New insights to cloud seeding for enhancing precipitation and for hail suppression

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ABSTRACT

Satellite synoptic microphysical observations of the impacts of aerosols on cloud microstructure and precipitation forming processes provide us with the extent and scale of inadvertent weather modification. Intended seeding signatures are detectable at much smaller scale by the same satellite technology. Inadvertent and intended weather modification have been regarded until now mostly as independent issues. In this brief review the two are contrasted and presented as different manifestations of the same sensitivity of precipitation- forming processes to the role of aerosols in the rate of conversion of cloud droplets into precipitation and the dynamic response of the clouds, which result in changes of the amount and distribution of precipitation. These considerations are applied here separately to orographic and convective clouds. It is shown that we can learn much on the potential of cloud seeding for precipitation enhancement by observing the opposite response of the clouds to inadvertent effects due to air pollution.

1. The double sided sensitivity of clouds to anthropogenic aerosols

Deliberate cloud seeding for rain enhancement with glaciogenic IN (Ice Nuclei) and hygroscopic large CCN (Cloud Condensation Nuclei) has the counterpart of inadvertent precipitation suppression by small CCN aerosols from smoke (Warner, 1968; Rosenfeld, 1999) and urban (Gunn and Phillips, 1957; Rosenfeld, 2000) particulate air pollution. A major assumption in cloud seeding is that accelerating the conversion of cloud drops to hydrometeors is followed by net enhancement of precipitation amounts on the ground. This acceleration of the precipitation forming processes is done by inadvertent (Hobbs et al., 1970; Mather et al., 1991) and intended (Cooper et al., 1997; Mather et al., 1997) hygroscopic seeding that enhances the coalescence. This is also done by adding IN for enhancing precipitation according to the "static seeding" conceptual model (e.g., Warburton et al., 1995).

We "seed" the clouds negatively and inadvertently with pollution aerosols on a much grander scale than we do positively with IN and giant 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.

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. Similarly, 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), and pollution tracks over land (Rosenfeld, 2000).

Changing the conversion rate of cloud drops into precipitation translates to a respective change in precipitation amount when the lifetime of the cloud drops is shorter than the required time for the cloud to produce most of its precipitation. Cloud lifetime is often a limiting factor in its precipitation for clouds that form on the upwind side of a topographical barrier and are forced to evaporate on its downwind side. Therefore precipitation amounts from orographic clouds are often sensitive to the aerosols. This can be quantified by measuring the orographic enhancement factor of the precipitation (Ro), as measured by the ratio of precipitation over the ridge with respect to the upwind lowland precipitation. Recent studies (Givati and Rosenfeld, 2004; Rosenfeld and Givati, 2006; Griffith et al., 2005; Jirak and Cotton, 2006, Rosenfeld et al., 2007) quantified the suppression of orographic precipitation by anthropogenic aerosols. The decreased precipitation was directly linked to the aerosols in time (Rosenfeld, 2007) and space (Rosenfeld, 2006b). These studies 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 decreasing of Ro over hills and mountains downwind of major coastal urban areas in California and Israel. The Ro decreased by 15 – 25% of the annual precipitation in hilly areas in California, Israel (Givati and Rosenfeld, 2004 and 2006) and China (Rosenfeld et al., 2007).

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, during which Ro 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. 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 1). 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.

