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NATURAL AND ARTIFICIAL RAIN ENHANCEMENT BY SEA SPRAY

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1. INTRODUCTION

Previous studies under the frame work of the Israeli rain enhancement program have shown that the typical air mass that is associated with rain clouds in Israel form in polluted air mass downwind of Europe (Lahav and Rosenfeld, 2000), which crosses the East Mediterranean in winter storms, which add to it sea spray at quantities that depend on the wind velocity. The air ingests additional local air pollution with its further transport inland. Newer observations have shown that when giant salt CCN are ingested into clouds in polluted air they restore the precipitation (Rosenfeld et. al., 2002). The most common source of these aerosols is sea spray, especially during high wind conditions.

Based on those observations, preliminary results of cloud physics measurements using a new method of cloud seeding were done during the winter periods of years 1999 and 2002 as part of the research program of the Israeli Rain Enhancement Project. We experimented with dispersion of fine spray of brine from the Dead Sea under cloud base. Based on data gathered during 6 research flights with a collaborating brine seeding aircraft we are able to report some outstanding results.

2. THE AIRCRAFT MEASUREMENT EQUIPMENT

Data was obtained from research flights of the Israeli 'King air C90' cloud physics aircraft in which the authors were the flight's scientists.

The main instruments used in this study were:SPP-100, CAS, 2DC, King, DMT hot-wire cloud liquid water content, temperature, dew point, pressure, GPS and ball variometer. The data system was the SEA-200.

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We documented the cloud evolution in a way that would be easy for comparison with Satellite data using the MODIS, NOAA-14 and TRMM overpasses within 3 hours of the flight. The analyses were done using the methods of Rosenfeld and Lensky (1998), and Rosenfeld (1999; 2000)

3. THE SEEDING SYSTEM

3.1 *The Seeding Material*

Composition of the brine, in gram of soluble per one liter of brine is: K (3.22), Na (3.3), Ca (37.8), Mg (94.3), Cl (345.0), Br (11.6), SO_4 (0.11). Total: 502 gr/(liter brine)

Brine is freely available on the return channel connecting the Northern and Southern basins of the Dead Sea. To avoid deposits and crystallization, the brine needs to be diluted by 10% of water.

3.2 *The Spray System*

Seeding was done by an agricultural sprayer (PT-6) capable of carrying about 1000kg (800 liters) of seeding material. In order to maintain geographical location, a GPS system was added to the flight instruments.

The spray system was designed for high capacity and smallest feasible drops. It consists of a high-pressure pump, which builds pressure around 50 bar and runs at a rate of 12-15 liters per minute. The pump is well capable of pumping the required solution (This is a salt mass equivalent to 30 hygroscopic flares burning simultaneously for duration of one hour).

The pipes and joins are made of stainless steel to avoid corrosion.

4. THE EXPERIMENT

All flights were conducted in the same manner and using the same work methods to obtain cross-referencing result data (to be able to compare the data of the flights).

4.1 *The Work Area*

Locating the work area requires preliminary observation from the ground, utilizing RADAR data and evaluating the

synoptic situation. Furthermore, limitations due to the Israeli Air Force activity must be taken in consideration.
The size of the work area is about 25X25km. The takeoff is from Sde-Dov airstrip. The runway is located just 200 meters from the Tel Aviv coast line, in a parallel orientation. Therefore sea spray was readily detectable by the CAS, starting from the takeoff run. The designated work area was generally an area in the northern part of Israel near the Lake of Galilee. To avoid as much as possible the sea-spray rising from the Mediterranean, the work area usually tends towards the east. A second evaluation of the conditions is performed in-flight and the final ground coordinates of the work area are then decided upon.
After the work area has been finalized, the seeding aircraft is launched and the research aircraft starts to penetrate the clouds at the upwind of the work area (on the western side) to produce cross-section profiles of these clouds. The clouds were chosen with consideration of the wind direction and the tight borders of Israel, therefore a compromise is always made, and clouds best suitable for seeding are not always available.

