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Precipitation effects of giant cloud condensation nuclei artificially introduced into stratocumulus clouds

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Abstract

To study the effect of giant cloud condensation nuclei (GCCN) on precipitation processes in stratocumulus clouds, 1–10 μm diameter salt particles (salt powder) were released from an aircraft while flying near cloud top on 3 August 2011 off the central coast of California. The seeded area was subsequently sampled from the aircraft that was equipped with aerosol, cloud, and precipitation probes and an upward-facing cloud radar. During post-seeding sampling, made 30–60 min after seeding, the mean cloud droplet size increased, the droplet number concentration decreased, and large drop (e.g., diameter larger than 10 μm) concentration increased. Average drizzle rates increased from about 0.05 to 0.20 mm h⁻¹, and liquid water path decreased from about 52 to 43 g m⁻². Strong radar returns associated with drizzle were observed on the postseeding cloud-base level-leg flights and were accompanied by a substantial depletion of the cloud liquid water content. The changes were large enough to suggest that the salt particles with concentrations estimated to be 10⁻² to 10⁻⁴ cm⁻³ resulted in a four-

fold increase in the cloud base rainfall rate and depletion of the cloud water due to rainout. In contrast, a case is shown where the cloud was already precipitating (on 10 August) and the effect of adding GCCN to the cloud was insignificant.

1 Introduction

The stratocumulus (Sc) cloud deck is the most persistent cloud type in the world, and
 the variations of the cloud amount and the albedo can significantly impact the climate system through their radiative effects on the earth system (e.g., Hartmann et al., 1992; Slingo, 1990). The addition of small amounts of giant cloud condensation nuclei (GCCN) to stratocumulus cloud may have little direct impact on radiative effects, but the impacts may be significant if the GCCN can initiate or enhance precipitation
 ²⁵ (Jensen and Lee, 2008). Nonetheless, the role of GCCN in precipitation production in stratocumulus clouds is less explored compared with the substantial work that has



been done on other types of clouds (e.g., Takahashi, 1976; Johnson, 1982; Tzivion et al., 1994; Mather et al., 1997; Yin et al., 2000a, b; World Meteorological Organization, 2000; Levin et al., 2006; Rosenfeld et al., 2010). Therefore, our study focuses on the role of GCCN in stratocumulus clouds.

- ⁵ The role of GCCN in precipitation production in stratocumulus clouds has been explored using Large Eddy Simulation (LES) and parcel models (Feingold et al., 1999; Lu and Seinfeld, 2005; Jensen and Lee, 2008). These studies show that GCCN introduced into non-precipitating stratocumulus clouds can promote the growth of drizzle drops by enhancing collision and coalescence processes. Analysis of NASA A-Train
- data also suggest that enhanced levels of sea salt particles over the ocean lead to faster collision-coalescence and accelerated precipitation responses (L'Ecuyer et al., 2009; Sorooshian et al., 2013). Despite this basic understanding, observing the effects of GCCN in real clouds with in-situ measurements is challenging. First, GCCN concentrations in nature (order 10⁻⁴ to 10⁻² cm⁻³) are many orders of magnitude less
 than CCN concentrations (order 10² cm⁻³), and thus are difficult to measure. Second,
- cause-and-effect relationships involving GCCN are difficult to isolate under natural conditions since other factors can affect and modulate drizzle production.

Marine stratocumulus clouds present laboratory-like conditions for evaluating how GCCN modify cloud properties. By introducing GCCN directly into a uniform cloud, the role that other factors may have in modifying the cloud can be minimized, and the background cloud conditions can be compared with the seeded cloud areas as shown by Ghate et al. (2007). The seeding by Ghate et al. (2007) used flares (in the size range of $0.1-2 \mu m$) to produce hygroscopic particles in clouds ranging in size between 1 and

20

 $5\,\mu$ m. The seeded cloud was then sampled with an instrumented aircraft flying within the Sc to examine the effects of the seeding on the cloud.

Flares, however, generate high number concentrations of small CCN particles simultaneous with much fewer giant CCN, and may not be optimal as seeder particles. Tzivion et al. (1994), Cooper et al. (1997), and Yin et al. (2000b), for example, showed that positive cloud responses to seeding (i.e., shift of size distribution toward larger sizes;



enhanced precipitation) increase with the size of the seeding particles. In particular, the particles (diameter) smaller than $2\,\mu$ m had a negative effect on the rain development in convective clouds (Yin et al., 2000b) based on the flares used in the South Africa seeding experiment (Mather et al., 1997). Furthermore, Segal et al. (2004), based on

- ⁵ 2000-bin spectral cloud parcel model, predicted that hygroscopic-seeding materials with diameters of 3–6 μm are optimal for enhancing precipitation in warm clouds. They also predicted that smaller-sized CCN aerosols suppress precipitation as shown in Yin et al. (2000b) and L'Ecuyer et al. (2009). L'Ecuyer et al. (2009) showed that the injection of sea salt and sulfate aerosols into warm maritime clouds leads to nearly opposite
- cloud responses. The addition of large-sized sea salt particles was found to enhance precipitation and lead to less vertically developed clouds, whereas addition of the considerably smaller-sized sulfate particles suppresses precipitation in clouds and results in the onset of light precipitation in clouds with higher liquid water paths.