Figure 1 implies that the suppressed orographic precipitation due to added air pollution can be counteracted by glaciogenic cloud seeding. It is not obvious that this should be the case, because the added air pollution could possibly render the cloud less susceptible to glaciogenic seeding. This would be the case if air pollution would also enhance the glaciation in clouds, but satellite inference suggests that the formation of ice hydrometeors was suppressed in pollution tracks (Rosenfeld, 2000). In addition, glaciation rate by the Bergeron-Findeisen mechanism does not depend on drop size in clouds with less than drizzle size (Korolev and Isaac, 2003). Furthermore, aircraft observations of clouds with supercooled water down to -37.5°C (Rosenfeld and Woodley, 2000) were replicated by model simulations with an explicit microphysics cloud model (Khain et al., 2001), which showed that the addition of large concentrations of small CCN (the same as polluting the cloud) slowed down substantially the glaciation to the observed rate. Simulating the same cloud but under pristine conditions resulted in a cloud that glaciated much faster and produced much more precipitation. Glaciogenic seeding is unlikely to make much difference in clouds that already glaciate rapidly. Finally, Givati and Rosenfeld (2005) have already shown that cloud seeding appeared to have enhanced precipitation most where the indicated decreasing trends of the orographic precipitation were the largest. In summary, all of the above justifies the view that suppression of orographic precipitation by air pollution and enhancing orographic precipitation by glaciogenic cloud seeding are the two sides of the same coin. This means that the observed sensitivity of supercooled clouds to decreasing precipitation by air pollution can be used as an indicator for the potential of precipitation enhancement by both hygroscopic and glaciogenic seeding.

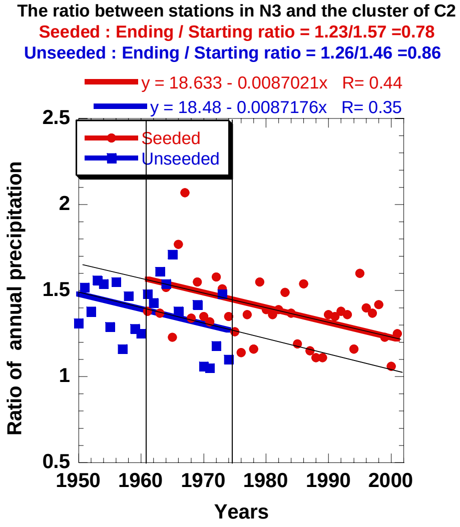

Figure 1: Change in the target/control annual ratio of precipitation during 1950-2001 for the seeded (Red points and trend line) and unseeded (Blue points and trend line) conditions, between stations in the targets areas of the upper Galilee to the control area at the northern coastal plain. The seeded trend line is shifted upward with respect to the unseeded line by 14%, significance=0.03. After Givati and Rosenfeld (2005).

2. A possible new concept of dynamic seeding

The traditional perception has been that micophysically 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, also generally produce overall more rainfall. This perception has been challenged by the author of this paper in observational (Andrea et al., 2004; Williams et al., 2002) and simulation (Khain et al., 2005; Lynn et al., 2005) studies. Rosenfeld (2006a) suggested that in very clean air, the fast coalescence a short distance above cloud base would cause early rainout from the lower levels of the clouds and so deprive the upper portions of the clouds for the water and the respective latent heat of freezing. Early rain formation also causes early downdrafts that replace the updrafts, which feed the clouds with heat and moisture. 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 onto large ice hydrometeors 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 2). 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. In dry atmosphere these added condensates would