4.2 *The Flight Measurements*

The seeding procedure:

The clouds chosen for seeding were usually young cumulus, with depth of about 6000ft, which did not precipitate naturally.
The seeding aircraft joins the research aircraft after the work area has been established (as described in section 4.1), and flies between several clouds just below cloud-base altitudes until it finds the most suitable one according to the following criteria:
A cloud with a high updraft velocity, one with a well defined looking base, and as isolated as possible from nearest cloud cells.
The seeding aircraft, then, starts seeding just below cloud-base altitude performing figure-8 turns while the research aircraft penetrates the ***same*** cloud maintaining safety altitude level of 1000ft above cloud-base to measure cross-section profiles of the seeded cloud. The measuring procedure takes place at 1000ft altitude intervals from the safety altitude level up to cloud-top.
Once the cloud has been penetrated, the research aircraft's path is coordinated with the seeding aircraft to remain above the seeding area during the seeding period and some time after it.
Average seeding duration is around 15 minutes, control measurements are collected from neighboring clouds before, during and after the seeding, so that we can compare the seeded with natural clouds. Furthermore we monitored clouds separately over sea and inland, for documenting potential differences between the two areas.

5. MODEL SIMULATION

Artificial hygroscopic seeding has been done in a wide range of particle sizes, but the concentrations were constrained by the amount of material that could be carried by the aircraft and its rate of dispersion into the clouds (Rosenfeld et.al,2003).
Hygroscopic flares appear to be an attractive alternate seeding option until one realizes that the flares used with positive results in South Africa (Mather at al., 1997) and Mexico (Bruintjes et al., 1999) produce mostly sub-micron large CCN (Cooper et al., 1997). Cooper et al. (1997) calculated that the sub-micron particles of the South African hygroscopic flare did not contribute to the enhanced coalescence. If this is true, only about 30% of the mass of the each flare was in particles that were sufficiently large for enhancing the coalescence and precipitation.
Because dispersion of the near-optimal size of 1-μm hygroscopic particles at large seeding rates is not yet technologically feasible with flares, the next best thing that we could think of was to develop a new seeding method that imitates what natures does with sea spray.
It was very important to simulate those different methods and test it with a 1-dimensional cloud model using various aerosol compositions (Khain et al., 1999) that contains 2000 size bins for the water particles, and simulates very accurately the nucleation and coalescence processes.
The size distribution of the spray was measured with the Israeli research aircraft flying in the plume of the seeder aircraft at a distance covered by less than 2 seconds of flight time. In view of the short distance and dry atmosphere (~50% relative humidity), the sprayed particles had not changed much between dispersion and measurement. The NaCl equivalent dry particle size distribution of the spray compared along with the particle size distribution of the South African hygroscopic flares and the background concentrations

that were used by Cooper et al. (1997) in their model simulations

6. RESULTS

6.1 *Previous Studies*

The motivation for seeding concentrated brine from the Dead Sea is based on model simulations and the results of field investigations in Israel trying to imitate what nature does with sea spray. Such spray system can produce more CCN of desirable size, (as specified by model simulations), in greater concentrations, over longer time periods, and at less cost than is possible currently with hygroscopic flare seeding systems.

An example that shows the influence of sea spray is given in Figures 1-4, presenting a case of clouds forming in air mass containing desert dust, which limited the visibility to 5 km. The flow was from the sea inland. The dust was originated over North Africa, and moved through the east Mediterranean to Israel. The strong surface wind (SW, 20 knot) caused a stormy sea with much sea spray.