The purpose of this paper is to report on results from airborne flights examining the ¹⁵ role that GCCN play in initiating precipitation in Sc clouds. To introduce GCCN without increasing the number of small-sized CCN that can suppress precipitation (e.g., Segal et al., 2007; L'Ecuyer et al., 2009), we employed a technique developed by Rosenfeld et al. (2010) who injected milled salt particles into convective cumuli. In the case we present here, GCCN in the form of milled salt particles were dispersed into uniform Sc ²⁰ clouds from an aircraft flying near the cloud top. After the GCCN were introduced into

the cloud, the aircraft sampled the seeded cloud deck with in situ instruments and an upward-facing cloud radar.

2 Instruments and techniques

2.1 Aircraft data

²⁵ The data used in this study were obtained from the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) *Twin Otter* (TO) aircraft that was flown in sup-



port of the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE, 2011), which took place off the central coast of California during July and August 2011 (Russell et al., 2013). The CIRPAS TO research aircraft was instrumented with (1) three in situ probes that characterize aerosol, clouds, and precipitation size distributions, (2) standard me-

- ⁵ teorological instruments that measure the atmospheric thermodynamic and wind structures, and (3) an upward-facing Frequency Modulated Continuous Wave (FMCW) cloud radar. Three probes relevant to this study were: (1) Passive Cavity Aerosol Spectrometer Probe (PCASP), (2) Cloud Aerosol Spectrometer (CAS) and, (3) Cloud Imaging Probe (CIP) that resolve particles in diameter ranges from 0.1–3, 0.6–60 and 25–
- 10 1550 μm, respectively. The FMCW cloud radar (operating at a wavelength of 3 mm) was mounted on top of the aircraft, and provided fine structure of cloud and precipitation (vertical resolution of 5 m and temporal resolution of 3 Hz). The aerosol, cloud and precipitation probe data were obtained at 1 Hz resolution, and the meteorological variables (e.g., temperature, humidity, winds, Gerber probe liquid water content, etc.) were
 15 acquired at both 1 Hz and 10 Hz resolutions. For detailed information on the probes and the cloud radar used in this study, see Russell et al. (2013), and Jung and Albrecht (2014, Table 1 and Fig. 1).

2.2 Salt powder and salt distribution system

The salt powder comprises milled salt particles coated with an agent to minimize sticking as described by Rosenfeld et al. (2010). We measured the size distribution of the salt in the laboratory by delivering powder to the viewing volume of the CAS using an atomizer bottle. The number and volume (percent) size distribution are shown in Fig. 1. The number concentrations are relatively constant in the diameter range of 0.8 to 12 μm, with a peak in the volume distribution at 10–12 μm. There are relatively few particles smaller than 0.8 or larger than 12 μm. The effective volume diameter (i.e. the diameter that would give the average volume of the distribution) is about 5 μm.

To eject these particles from the aircraft into the clouds, we designed and fabricated a fluidized bed delivery system. The apparatus used an auger to feed salt powder at



a controllable rate from a reservoir into a fluidized bed of sandblasting grit from which a filtered pump exhaust ejected the salt powder into the airstream outside the aircraft. The flow into the fluidized bed was baffled to give a uniform airflow through a fine mesh membrane at the base of the bed, and the flow was adjusted such that the salt powder,

- ⁵ but not the grit, was ejected. The purpose of delivering the powder through this fluidized bed was to break up salt particles that might be stuck together. Laboratory tests were carried out to determine auger delivery rates, and to determine proper flow rates to eject salt only while preserving the grit throughout the delivery. The salt delivery system was set to disperse the salt powder at a rate of about 0.75 g per second, which was
- ¹⁰ intended to give GCCN concentrations of an order 10^{-2} to 10^{-4} cm⁻³. For an average salt particle diameter of 5 µm, we estimate that about 5 × 10^{9} salt particles were emitted per second. A schematic and a photo of the salt powder delivery system are shown in Fig. 2.
- Once the salt powder is emitted from the aircraft, it is dispersed, but the exact dispersal rate is unknown. The TO aircraft, with wing span of about 20 m, flew at a speed of about 60 m s⁻¹ during the salt dispersal. Assuming that initial dispersion due to aircraft induced turbulence extends more than twice its wingspan, the salt plume crosssectional area may be expected to quickly expand to about 50 m× 50 m. If 5×10^9 particles are emitted along the 60 m path flown in 1 s, after 10 min, the salt concentration would then be about 3.5×10^{-2} cm⁻³. If the cross sectional area of the plume expands to 100 m × 100 m, the concentration would be reduced to about 1.7×10^{-2} cm⁻³, and to about 1×10^{-3} cm⁻³ for a 200 m × 200 m area. Thus, we estimate that after 10 min or more, the particle concentrations would be of the order of 10^{-2} to 10^{-3} cm⁻³, which lies in the range used in simulations by Feingold et al. (1999).