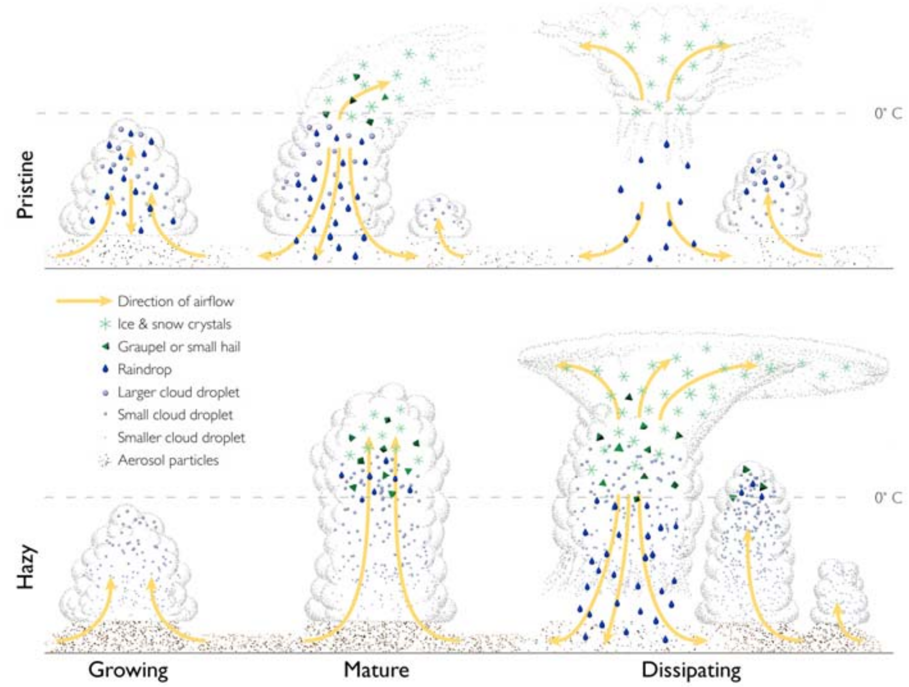

Figure 2: The conceptual model for pollution aerosols invigorating warm-base convective clouds. The early rain formation in the pristine case invokes early downdraft and prevents the lifting of much water to the supercooled levels, so that the cloud dies early with a moderate amount of rainfall. In the 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 (From Rosenfeld, 2006a).

mostly evaporate and a net reduction of precipitation can occur (Khain et al., 2001 and 2005). But in a moist atmosphere the reduced evaporation would leave more condensates to form precipitation that reach the surface, in spite of the lower precipitation efficiency (Khain et al., 2005; Rosenfeld, 2006a). The idea of invigoration of convection by addition of large concentration of small CCN received additional support by recent simulation studies (Van den Heever et al., 2006, Teller and Levin, 2006).

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. This also means that seeding microphysically maritime clouds in a moist atmosphere with small CCN might lead to precipitation enhancement through dynamic enhancement of the convection. This concept can serve as a basis for a new direction in research on rain enhancement from tropical convective clouds.

Andreae et al. (2004) suggested that this imposes a risk that the aerosol-induced invigoration of the convective storms along with the increased amount of water that is raised to the supercooled levels can produce large 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. However, the other side of the same coin is hygroscopic seeding with giant CCN to reverse that process and suppress hail. This supports the conceptual model of hail suppression by hygroscopic seeding for early rainout (Young, 1977; Cotton and Pielke, 1995; WMO, 19896), which is in fact seeding with large hygroscopic particles that reverses the effect of the pollution aerosols by making the cloud more microphysically maritime. The larger numbers of rain drops freeze into larger numbers of ice hydrometeors that fall earlier and deplete the available water and so reduces the size of the hailstones. This conceptual model is the basis for some operational hail suppression hygroscopic seeding (Berthoumieu et al., 1999).

3. The challenge of targeting clouds and documenting seeding effects

It is obvious that a precondition for cloud seeding to work is that the seeding agent must be ingested into the part of the cloud where its intended effect is expected. The seeding material is mixed very inhomogeneously in the cloudy turbulent atmosphere, so that tracking the seeding material with tracers is highly desirable. It can be done using radar chaff, seeding chemicals that can be identified in the precipitation (Linkletter and Warburton, 1977; Warburton et al., 1995) and SF_6 gas (Stith et al., 1996; Reinking and Marter, 1996). Aircraft measurements of the cloud's response are often ambiguous without tagging the seeded cloud volume with a tracer. This has been proved to be the case in a hygroscopic seeding experiment that was conducted recently by the author of this paper in west Texas. Usually only a small portion of the monitored cloud volume contained seeding agent, as marked by the SF6. The seeded cloud volume had substantially larger cloud drops than the unseeded volume of the same cloud at the same time and altitude.

