clouds where the water ascends to higher altitude and freezes before precipitating. This results in additional latent heat release at greater heights, inducing higher and more extensive clouds and anvils. This additional ice precipitation melts at the lower elevations and takes back there the additional heat from freezing. This added cooling enhances the downdrafts and so further invigorates and organizes the storm system. The overall effect is stronger convective overturning for the same atmospheric lapse rate, which results in greater consumption of the instability (see illustration in Figure 1). Energetically, greater upward transport of heat occurs for the same amount of precipitation reaching the surface. This means a greater conversion of potential to kinetic energy, leading to overall invigoration of the storms and surface precipitation, in spite of the lower precipitation efficiency (Rosenfeld, 2006a). It is suggested here that this has been a major confounding factor in our understanding of seeding effects on precipitation enhancement from deep convective clouds, especially with hygroscopic seeding.

Furthermore, the aerosol induced invigoration of the convective storms can induce them to produce hail. For example convective storms that ingested smoke from forest fires in the Amazon were reported to produce hailstorms (Andreae et al., 2004) – a phenomenon that is uncommon otherwise in the equatorial rain forests.

2. SUPPRESSION OF OROGRAPHIC PRECIPITATION BY AIR POLLUTION

Net enhancement of surface precipitation can be expected with the greatest confidence when seeding shallow clouds that naturally do not reach the minimum depth for the onset of precipitation. This has been demonstrated already by the glaciogenic seeding of supercooled stratus. On the other side of the same coin, it was shown also that polluting shallow maritime precipitating clouds can prevent their precipitation, as is the case for ship

tracks over ocean (Coackley et al., 1987, Rosenfeld et al., 2006), and in shallow clouds over land (Rosenfeld, 1999, 2000, Andreae et al., 2004).

The slowing of the conversion rate of cloud water into precipitation is more likely to be manifested as a net reduction of surface precipitation in orographic clouds, because such clouds are often shallow and short lived due to their forced termination downwind of the ridge line. Borys et al., (2003) showed that the addition of as little as 1 g m^{-3} of sulfate aerosols to a clean background can reduce the orographic snowfall rate in the Colorado Rocky Mountains by up to 50%, due to suppression of the riming of ice crystals with the smaller cloud droplets.

Accumulated rain in Control simulations, $t=3\text{h}$

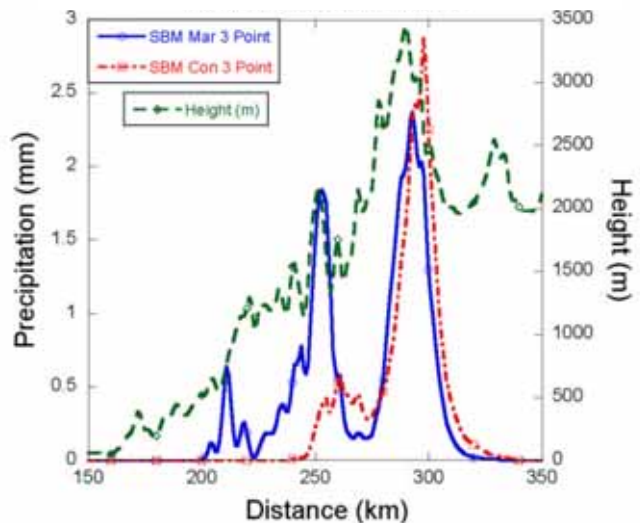


Figure 2: Simulated accumulated precipitation along a cross section of the Sierra Nevada during 3 hours for orographic clouds developing in pristine (blue) and polluted (red) air masses. The green line denotes the topographic elevation of this cross section. The simulation is done with the spectral bin model of the Hebrew University (from Lynn et al., 2007).

Recent studies (Givati and Rosenfeld, 2004 and 2005; Rosenfeld and Givati, 2006) quantified the suppression of orographic precipitation by anthropogenic aerosols. They showed that such suppression is quite prevalent, especially during winter on the west coast of continents in the subtropics and mid-latitudes, where the precipitation over the hills is a major source for the scarce water there. Pristine maritime air passing over the populated coastal plains becomes polluted before ascending and forming clouds over the hills downwind. Givati and Rosenfeld (2004) quantified the rainfall losses over hills and mountains downwind of major coastal urban areas in California and Israel. The losses were found to be 15 – 25% of the annual precipitation in hilly areas in California