3 Results

3.1 Seeding case

During E-PEACE, salt powder was ejected into cloud decks during nine flights. However, due to the ineffective seeding and sampling strategies on some flights and the presence of precipitation at the time of seeding on others, we are able to identify only one case on 3 August 2011 in which seeding impacts are evident throughout the entire cloud deck depth. But there are several cases showing seeding impacts exclusively at the cloud heights that are not precipitating at the time of seeding.

In this study we focus on the 3 August 2011 case when a Sc cloud deck was sampled with the TO in an area (35.8.1–36.4.1° N; 122.8–122.2° W) about 100 km southwest of Monterey between 16:00 UTC and 20:00 UTC. The boundary layer thermodynamic and aerosol vertical profiles, shown in Fig. 3, were obtained during a descent and an ascent of the aircraft through the cloud deck, approximately 10–30 min prior to flying horizontal background cloud-sampling-legs, and about an hour prior to the cloud seeding (Fig. 4

- and Table 1). The cloud deck was about 300–350 m thick (Fig. 3b) and capped by an inversion (with inversion strength $\Delta\theta$ of ~ 5–6 K) at heights of about 625–645 m (Fig. 3). The inversion strength calculated from these two profiles is slightly weaker than those calculated from the entire period of the experiments ($\Delta\theta \sim 7 \pm 2$ K based on 25 flights). By comparison, these are weaker than those reported at the coast of northern Chile in
- the Southeastern Pacific during VOCALS-REx (e.g., ~ 12 K from Zheng et al., 2011). The cloud liquid water content (LWC) profiles, Fig. 3b, are very consistent with those typical of a uniform, non-precipitating Sc cloud deck. The accumulation mode aerosol varies in concentration from 200 to 500 cm⁻³ in the sub-cloud layer in the ascent profile, and from 200 to 800 cm⁻³ above the cloud layer in both the ascent and the descent soundings (Fig. 3c).



3.2 Sampling strategy

Flight paths and time series of the altitudes flown on 3 August 2011 are shown in Fig. 4. Detailed information of each leg segment is summarized in Table 1. To characterize the background conditions, the clouds and the aerosol beneath them were sampled

- ⁵ with in situ probes and the cloud radar at four altitude levels, including one sub-cloud layer and three cloud levels before the seeding (Fig. 4b–e), hereafter referred to as *pre-seeding (cloud sampling) legs*. The seeding flight pattern is shown in Fig. 4f. After seeding, the seeded cloud was sampled downwind of the seeded area at similar levels as characterized before (hereafter referred to as *post-seeding (cloud sampling) legs*).
- ¹⁰ To ensure that the seeded areas were sampled, the post-seeding sampling areas (red in Fig. 4g–i) were selected by using wind speed and wind direction measurements along the seeding path to advect the seed plume downstream.

The salt powder was dispersed as the TO flew near the cloud top (shown as dark blue in Fig. 4f–j). Note that this seeding flight pattern is almost identical to the pre-seeding

¹⁵ cloud top leg (Fig. 4e). During the seeding, the wind was 12 m s⁻¹ from the northwest (~ 330°). After seeding, the seeded air mass was sampled along the wind near cloud base (Fig. 4g), mid-cloud (Fig. 4h), and near cloud top (Fig. 4i). These post-seeding legs were made about 30–60 min after the clouds were seeded (Fig. 4a and Table 1).

The estimated post-seeding areas at cloud top, mid-cloud and cloud-base are shown

- in Fig. 5 (gray shades), along with the seeding and post-seeding leg patterns. Here, the seeding pattern has been advected using the winds and elapsed time between seeding and post-seeding cloud sampling periods. If the cloud is seeded between A (starting time of seeding legs) and A' (ending-time of seeding legs) and the post-seeding legs are made between B (starting-time of post-seeding legs) and B' (ending-time of post-seeding legs), then four elapsed time periods are possible; (1) A'-B, (2) A'-B', (3)
- A–B, and (4) A–B'. Here, A'–B (A–B') corresponds to the shortest (longest) elapsed time periods between the time of seeding and post-seeding and shown as the darkest (lightest) colors in Fig. 5. The post-seeding sampling-pattern (red) is located well within



the advected (shaded) areas, showing that the seeded area is properly sampled during the post-seeding cloud sampling leg. To compare changes in cloud and precipitation properties between pre- and post-seeding legs, post-seeding data from cloud sampling legs (red) made within the advected seeding area (i.e., gray shades) are used.

5 3.3 Seeding results

Cloud droplet size (effective diameter, *D*), number concentrations (*N*_d), and precipitation rate (*R*) measured on the pre- and post-seeding legs are shown in Fig. 6. The number concentration of cloud droplets is obtained from the Cloud Aerosol Spectrometer (CAS). The precipitation rate is calculated from the Cloud Imaging Probe (CIP) ¹⁰ drop size distributions N(D) as $R = \frac{\pi}{6} \int_0^\infty N(D) D^3 u(D) dD$ where u(D) is the fall speed of particle size *D* (Rogers and Yau, 1989). The effective diameter is calculated in two ways: (i) first, it is calculated from drop size distributions (DSDs) obtained from CAS to show the changes in cloud droplet size exclusively (shown in Fig. 6); (ii) second, it is calculated from DSDs obtained by combining the CAS and CIP probes data to include ¹⁵ cloud droplets, drizzle and rain drop embryos (shown as numbers in parenthesis in Table 2).