Remote sensing of the seeding signature from space is powerful, as it can provide in near real time feedback to the targeting efficacy of the cloud seeding. Fig. 3 shows glaciated seeded tracks in supercooled layer clouds that were observed to exist for more than an hour after seeding, with a very slow spreading rate reaching a width of less than 15 km by that time (Yu et al., 2005), with a spreading rate of the seeding signature of 1 to 2 ms^{-1}. This is consistent with previous in situ measurements of a spreading rate of 1 ms^{-1} in orographic clouds as done by Deshler et al. (1988) over the Sierra Nevada and 2 ms^{-1} as measured over the Grand Mesa of Colorado by Holroyd et al. (1988).

Satellite observed signatures of glaciogenic seeding for hail prevention in Alberta, Canada, show (Fig. 4) that seeding glaciated only portions of the convective elements (Rosenfeld and Woodley, 2003). Similar observations were made by the author of this study (unpublished) also for cloud seeding for hail suppression in Argentina.

Resolving the issues of targeting the clouds with the seeding agents and verifying that the clouds have the desired microphysical response to the seeding is a fundamental requirement without which one cannot expect to run a seeding project with informed decisions and reliable evaluation of seeding efficacy.

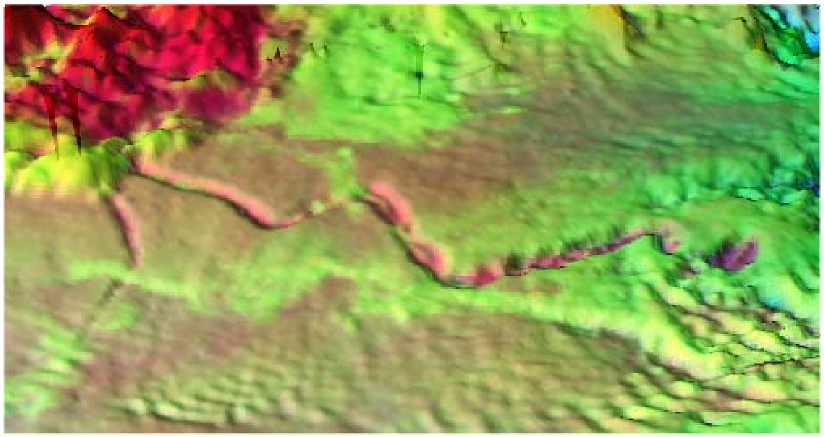

Figure 3: A silver iodide seeding track in clouds composed of small super-cooled drops over central China. The ~300-km long track appears red because the cloud drops froze and converted to snow that fell from the cloud top and left in the cloud field a channel of the size of the Grand Canyon. The color classification scheme is as in Figure 4. (From Rosenfeld et al., 2005).