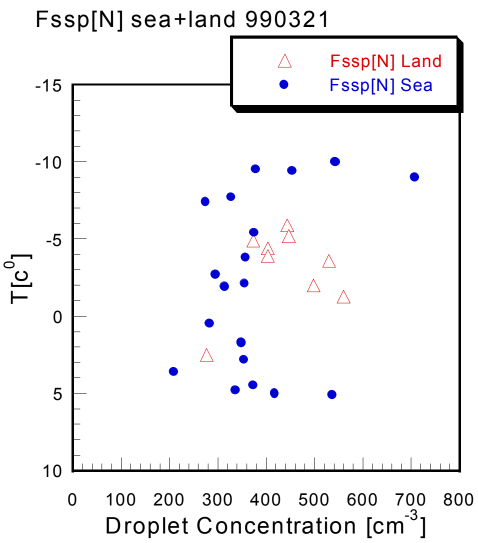


FIGURE 1: Cloud Droplet concentration [cm^{-3}] as measured by the SPP-100 over the Sea and Land on 21.3.99.

Fig 1 shows that the concentration is changing in the range 300-600 droplets cm^{-3} and there is almost no difference between sea and land. However according to Fig 2 the r_e over land is smaller by 2µm than over the sea.

Figures 3 and 4 show the drop size distribution at different depths above cloud base, as indicated by the temperature relative to cloud base temperature (the amount of CLWC is the same for both cases). The distribution over the sea is wider. *We suggest that the sea spray is responsible for that. Because the desert dust prevailed equally over sea and land, it is unlikely that the desert dust was responsible for widening the distribution over sea*. When the clouds are moving from sea inland they lose their large CCN (sea spray), but remain with the desert dust, and so become more continental.

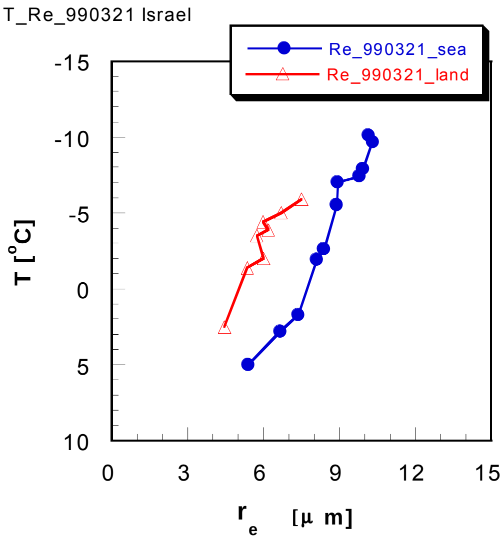


FIGURE 2: The effective radius [µm] of cloud droplets as measured by the SPP-100 over the Sea and Land on 21.3.99.

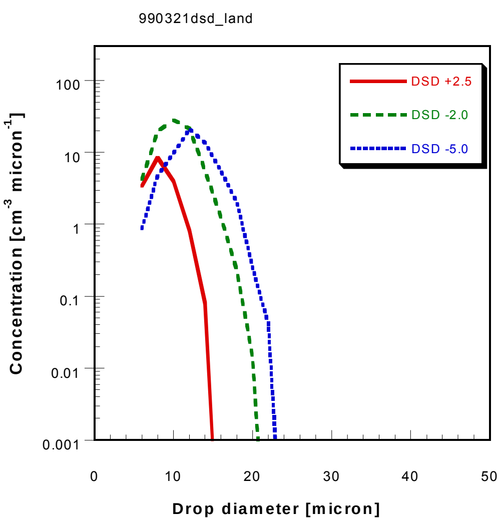


FIGURE 3: The Drop Size Distribution as measured by the SPP-100 at a distance of about 40-km inland on the 21.3.99

According to the satellite analysis presented in Fig 5, the re decreased moving from sea inland and farther east over Jordan.

The clouds at the -10^{0}C isotherm exceeded the 14μm precipitation threshold (Rosenfeld and Gutman,1994) over sea, barely reached it over Israel, and were mostly below it over Jordan.