Before seeding (grey in Fig. 6a), the majority of cloud droplets had diameters between 10 and 30 μ m. After seeding, the main population showed a significant broadening and an increase in sizes from a few μ m to hundreds of μ m. The mean effec-

- ²⁰ tive diameter of cloud droplets was between 13.5 and 21.4 µm from the pre-seeding legs, and between 16.6 and 26.2 µm from the post-seeding legs (Table 2). The mean effective diameter of drops that include drizzle and rain drop embryos (*D* shown in the parenthesis in Table 2) ranged between ~ 15 and 23 µm for the pre-seeding legs, and between ~ 24 and 44 µm for the post-seeding legs, suggestive of an increase in
- ²⁵ size of drizzle and rain drop embryos more than that of cloud droplets after seeding. Further, a substantial decrease in cloud droplet number concentration (N_d) was also observed during post-seeding legs (Fig. 6b, Table 2). The mean N_d calculated from pre-seeding legs was about 140–170 cm⁻³ throughout the cloud, and was reduced to



about 70–100 cm⁻³ after seeding, which is consistent with what would be expected with enhanced droplet collision-coalescence. Precipitation rates (Fig. 6c, Table 2) were less than 0.1 mm h⁻¹ (0.04–0.09 mm h⁻¹) before seeding and increased to about 0.2 mm h⁻¹ after seeding. The LWC, before and after seeding, are also summarized in Table 2. After seeding, LWC decreased to about 0.04–0.25 gm⁻³ from 0.09–0.31 gm⁻³. Liquid water path (LWP) was calculated by integrating an average LWC at cloud-base, mid-

- cloud, and cloud-top levels during pre- and post-seeding cloud sampling, after they were linearly interpolated with height. The LWP was about 52 gm⁻² before seeding, and decreased to about 43 gm⁻² after seeding.
- As noted above, the post-seeding legs were made about 30 min to 1 h after the cloud was seeded (Table 1), allowing sufficient time for the salt seeding effects to be distributed throughout the cloud due to large eddy transport through the depth of the boundary layer operating on characteristic time scales of 10 to 20 min. In the flare seeding by Ghate et al. (2007), the post-seeding sampling was made about 10 to 30 min after the flare burns. In that case, the effects on the droplet size distribution
- are clearly seen, but no drizzle was observed. The lack of observable drizzle in those experiments may have been partly due to the premature post-seeding cloud sampling (i.e., 10 to 30 min after seeding), but may also have been due to the nature of the flares that they used, which produce higher concentration of smaller-sized salt particles than the salt power used in this experiment.

Changes in drop size distributions, before and after seeding, are shown in Fig. 7. Overall, number concentration of smaller sized cloud droplets (e.g., $D < 20-50 \,\mu$ m) decreased during the post-seeding legs (see the changes between blue and red),

whereas the number concentration of large droplets ($D > 50 \,\mu$ m) increased. The decrease in smaller sized droplets concentration is large at the cloud top where the GCCN is directly injected, and also near the cloud base. The maximum diameter, at which the depletion of small-sized-droplets occurred, increased closer to the cloud base. For example, near cloud tops, droplets smaller than 20 μ m decreased in number substantially. At cloud base, number concentrations of droplets smaller than 50 μ m



have decreased. The increase in larger-sized-droplets during the post-seeding legs was substantial through all three cloud level-legs. In particular, bimodal patterns were observed at the cloud base in the ranges between 50 and ~ 200 μ m, and between 300 and ~ 1000 μ m. Increases in larger drops (e.g., *D* > 50 μ m) and decreases in smallersized-droplets (e.g., *D* < 20–30 μ m) during post-seeding legs are consistent with the enhancement of collision-coalescence effects due to the salt. These changes in the droplet distributions in the seeded areas (i.e., appearance of a tail of large drops on the upper end of droplet distribution) are similar to those reported by Ghate et al. (2007) in areas of Sc clouds seeded by flares, and by Rosenfeld et al. (2002) in the convective

¹⁰ clouds seeded by GCCN, as well as by other numerical experiments on the impact of GCCN on precipitation and cloud structures (e.g., Johnson, 1982; Cooper et al., 1997; Rosenfeld et al., 2010).