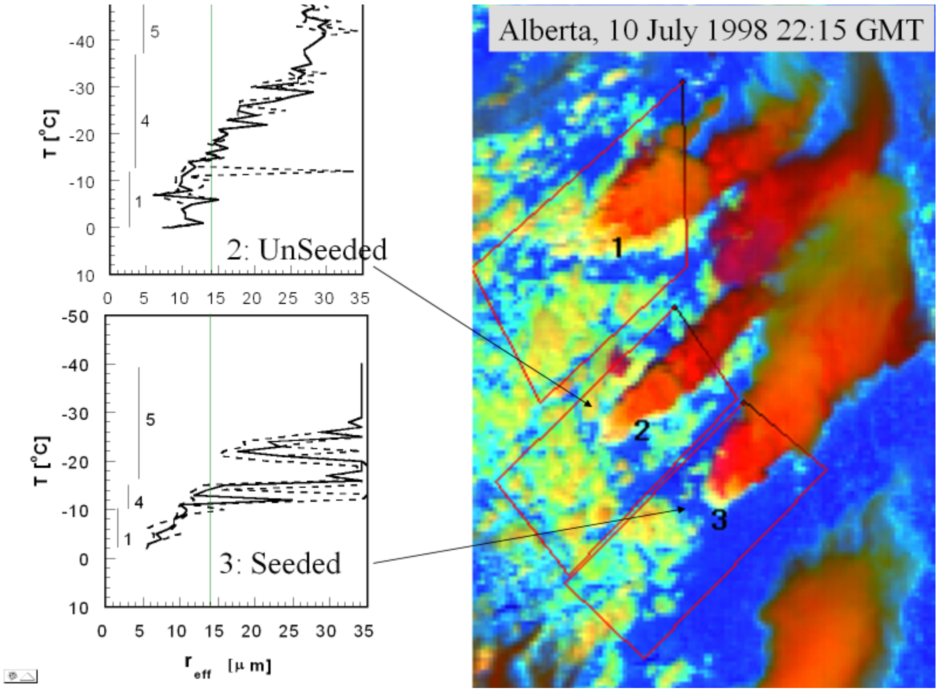

Figure 4**:** Hailstorm Cb clouds in an area of about 150x150 km over Alberta, Canada, as observed by the NOAA/AVHRR overpass of 10 July 1998 at 22:15 GMT. According to the color classification scheme of Rosenfeld and Lensky (1998), the yellow color of the cumuliform cloud elements indicates that they are composed of supercooled droplets. The red areas are glaciated portions of the clouds. The T-r_e graphs are for frames 2 and 3 superimposed on the satellite image. The T- r_e graphs for area #2 shows very deep supercooled water and mixed phase clouds with glaciation occurring only at –37°C. The same applies to Area 1 (not shown). The clouds in Area 3 were seeded with AgI ice nuclei, and glaciated between –15 to –25°C in different parts of the cloud, as indicated by the T- r_e graph for that area. The glaciation is apparent by the abrupt increase of the indicated effective radius to their saturation value of 35 μm. Hail was observed in the area on that day. However, clouds 1 and 2 occurred over remote areas where there were no observations. After Rosenfeld and Woodley (2003).