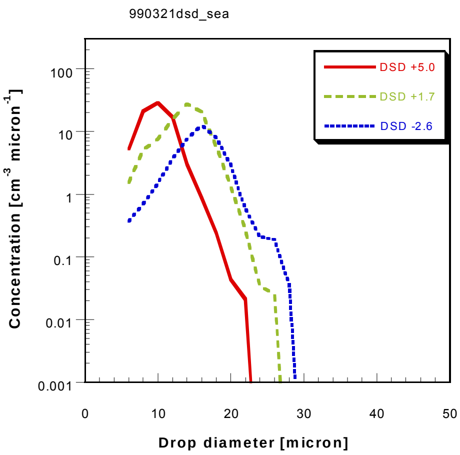


FIGURE 4: The Drop Size Distribution as measured by the SPP-100 over the sea on the 21.3.99.

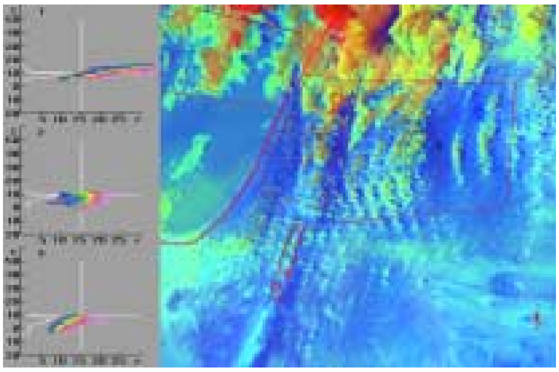
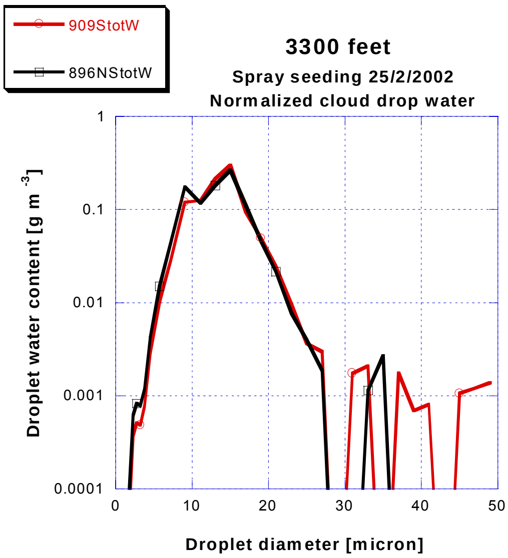
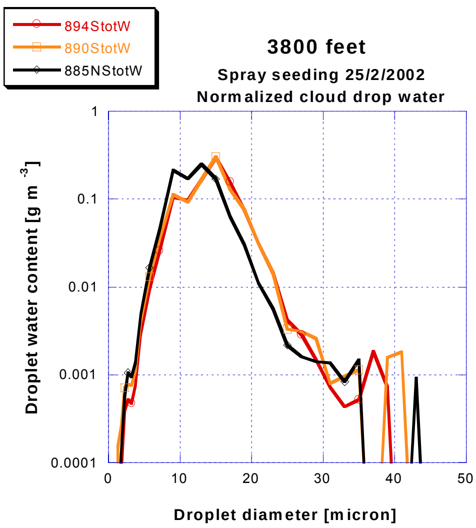


FIGURE 5: Analysis of the Temperature (T) vs. effective radius (r_{eff}) relationship, based on the AVHRR data from the NOAA-14 overpass on the 21.3.99, over Sea, land (west of the Jordan River) and Trance Jordan. The vertical line is the 14μm precipitation threshold.

6.2 *Hygroscopic Spray-Seeding Test Cases*

On 25 February 2002 experimental spray seeding took place in northern Israel over lower and western Galilee, using a seeder aircraft circling just below cloud base and a cloud physics aircraft penetrating the seeded and the adjacent similar clouds at various levels above cloud base (see 4.1). Cloud tops reached 9000 feet, at –3.5^{o}C. Very light rain showers occurred from these clouds from all-warm-rain processes. Mean cloud base droplet concentrations > 2μm were about 450cm^{-3} for both unseeded and seeded clouds. The proximity to the sea likely added a background of natural sea spray particles at unknown concentration. The surface wind over sea was about 15 knots. From visual inspection, white caps did not occur at the sea surface of the coastal waters. According to Figure 6, the near cloud-base spectra of the seeded and unseeded clouds were similar, but they deviated with altitude such that the DSD of the seeded clouds widened somewhat faster than the unseeded clouds.