Radar returns from the upward facing cloud radar during the cloud-base level legs, before and after seeding, are shown in Fig. 8. Cloud-base level legs were conducted ¹⁵ with the TO flying near the cloud-base altitude at average height of 339 and 307 m during the pre- and post-seeding legs, respectively. Before seeding (Fig. 8a), radar returns reached about 270 m above the level leg altitude (i.e., 609 m mean sea level (m.s.l.); 270 m above radar level +339 m from the ground), and the radar reflectivity was on average about -37 dBz with maximum of -25 dBz in a height range of 50 and 100 m above the radar, for example. During the post-seeding legs (Fig. 8b), radar echoes appeared up to about 300 m above the level leg altitude (i.e., ~ 607 m m.s.l.). The average radar reflectivity between 18:49:32 and 18:49:40 in a height range of 50 and 100 m, for example, was about -21 dBz with maximum of -18 dBz. The radar

measurements in Fig. 8 showed a significant increase in radar returns during the postseeding legs compared with the pre-seeding legs, although the cloud-top height and cloud depths are nearly identical for the two cases.

The time series of radar reflectivity for the period of increased radar reflectivity (box in Fig. 8b) was shown in Fig. 8c along with LWC and drizzle rates (Fig. 8d). In Fig. 8d, LWC decreased as drizzle rates increased, indicating that drizzle may be consuming



the cloud water. In Fig. 8c and d, the variability in the radar reflectivity was clearly correlated with the drizzle rates observed at this level and inversely correlated with the cloud liquid water content.

- We further calculated the radar reflectivity at the level of cloud legs by combining data from the cloud and precipitation probes before and after seeding as comparison to the actual radar measurements. Radar reflectivity is calculated as $z = \int N(D)D^6 dD$ where N(D) is the drop size distribution (DSD) of particle size D, which is obtained from CAS and CIP, in units of mm⁶ m⁻³. Radar reflectivity Z is reported in units of dBz, where Z = $10 \log(z)$. The calculated median radar reflectivities for pre- and post-seeding legs were -32 dBz < Z < -31 dBz, and -17 dBz < Z < -14 dBz, respectively (Table 2), which is consistent with typical values of Z for non-precipitating and precipitating clouds (Jung
- 2012; Frisch et al., 1995). The large changes in the radar reflectivity between the preand post-seeding cloud-base legs (Fig. 8) were consistent with the changes in the calculated reflectivity (Table 2).
- ¹⁵ Clouds were seeded on another TO flight made on 10 August (details not shown here). Although a similar seeding and sampling strategy was used on that flight, the cloud deck was already precipitating at the time of seeding, and no additional precipitation enhancement was noted. Changes in cloud droplet size (*D*), number concentrations (*N*_d), and precipitation rate (*R*) between the pre- and post-seeding legs are shown
- in Fig. 9 for the 10 August case. Before seeding, cloud droplet number concentrations were about 180–190 cm⁻³ from cloud base to cloud top; they then decreased to 150–160 cm⁻³ after seeding. However, the decrease is not as large as that observed on 3 August. The mean precipitation rate (Fig. 9c) decreased after seeding, from 0.15 to 0.1 mm h⁻¹, though the median precipitation rate was almost the same and/or slightly
 enhanced from 0.04 to 0.05–0.06 mm h⁻¹. The accumulation mode aerosol was constant through the boundary layer with less than 200 cm⁻³ (not shown). These results are consistent with the previous modeling results, which demonstrate that the injec
 - tion of GCCN has the greatest potential for altering cloud behavior in non-precipitating clouds having a high concentration of small drops and/or aerosol (e.g., Feingold et al.,



1999; Yin et al., 2000a; Lu and Seinfeld, 2005; Zhang et al., 2006; Jensen and Lee, 2008), and hence, conditions on 10 August 2011 were not optimal for generating a strong precipitation signal, as confirmed by our measurements.

4 Conclusions

- To study the effect of giant cloud condensation nuclei (GCCN) on precipitation in Sc clouds, we released 1–10 μm diameter salt particles from an aircraft while flying near cloud tops during the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE, 2011). Results from the 3 August 2011 flight provide evidence for a strong change in droplet number and size in the clouds that were seeded with giant nuclei. The GCCN
 were released in a cross-wind zigzag pattern at a fixed level (near cloud top) in a uniform cloud deck using a device designed to minimize the clumping of the salt and provide concentrations in the range of 10⁻² to 10⁻⁴ cm⁻³. The seeded area was then sampled downstream as estimated by advection of the area using observed winds and the elapsed time between seeding and post-seeding cloud sampling periods. During
- ¹⁵ the post-seeding cloud sampling legs, conducted 30–60 min after seeding, the mean cloud droplet size had increased, droplet number concentrations decreased and large drops appeared in the size distributions. Average drizzle rates increased from about 0.05 to 0.20 mm h⁻¹. Strong radar returns associated with drizzle were observed on the post-seeding cloud-base legs and were accompanied by a substantial depletion of
- the cloud liquid water content. The changes were large enough to suggest that the salt seeding resulted in a four-fold increase in the cloud base rainfall rate and an associated depletion of the cloud water due to rainout. The reduction of cloud droplet number concentrations indicates invigorated collision-coalescence between drops. Furthermore, the drop diameter at all altitudes in the cloud deck increased in the seeded area. Thus,
- the observational evidence confirms the particular chain of events that is expected after a cloud seeding event: faster onset of rain owing to the broadening of cloud drop distribution.