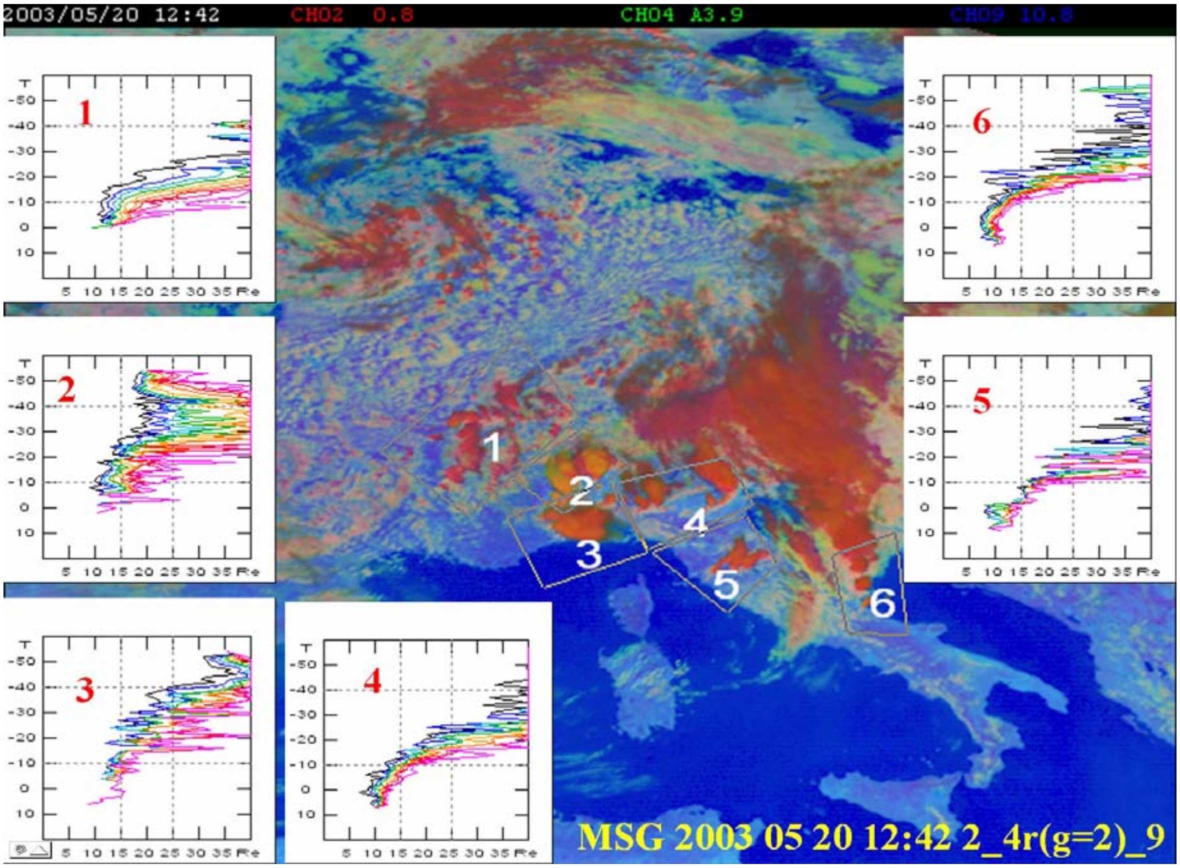

Figure 5**:** The first hail clouds detected by microphysical rendering of the MSG geostationary satellite. The colors in this image are the same RGB composite as in Figure 4, where the visible modulates the red, the thermal IR modulates the blue, and 3.9 μm reflectance component modulates the green. Clouds with smaller particles reflect more 3.9 μm radiation. Smaller particles that extend to large heights with cold temperatures are indicative of potential hail clouds, as in areas 2 and 3. The clouds elsewhere have larger particles, and hence are much less threatening and also less susceptible for modification by seeding.

4. Detecting and seeding potential of hail clouds

The detectability of seeding signatures implies also the potential to detect seedable clouds by their satellite retrieved microstructure.

The traditional conceptual model of cloud seeding for hail suppression relies on seeding the clouds with large concentrations of ice nuclei, so that large numbers of ice hydrometeors compete for the available supercooled water and no particle grows to the size of a large hailstone. Therefore, effective seeding for hail suppression should create a larger number of hydrometeors lower in the cloud and induce glaciation at warmer temperatures. Either way, the composition of potential hail clouds can be characterized by the lack of significant warm rain processes and the large depth of supercooled water in the convective elements. Such clouds are composed of small drops that grow only slowly with height and have depths well above the 0°C isotherm level. In situ aircraft measurements of hailstorms in Mendoza, Argentina, revealed nearly adiabatic supercooled water occurring occasionally all the way to the homogeneous freezing isotherm of -38°C (Rosenfeld et al., 2006b). The aim of the seeding is to increase the cloud drop size in the case of hygroscopic seeding, or to glaciate the cloud water at a small depth above the 0°C isotherm level when using glaciogenic seeding (WMO, 1996). Potential hail clouds can be identified by satellite observations of the vertical profiles of cloud microstructure, using the methodology developed by Rosenfeld and Lensky (1998). The seeding signature can also be identified from space as regions having anomalously warm glaciation temperatures (see example in Figure 4). Previous methods for revealing microphysical seeding signatures in the clouds required in situ measurements with airplanes.

5. Future directions of cloud seeding

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 METEOSAT Second Generation (MSG) allows us to detect operationally the vertical profiles of cloud composition and particle effective radius and thereby identify fast growing clouds with the potential of producing hail (see example in Figure 5). The retrieval is possible both day and night, using the methodology developed by the author in Rosenfeld et al. (2006a). This is now possible at a nominal resolution of 3 km and 15 minutes. The MSG is therefore becoming a key tool for evaluating the potential for cloud seeding and directing the operations. The MSG capabilities will be exceeded by GOES-R geostationary satellite over the western hemisphere, which is now planned to be deployed by 2014 (Schmit et al., 2004).

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