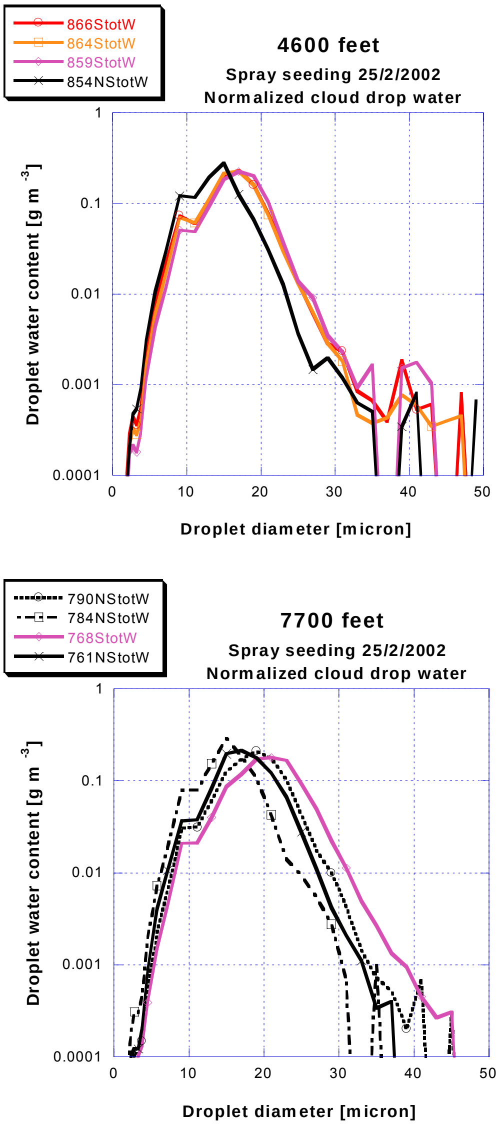


Figure 6: Normalized drop size distributions from full cloud passes of spray-seeded (colored lines) and not seeded (black lines) clouds on 25.2.2002 at various altitudes. Cloud base was at 2500 feet. The drop size distributions were normalized to integrated liquid water contents of 1 g m^{-3} to neutralize the impact of random fluctuations in cloud water content.

Raindrops of 0.4 to 0.8µm diameter appeared in the seeded clouds at 7900 feet, starting at 10 minutes after initial seeding. After an additional 7 minutes the seeder aircraft reported the first raindrops falling through cloud base. These raindrops became "large" (by the appearance of the impacts on the windshield of the seeder aircraft) after additional 4 minutes. The seeding was terminated after 25 minutes because the cloud drifted out of the area where air traffic control allowed flight. Small raindrops of about 200 micron appeared just at the top of the unseeded clouds (9000 feet).

Figure 7 shows the differences between seeded cloud and unseeded clouds in various altitudes as inspected by the 2DC and the integrated DSD as detected by the CAS on the 25.2.02. We can see that in the seeded clouds raindrops of 0.4 to 0.8µm diameter appeared at 7900 feet, while in the unseeded clouds only small rain drops appeared near the top.