and Israel (Givati and Rosenfeld, 2004 and 2005). They showed that the suppression occurred mainly in the relatively shallow orographic clouds within the cold air mass of cyclones and not in warm air masses or in the summer. They defined the suppression of orographic precipitation as a reduction in the orographic enhancement factor R_o , where R_o is defined as the ratio between the precipitation amounts in the hills to the precipitation in the upwind lowland. The R_o time series for relatively pristine areas crosswind to the polluted areas did not show any trend with time, and so served as controls for the polluted areas. Lynn et al. (2007) demonstrated the plausibility of the mechanism proposed by Givati and Rosenfeld (2004) by simulating with an explicit microphysics cloud model the suppression of the orographic precipitation over the Sierra Nevada when high concentrations of CCN were added (see Figure 2).

Rosenfeld and Givati (2006) quantified the effect of aerosols on precipitation not only in California but also farther inland through much of the western U.S. Trend analyses of the orographic winter precipitation enhancement factor along the mountain ranges of the western USA showed a pattern of decreasing ratio during the last century by as much as -24%. The decrease occurred from the southern border of California with Mexico to central California. The decrease ceased in northern California and Oregon, and renewed with R_o reduced by 14% to the east of the Puget Sound and Seattle area in Washington State. Similar decreases occurred also well inland, over Arizona, New Mexico, Utah and the Colorado Rockies. Both absolute precipitation amounts and R_o were affected by fluctuations in the atmospheric circulation patterns such as those associated with the Pacific Decadal Oscillations and the Southern Oscillations Index. However, these climatic fluctuations can not explain the observed multi-decadal trends in R_o (Rosenfeld and Givati, 2006). The negative trends in R_o were found to be associated with elevated concentrations of fine aerosols (Rosenfeld and Givati, 2006). Preliminary results from aircraft measurements in California showed that anthropogenic aerosols indeed interact with the clouds and suppress the precipitation forming processes there (Rosenfeld, 2006b). Similar decreasing trends in R_o of up to 30% were noted on the eastern slopes of the Rocky Mountains during easterly flows, downwind of Denver and Colorado Springs (Jirak and Cotton, 2006).

Rosenfeld et al. (2007) used a unique dataset of observations of precipitation, visibility and winds since 1954 at the top of Mount Hua, China (32°23'N, 109°54'E, 2160 m). A strong decreasing trend in the visibility has been observed (see Figure 3), indicating a respective increasing trend of particulate air pollution. The ratio between the precipitation at Mount Hua and at the nearby lowland rain gauges decreased during the measurement period by about 20%. The decrease

was greater for shorter visibility distance (see Figure 4) and for stronger winds at the mountaintop.

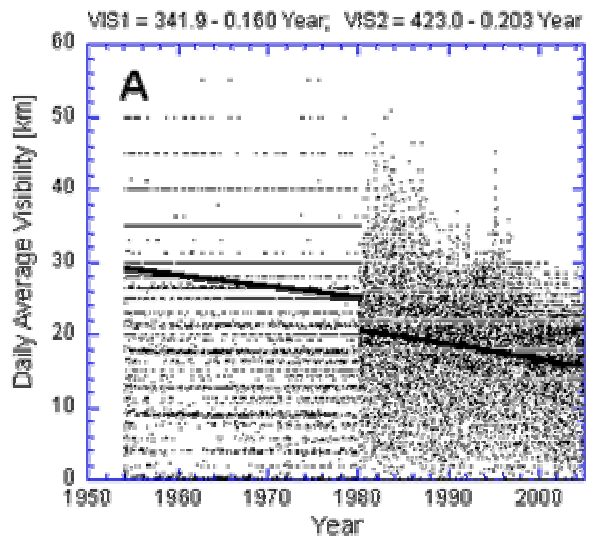


Figure 3: The trend of the observed visibility at Mt. Hua during the whole observation period. Each point represents the averaged visibility for one day. The linear trends are calculated separately for the periods before and after 1980, when the observation methodology was changed. From Rosenfeld et al., 2007.