The results show the enhancement of precipitation by artificially introducing GCCN into a stratocumulus cloud. As in Ghate et al. (2007), the usefulness of marine Sc clouds to study cause and effect relationships associated with GCCN is demonstrated. However, tracking the exact movement of the cloudy air mass that has been seeded with GCCN using a single aircraft is challenging. Use of tracers such as radar chaff (Jung and Albrecht, 2014) or SF₆ (Rosenfeld et al., 2002, 2010) for tracking the seeded areas would facilitate these studies of cloud modification by GCCN. Furthermore, a scanning-cloud-radar would provide a full view of the 3-D temporal evolution of the cloud in which GCCN are injected. Nevertheless, the results in this study support the

idea that giant nuclei – produced either naturally or anthropogenically – can initiate drizzle and impact the cloud structure as shown in Levin et al. (2005) for dust aerosols coated with sea salt and sulfate during the Mediterranean Israeli Dust Experiment campaign. Since the concentrations of GCCN used in this study are in the range of those observed in nature under strong wind conditions, we concur with the conclusions of Jensen and Lee (2008) that it may be necessary to include GCCN effects in climate models.

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References

²⁵ Cooper, W. A., Bruintjes, R. T., and Mather, G. K.: Calculations pertaining to hygroscopic seeding with flares, J. Appl. Meteorol., 36, 1449–1469, doi:10.1175/1520-0450(1997)036<1449:CPTHSW>2.0.CO;2, 1997.



Discussion **ACPD** 15, 47–76, 2015 Paper **Precipitation effects** of giant CCN E. Jung et al. **Discussion** Paper **Title Page** Abstract Introduction Conclusions References **Tables** Figures **Discussion** Paper Close Back Full Screen / Esc Discussion

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Feingold, G., Cotton, W. R., Kreidenweis, S. M., and Davis, J. T.: The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: implications for cloud radiative properties, J. Atmos. Sci., 56, 4100-4117, 1999.

Frisch, A. S., Fairall, C. W., and Snider, J. B.: Measurement of stratus cloud and drizzle param-

- eters in ASTEX with a $K\alpha$ -Band Doppler Radar and a microwave radiometer, J. Atmos. Sci., 5 52, 2788-2799, doi:10.1175/1520-0469(1995)052<2788:MOSCAD>2.0.CO;2, 1995.
 - Ghate, V. P., Albrecht, B. A., Kollias, P., Jonsson, H. H., and Breed, D. W.: Cloud seeding as a technique for studying aerosol-cloud interactions in marine stratocumulus, Geophys. Res. Lett., 34, L14807, doi:10.1029/2007GL029748, 2007.
- Hartmann, D. L., Ockert-Bell, M. E., and Michelsen, M. L.: The effect of cloud type on earth's 10 energy balance - global analysis, J. Climate, 5, 1281-1304, 1992.
 - Jensen, J. B. and Lee, S.: Giant sea-salt aerosols and warm rain formation in marine stratocumulus, J. Atmos. Sci., 65, 3678–3694, doi:10.1175/2008JAS2617.1, 2008.

Johnson, D.: The role of giant and ultragiant aerosol particles in warm rain initiation, J. Atmos. Sci., 39, 448-460, 1982.

- Jung, E.: Aerosol-cloud-precipitation interactions in the trade wind boundary layer, available from: http://gradworks.umi.com/35/49/3549376.html (last access: 6 November 2014), 2012. Jung, E. and Albrecht, B.: Use of radar chaff for studying circulations in and around shallow cumulus clouds, J. Appl. Meteorol. Clim., 53, 2058–2071, doi:10.1175/JAMC-D-13-0255.1,
- 20

30

15

2014.

L'Ecuyer, T. S., Berg, W., Haynes, J., Lebsock, M., and Takemura, T.: Global observations of aerosol impacts on precipitation occurrence in warm maritime clouds, J. Geophys. Res.-Atmos., 114, D09211, doi:10.1029/2008JD011273, 2009.

Levin, Z.: On the interactions of mineral dust, sea-salt particles, and clouds: a measurement

- and modeling study from the Mediterranean Israeli Dust Experiment campaign, J. Geophys. 25 Res., 110, D20202, doi:10.1029/2005JD005810, 2005.
 - Lu, M. L. and Seinfeld, J. H.: Study of the aerosol indirect effect by large-eddy simulation of marine stratocumulus, J. Atmos. Sci., 62, 3909-3932, doi:10.1175/jas3584.1, 2005.
 - Mather, G. K., Terblanche, D. E., Steffens, F. E., and Fletcher, L.: Results of the South African cloud-seeding experiments using hygroscopic flares, J. Appl. Meteorol., 36, 1433-1447, 1997.
 - Rogers, R. R. and Yau, M. K.: A Short Course in Cloud Physics, 3rd edn. International Series in Natural Philosophy, Pergamon Press, Oxford, 290 pp., 1989.

Rosenfeld, D., Lahav, R., Khain, A., and Pinsky, M.: The role of sea spray in cleansing air pollution over ocean via cloud processes, Science, 297, 1667–1670, doi:10.1126/science.1073869, 2002.