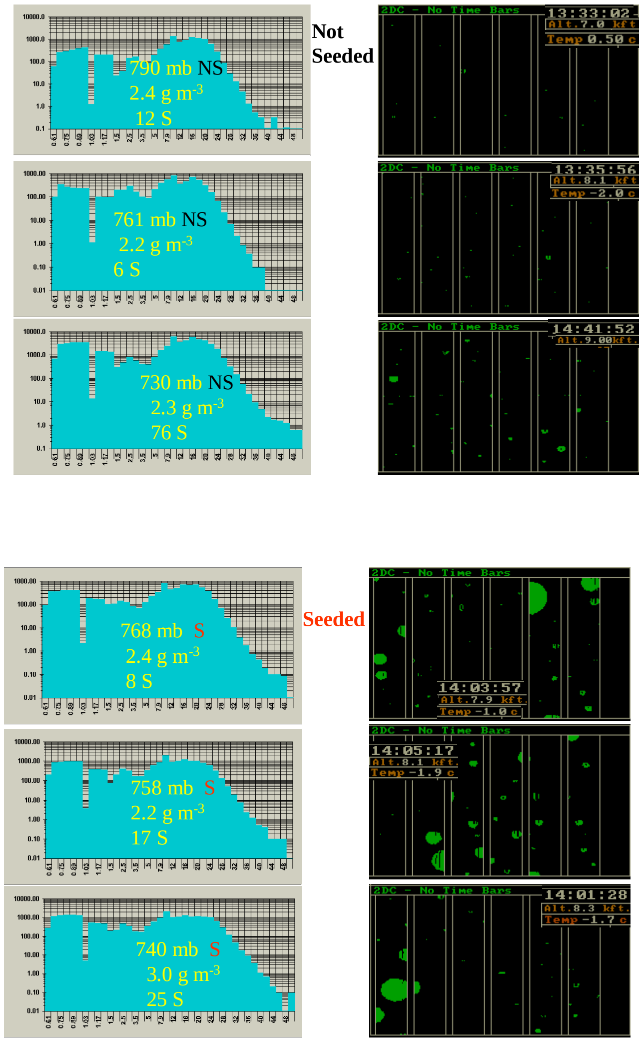


Figure 7: The 2DC images (right) and the integrated DSD (left) as detected by the CAS on the 25.2.02.

A second seeding flight took place on 19 April 2002 in lower eastern Galilee farther away from the sea.
The surface wind over the sea was 8 knots, and no white caps were observed in the coastal waters. Cloud base was at 5000 feet above sea level. Relative to the 25 February 2002 flight, a much smaller background of sea spray was expected, and the clouds were more microphysically continental. Cloud tops reached 9500 feet at the –2°C isotherm, for a cloud depth of 1.5 km, and the clouds produced no natural rainfall. They had poor organization and weak updrafts, but they were the best that could be found within the constraints of the research flight. The initial small cloud cluster was seeded for 25 minutes with 300 l of brine until its base disintegrated.
Subsequent regeneration of the convective elements 10 minutes later followed with their seeding for an additional 17 minutes. The first small (130µm) raindrops were observed near cloud top 16 minutes after seeding started. Subsequently, up to 0.5µm drops in concentrations of up to 4 l^{-1} were observed. The maximum total precipitation particles observable by the 2DC instrument reached 28 l^{-1}.
No raindrops and only a few 2DC dots (the smallest resolved drizzle particles) were observed in the non-seeded clouds, which were sampled around the seeded small cloud cluster.

6.3 *Model Simulation*

The NaCl equivalent dry particle size distribution of the spray is given in Figure 8, along with the particle size distribution of the South African hygroscopic flares and the background concentrations that were used by Cooper et al. (1997) in their model simulations.

The simulated cloud had a base height of 700 m, a temperature of 21°C, and an updraft of 2 m s^{-1}. The updraft accelerated to about 10 m s^{-1} near the 5 km level and there leveled off. The model-simulated rainfall flux (with respect to the rising air) and the drop effective radii are presented in Figures 9 and 10, respectively.