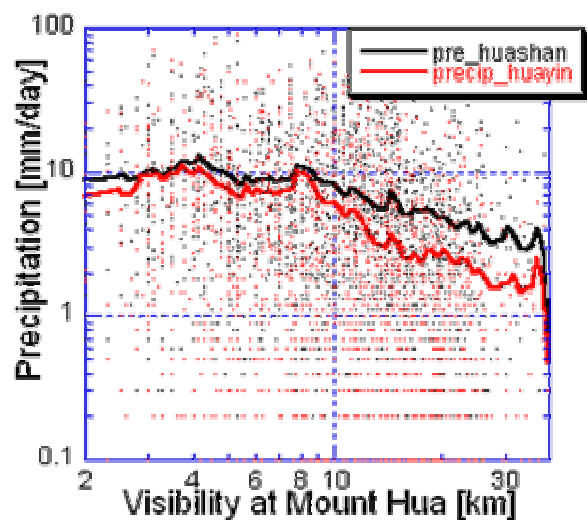


Figure 4: The daily rainfall at Mt. Hua and Huayin as a function of the visibility at Mt. Hua, for 1980-2004. The lines are interpolated curve fits with a weight applied. The weight is applied to 20% of the data (-10% to +10% of the data around the current point). Note that R_o , which is the distance between the lines along the logarithmic ordinate, is reduced for smaller visibility distance. From Rosenfeld et al., 2007.

This is consistent with the shorter lifetime available for conversion of the cloud water to precipitation when the cloud parcels pass faster and live for a shorter time due to stronger wind speeds across the mountain barrier. The decrease in Ro over Mount Hua (see overall trend in Figure 5) occurred mainly by decreasing the probability for light and moderate rain days, with little change in the probability for days with rain > 30 mm at the mountain top. These additional analyses provide physical fingerprints of the processes and support the hypothesis that the trend of increasing air pollution aerosol concentrations is responsible for the observed decreasing trend of the orographic precipitation by slowing down the conversion of cloud water into precipitation in the short living orographic cloud elements. It is the first time that a proxy to CCN concentrations in the free troposphere – the visibility at the top of Mount Hua at height of 2160 m above sea level – has been shown to be directly correlated with the decreasing trend of Ro.

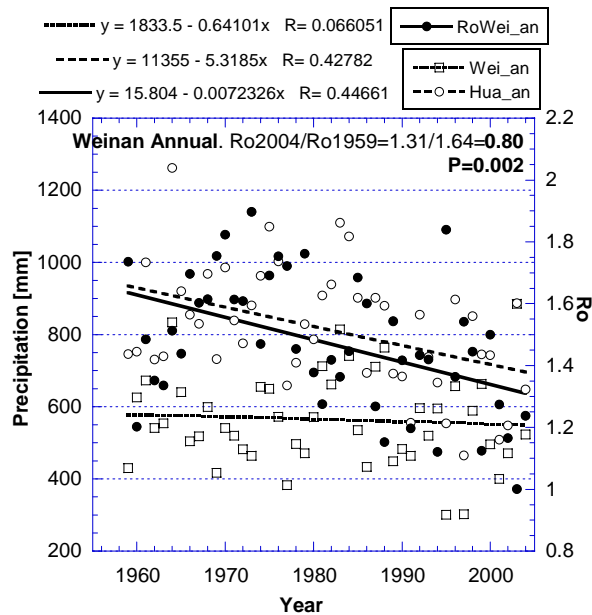


Figure 5: The trends of annual precipitation amounts and ratios, Ro, between Mt.Hua and the plain station of Weinan. The overall decreasing trend in Ro is given as a text line within each plot, as the ratio between Ro as estimated by the regression line at the ending of the time series divided by Ro at the beginning. The regression equations for the three lines are given above the top of each plot. From Rosenfeld et al., 2007.

3. ENHANCING OROGRAPHIC PRECIPITATION BY CLOUD SEEDING

Experimental randomized glaciogenic cloud seeding in northern Israel, which was reported to enhance rainfall there by 13-16% (Gagin and

Neumann, 1974 and 1981), 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 –2002 the Ro of the hilly areas decreased by 15%, in spite of the reported positive seeding effect over the hills there. When separating the time series to seeded and unseeded conditions they found that the trend line of Ro was shifted upward by 12%-14% for the seeded rain time series compared to the unseeded time series (see Figure 6). Thus, the opposite effects of air pollution and seeding appear to have nearly canceled each other in recent years, leading to the false impression that cloud seeding is no longer effective. However, the findings here suggest that if the operational seeding were to stop, Ro would decrease further by about 12%-14% (See Figure 2). The sensitivity of Ro to both seeding and pollution effects was greatest in the areas with the greatest natural orographic enhancement factor and practically non-existent in areas where Ro is near unity. This suggests that the orographic clouds are the most sensitive to air pollution as well as to cloud seeding effects on clouds and precipitation, in agreement with the large susceptibility of precipitation from such short living shallow clouds to aerosols.