Rosenfeld, D., Axisa, D., Woodley, W. L., and Lahav, R.: A quest for effective hygroscopic cloud

- seeding, J. Appl. Meteorol. Clim., 49, 1548–1562, doi:10.1175/2010JAMC2307.1, 2010.
 Russell, L. M., Sorooshian, A., Seinfeld, J. H., Albrecht, B. A., Nenes, A., Ahlm, L., Chen, Y. C., Coggon, M., Craven, J. S., Flagan, R. C., Frossard, A. A., Jonsson, H., Jung, E., Lin, J. J., Metcalf, A. R., Modini, R., Mülmenstädt, J., Roberts, G. C., Shingler, T., Song, S., Wang, Z., and Wonaschütz, A.: Eastern pacific emitted aerosol cloud experiment, B. Am. Meteorol.
 Soc., 94, 709–729, doi:10.1175/BAMS-D-12-00015.1, 2013.
 - Segal, Y., Khain, A., Pinsky, M., and Rosenfeld, D.: Effects of hygroscopic seeding on raindrop formation as seen from simulations using a 2000-bin spectral cloud parcel model, Atmos. Res., 71, 3–34, doi:10.1016/j.atmosres.2004.03.003, 2004.

Segal, Y., Pinsky, M., and Khain, A.: The role of competition effect in the raindrop formation, Atmos. Res., 83, 106–118, doi:10.1016/i.atmosres.2006.03.007, 2007.

Slingo, A.: Sensitivity of the Earth's radiation budget to changes in low clouds, Nature, 343, 49–51, doi:10.1038/343049a0, 1990.

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30

Sorooshian, A., Wang, Z., Feingold, G., and L'Ecuyer, T. S.: A satellite perspective on cloud water to rain water conversion rates and relationships with environmental conditions, J. Geophys. Res.-Atmos., 118, 6643–6650, doi:10.1002/jgrd.50523, 2013.

Takahashi, T.: Warm rain, giant nuclei and chemical balance – a numerical model, J. Atmos. Sci., 33, 269–286, 1976.

Tzivion, S., Reisin, T., and Levin, Z.: Numerical simulation of hygroscopic seeding in a convective cloud, J. Appl. Meteorol., 33, 252–266, 1994.

Yin, Y., Levin, Z., Reisin, T. G., and Tzivion, S.: The effects of giant cloud condensation nuclei on the development of precipitation in convective clouds – a numerical study, Atmos. Res., 53, 91–116, doi:10.1016/S0169-8095(99)00046-0, 2000a.

Yin, Y., Levin, Z., Reisin, T. G., and Tzivion, S.: Seeding convective clouds with hygroscopic flares: numerical simulations using a cloud model with detailed microphysics, J. Appl. Meteorol., 39, 1460–1472, 2000b.

World Meteorological Organization: Report of the WMO workshop on hygroscopic seeding, WMP Rep. 35, WMO/TD 1006, Geneva, Switzerland, 68 pp., 2000.



Zhang, L., Michelangeli, D. V., and Taylor, P. A.: Influence of aerosol concentration on precipitation formation in low-level, warm stratiform clouds, J. Aerosol. Sci., 37, 203-217, doi:10.1016/j.jaerosci.2005.04.002, 2006.

Zheng, X., Albrecht, B., Jonsson, H. H., Khelif, D., Feingold, G., Minnis, P., Ayers, K., Chuang, P., Donaher, S., Rossiter, D., Ghate, V., Ruiz-Plancarte, J., and Sun-Mack, S.: Observations of 5 the boundary layer, cloud, and aerosol variability in the southeast Pacific near-coastal marine stratocumulus during VOCALS-REx, Atmos. Chem. Phys., 11, 9943–9959, doi:10.5194/acp-

11-9943-2011, 2011.

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Table 1. Summary of flight legs and soundings during the flight on 3 August 2011.

-	Flight level-leg		Pre-seeding legs					
			Cloud-base		Mid-cloud		Cloud-top	(CT)
-	Shown in Fig. Flight time (hh Flight heights Flight direction	4 n:mm:ss) n	c 17:21:00– 339 m NW to SE	17:38:24	d 17:39:36– 481 m SE to NW	17:58:12	e 18:02:24– 582 m NW to SE	18:22:48
Flight level-leg		Seeding		Post-see	ding legs			
		Seeding at CT		Cloud-base		Mid-cloue	d	Cloud-top
Shown in Fig. 4 Flight time (hh:mm:ss) Flight heights Flight direction		f 18:02:00 582 m NW to SI	–18:20:00 E	g 18:48:36- 307 m NW to SE	–18:55:48 E	h 18:57:00 421 m SE to NV	–19:06:54 V	i 19:09:54–19:17:24 594 m NW to SE

Table 1. Continued.