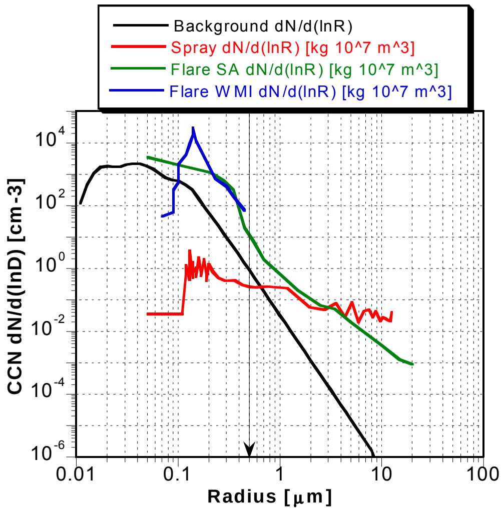


Figure 8: Size distribution of CCN in dry NaCl equivalent, for a spray of Dead Sea brine (red line), South African hygroscopic flares (green line), a hypothetical flare that produces only sub-micron particles (blue line), and the background CCN (black line) as assumed for the simulations of Cooper and Bruintjes (1997). The concentrations are calculated for 1 kg of dry material diluted in 10^7 m^3 of air.

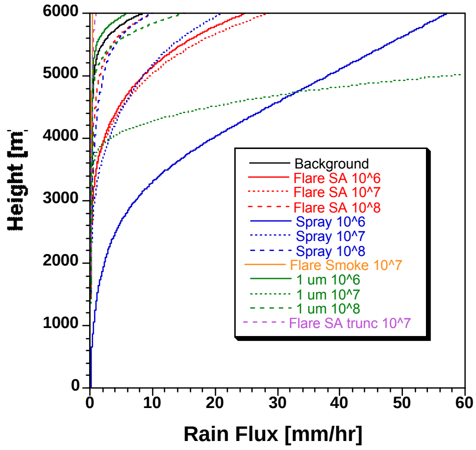


Figure 9: Simulated rain flux for clouds containing the background CCN (black line) as assumed for the simulations by Cooper and Bruintjes (1997) and in addition, the dry NaCl equivalent of spray of Dead Sea brine (blue line), South African hygroscopic flares (red line), the South African flare with particle truncated at diameters > 1-µm (purple line), and a hypothetical flare that produces only 1-micron particles (green

line). The concentrations are calculated for 1 kg of dry material diluted in 10^6 to 10^8 m^3 of air, as shown in the legend.

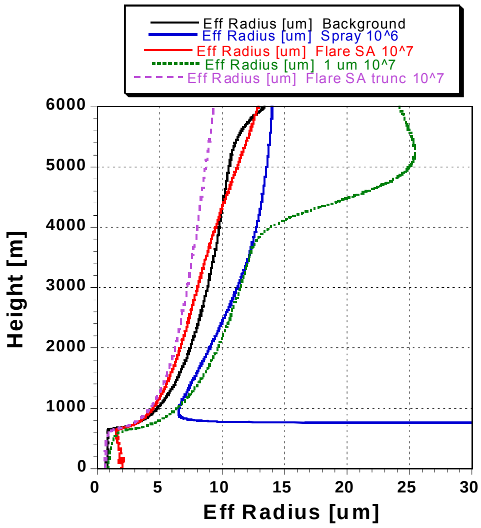


Figure 10: Simulated effective radius of cloud droplets, for clouds containing the background CCN (black curve) as assumed for the simulations by Cooper et al. (1997) and in addition, the dry NaCl equivalent of a spray of Dead Sea brine (blue curve), South African hygroscopic flares (red curve), and the South African flare with particles truncated at diameters > 1-µm (purple curve) and a hypothetical flare that produces only 1-micron particles (green curve). The concentrations are calculated for 1 kg of dry material diluted in 10^7 m^3 of air, except for the spray that is dilute in 10^6 m^3 of air.

The calculation assumed that the dry mass of 1-kg seeded particles was diluted in 10^6, 10^7 or 10^8 m^3 of air well below cloud base. The results show the following: Background aerosols started to develop precipitation (R>2 mm/hr) at a height of 5.5 km. Seeding with the South African flares at a dilution of 1-kg in 10^8 m^3 lowered the rain onset slightly from 5.5 to 5.3 km. Increasing the concentration of the flare effluent to 1-kg in 10^7 m^3 had a much larger effect and lowered the rainfall onset to 4700 m. Further increase of the concentration to 1-kg in 10^6 m^3 did not result in additional enhancement of the precipitation. This means that the concentration of 1-kg in 10^7 m^3 is already near the optimum.