The ratio between stations in N3 and the cluster of C2
Seeded : Ending / Starting ratio = 1.23/1.57 =0.78
Unseeded : Ending / Starting ratio = 1.26/1.46 =0.86

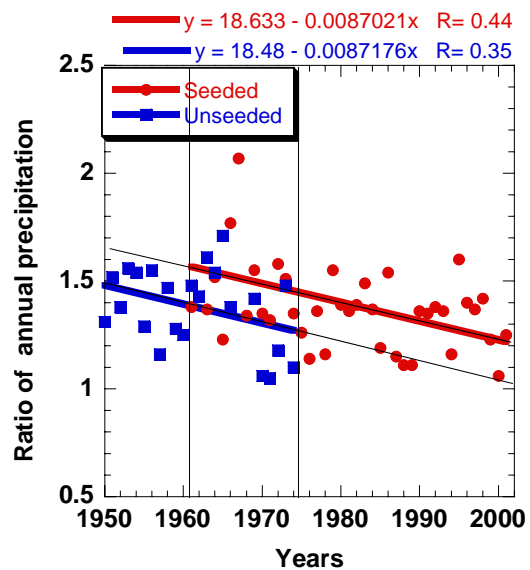


Figure 6: Change in the target/control annual ratio of precipitation during 1950-2001 for the seeded (Red points and trend line) and unseeded (Blue points and trend line) conditions, between stations in the targets areas of the upper Galilee to the control area at the northern coastal plain. The seeded trend line is shifted upward with respect to the unseeded line by 14%, significance=0.03. After Givati and Rosenfeld (2005).

These results suggest that the conceptual model on which the Israeli cloud seeding experiments was based is not exactly as postulated. The seeding was originally aimed at the convective clouds that formed over sea and the coastal plain, with the intent of nucleating ice crystals and forming graupel earlier in the cloud lifecycle (Gagin and Neumann, 1974). However, it appears that cloud seeding did not enhance the convective precipitation, but rather increased the orographic precipitation, probably by the Bergeron- Findeisen process (Bergeron, 1935).

The lack of enhancement of the convective clouds in Israel might be explained by their tendency to mature and dissipate inland during the winter storms. Seeding of mature convective clouds cannot affect them much. The lack of enhancement is also consistent with the microphysically maritime nature of the convective clouds. This appears to be caused mainly due to the natural hygroscopic seeding by sea spray in the winter storms that enhance the warm precipitation (Rosenfeld et al., 2002) as well as promoting the formation of ice hydrometeors that is followed by ice multiplication (Hallett and Mossop, 1974). These suggestions are supported by the results of glaciogenic cloud seeding in Tasmania which targeted a hilly area by seeding along an upwind coastline. The seeding in Tasmania was shown to enhance precipitation from the stratiform orographic clouds, but not from the convective clouds (Ryan, 1997).

This potentially resolves the microphysical questions put forth by Rangno and Hobbs (1995), who asserted that cloud seeding as done in Israel could not have possibly caused the statistically documented rain enhancement from the convective clouds there.

The meaning of the results that are presented here is that statistical evaluations of non-randomized seeding efficacy on orographic precipitation without taking into account the pollution effects will likely lead to erroneous results and misleading conclusions. This fact can explain why such models that estimated the seeding effects in northern Israel based on historical comparisons (Nirel and Rosenfeld, 1995) showed decreases in apparent seeding effect along the years.

4. CONCLUDING REMARKS

The contrasting pollution and seeding effects at the same clouds are not unique to the study shown here. Many places in the world such as California and China are likely influenced by those opposite effects. The effect of air pollution on the orographic precipitation was documented and quantified in those two places, but it was not separate from the possibly positive effect of decades of glaciogenic cloud seeding of the orographic clouds there.

The double sided sensitivity of clouds to the damaging effects of pollution aerosols and potential

corrective effects of cloud seeding provides us with another powerful tool for assessing the potential for rain enhancement of orographic precipitation. Areas that have experienced significant trend of reduction in the orographic enhancement factor are likely manifesting the sensitivity of the clouds to aerosols, and hence representing a potential for rain enhancement by cloud seeding.

The multispectral capabilities of the recently commissioned satellites was the trigger for the new insights to the aerosol impacts on reducing cloud drop size and slowing precipitation forming processes. This satellite methodology can have similar impact on gaining insights and efficacy of cloud seeding for rain enhancement. The retrieval of cloud top microstructure is possible both day and night, using the methodology developed by the author in Rosenfeld et al. (2006a).

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