Elight level-leg	Clear-sky (bounda	Clear-sky (boundary layer) legs					
i light lovel log	Sub-cloud layer	Sub-cloud layer					
Shown in Fig. 4 Flight time (hh:mm:s Flight heights Flight direction	b ss) 17:06:54–17:18:30 24 m SE to NW	f 5 18:27:36–18:34:30 22 m SE to NW	f 18:36:00–18:46:69 175 m SE to NW	j 19:18:00–19:22:48 669 m SE to NW			
	Soundings	ascent	descent				
Shown in Fig. 4 Flight time (hh:mm:ss) Flight heights Flight direction		black 16:52:15–16:58:19 – –	red 17:06:47–17:10:48 – –				



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Table 2. The mean value of effective diameter *D*, number concentrations N_d of cloud droplets, precipitation rate, *R*, and the median value of calculated radar reflectivity *Z* on 3 August 2011 for pre- and post-seeding legs at cloud top, mid-cloud and cloud-base heights. *D* shown in the parenthesis is calculated from drop size distributions obtained by combining the CAS and CIP probes.

		3 Aug 2011 Legs	<i>D</i> (μm) Pre-seeding	Post-seeding	N _d (cm ⁻³) Pre-seeding	Post-seeding	-
		Тор	21.4 (22.9)	26.2 (29.9)	143	70	-
		Mid	17.2 (18.1)	18.1 (23.9)	171	100	
		Base	13.5 (15.0)	16.6 (44.3)	162	77	
-	3 Aug 2011 Legs	<i>R</i> (mmh ⁻¹) Pre-seeding	Post-seeding	LWC (gm ⁻³) Pre-seeding	Post-seeding	Z (dBz) Pre-seeding	Post-seeding
	Top Mid Base	0.09 0.06 0.04	0.21 0.17 0.16	0.31 0.26 0.09	0.25 0.12 0.04	-31.8 -32.1 -31.0	-17.1 -16.3 -13.8
		0.04	0.10	0.09	0.04	-31.0	-15.0





Figure 1. Relative (percent of total) (a) number and (b) volume distributions of powdered salt delivered to CAS sampling volume from atomizer.





Figure 2. A pictorial schematic and photo of the salt powder delivery system.

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Figure 3. Profiles of **(a)** potential temperature (θ , K), **(b)** liquid water contents (LWC, gkg⁻¹), and **(c)** accumulation mode aerosol concentrations (#/cc, PCASP) during the aircraft ascents (black) and descents (red) between 16:52:15–17:10:48 UTC (hh:mm:ss). Aerosol concentrations obtained from sub-cloud layer and above cloud layer are shown as grey colors (mean value is shown as cyan square). The heights and spatial locations of data used are shown in Fig. 4.





Figure 4. (a) Time series of flight altitudes and **(b–j)** flight paths on 3 August 2011. The flight pattern for salt seeding is shown as dark blue colors in Fig. 1f. The mean wind speed (12 m s^{-1}) and direction (329°) for the seeding period are shown in Fig. 1f. The detailed information of each level leg, such as flight heights and duration, is summarized in Table 1.





Figure 5. Salt seeding pattern (blue) with estimated advected seeding area at **(a)** cloud top, **(b)** mid-cloud and **(c)** cloud base. The seeding and post-seeding cloud sampling areas are shown as blue and red colors, respectively, at each level. The estimated seeding area for the post-seeding flights are shown as gray shades. The darker gray area points are the advected points calculated with the shorter possible elapsed times.





Figure 6. Changes in cloud droplets' (a) size and (b) number concentration, (c) drizzle rate during cloud-base, mid-cloud and cloud top legs on 3 August 2011. Data obtained from preseeding legs (1 s values) are shown as grey (mean value as yellow square); data obtained from post-seeding flights are shown as red (mean value as blue square). (a) and (b) are calculated from CAS, and (c) is calculated from CIP probes.





Figure 7. Drop size distributions (DSDs) obtained from level legs at **(a)** cloud top, **(b)** midcloud, and **(c)** cloud base before (blue) and after (red) seeding on 3 Auguest 2011. DSDs are calculated from CAS (thin) and CIP (thick) probes for the pre- and post-seeding legs. "BEFORE" and "AFTER" indicates pre- and post-seeding legs, respectively. The values are based on the averages for each level leg, shown in Fig. 4 and Table 1.





Figure 8. (a) The radar reflectivity (in dBz, reflectivity Z is proportional to D^6 of droplet diameters) shows precipitation above the cloud radar in (a) an area of cloud sampled before seeding and the (b) same air mass sampled after seeding during cloud-base level leg. Y axes in (a– c) indicates the altitudes above the radar during the cloud-base level leg. The drizzle rates in (a) and (b) are estimated from the CIP (units of hundredth of mm day⁻¹). The outlined box in panel (b) indicates where a detailed analysis is made for (c) the radar reflectivity in dBz and (d) drizzle rates (from CIP) in mm day⁻¹ and the cloud liquid water content (from PVM-100) in gm⁻³.





Figure 9. As in Fig. 6, but for 10 August 2011, where the cloud is initially precipitating at the time of seeding. Data obtained from pre-seeding legs are shown as grey (mean value as black square); data obtained from post-seeding legs are shown as red (mean value as blue square). Median value of drizzle rates are shown as cross symbols in Fig. 9c.