Truncating all the particles with diameters > 1µm at the “optimal” concentration of 1-kg in 10^7 m^3 resulted in a strong suppression of the precipitation compared to the background. Its effect was similar to the hypothetical smoke flare (blue line in Figure 8). According to Figure 10 the truncated distribution created a cloud with reduced droplet sizes with respect to the background. Even the “optimal” concentration of the un-truncated flare reduced the droplet size in the lower part of the cloud. This suggests that the smaller flare particles still nucleated and that they actually caused the cloud to produce more droplets at its base. The raindrop-embryo effect, produced by the super-micron flare particles, were mainly responsible for the rain enhancement, and they worked against the suppressing effect of the smaller particles.

If sub-micron particles do not contribute to the apparent seeding effect, it is worthwhile to see what would be the result for a flare with a narrow distribution near 1-µm, which Cooper et al., (1997) have shown would produce optimal results. Here again, at a dilution of 1-kg in 10^8 m^3 only a slightly positive effect was noted, but it was dramatically increased when the concentration increased to 1-kg in 10^7 m^3. According to Figure 9, the rainfall enhancement occurred due to the size increase of the cloud-base droplets, which coalesced into drizzle and then continued their growth to raindrops at a height of 3.9 km. Increasing the concentration further, resulted in a return to near background precipitation, probably due to excessive concentrations of 1µm CCN, which already constituted the bulk of the cloud droplets.

Dispersion of 1µm salt particles in sufficient quantities for cloud seeding is still an unresolved technological challenge. The Israeli spray system was designed for practical production of large quantities of particles > the 1µm critical size. According to Figure 9 the flares and spray gave very similar profiles of rainfall for the dilutions of 1-kg in 10^7 m^3, which is optimal for the flares. However, the rate of dispersion of dry hygroscopic material with the spray is 15 times that of flares, assuming that the two are burned simultaneously. Due to these practical realities, comparisons of flares and spray in Figures 9 and 10 have to be, for example, between flares with a dilution of 1-kg in 10^7 m^3 and sprays with a dilution of

1-kg in 10^6 m^3. Thus, by increasing the spray concentration to 1-kg in 10^6 m^3 to simulate the real situation, the rain fluxes were enhanced further, even beyond the composition of the "optimal flare" of 1μm particles, at least initially in the clouds. The rain started forming at a height of < 2 km, but its development with height was slower than for the "optimal flare" of 1μmparticles. The large advantage of the 1μm "optimal" device is that it converts most cloud water quickly to drizzle and rainfall between 4 and 5 km, leading to very efficient precipitation in clouds that exceed this depth, whereas the spray seeding would leave most of the water still in the form of cloud droplets. The large number of drizzle particles can also recalculate into the cloud more easily and spread the seeding effect to cloud portions that are not seeded directly.

7. SUMMERY AND DISCUSSION

The recent observations of the effects of the ingestion of natural hygroscopic aerosols on clouds give strong indications of the probable effects of artificial hygroscopic seeding on warm and ice precipitation processes.

Experiments of artificial addition of sea spray to clouds inland have shown that warm rain has returned to the clouds, which behave as natural clouds closer to the coastline. The newer observations have shown that when giant salt CCN are ingested into such clouds they restore the precipitation. The most common source of these aerosols is sea spray, especially during high wind conditions. Artificial brine spray seeding is shown to have similar effect as natural sea spray over ocean, leading to enhanced coalescence and precipitation in both cases.
These observations and model simulations suggest that there is a large potential for precipitation enhancement for a cloud seeding method that could modify the microstructure of clouds having little natural coalescence in order to imitate clouds with active coalescence processes.

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