We greatly appreciate the thoughtful comments provided by the reviewers. We have given each considerable attention as described in the responses outlined below and have modified the manuscript in response to these comments.

Interactive comment on "Precipitation effects of giant cloud condensation nuclei artificially introduced into stratocumulus clouds" by E. Jung et al.

J. Jensen (Referee)
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Major comments:
Interesting paper, likely effect demonstrated. That said there are some unresolved questions. If only one in 9 cases showed demonstrated effects of adding GCCN, then why did the other ones not. The authors suggest that it was due to clouds already precipitating. There may have been other reasons, e.g. insufficient cloud depth, etc.

We may have mislead the reviewers/readers by the statement "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 section 3.1. The primary reason that we did not see the effects of adding GCCN was due to the ineffective seeding and sampling strategies. For a given case, if the seeding and sampling strategies are definitely inadequate (such as no post-seeding sampling legs: 2-3 cases) we did not examine the case further. Accordingly, there were four less-than-ideal and two ideal cases of seeding experiments in terms of seeding and sampling strategy (Table1). Consequently we analyzed the two cases in detail in the same manner (3 August and 10 August 2011) and less detail for the four less-than-ideal seeding cases when the post-seeding cloud legs were located within the estimated seeding area. Based on these 7 cases (however, heavily relying on the two ideal cases, since the four less-than-ideal cases neither provided new insight nor altered the results shown for the two ideal cases) we concluded that the seeding effects were not effective when the cloud was already precipitating, since other conditions are relatively similar to each other or are closely related to precipitation production (such as cleaner environment in the presence of rain). It should be noted that the primary purpose of most of the flight plans (E-PEACE) was not the salt-seeding experiments.

To better understand the individual seeding cases, the summary of salt seeding experiments is given in Table 1 and the flight patterns of the individual 6 cases (two ideal, four less-than-ideal) are shown in Fig. 1, which are also shown in the Appendix A in the modified manuscript. Further, a detailed analysis for 10 August case is shown in the last section of this response for a direct comparison with the 3 August 2011 case, which was shown in the manuscript. The text in the manuscript was modified to clarify that the flight patterns and sampling strategies for several of cases flown were inadequate for a complete analysis.

Table 1. Summary of salt seeding experiments

Date	Description	Cloud level (m) from Table 4 of Russell et al. (2015)
7/8	The TO did not sample the cloud after salt seeding. No post-seeding legs.	257-362 m (Thin cloud layer)
7/9	We performed two salt seeding experiments. However there was no post-seeding cloud-sampling leg for the first experiment. For the second experiment, the reference cloud legs (i.e., non-salted cloud sampling legs) were possibly contaminated by the first salt seeding experiment by the method shown in Fig. 5 in the manuscript.	283-570 m (Thick, wet cloud layer)
7/26	The seeding/sampling strategy was not an ideal (seeding and sampling pattern was perpendicular, and there was no sufficient post-seeding sampling). During the post-seeding flights in the mid-cloud and cloud-base heights, the seeded area was already advected far southeast. Only cloud top legs (post-seeding flight) were sampled from the estimated seeding area, and the seeding effects were shown at least in the cloud top leg.	253-560 m (Thick cloud layer)
7/29	NO post-seeding sampling legs. Right after injecting salt power, TO sampled the cloud at the same height as seeding, but it was found that the TO flew slightly above the seeding height (no LWC is detected).	265-534 m (High wet clouds)
8/2	The seeding/sampling strategy was not an ideal. Intersection with seeded area was small since the post-seeding was not made in the downstream of the seeding area. Seeding effect was not seen.	310-613 m (Thick, wet cloud layer)
8/3	Descent case solely based on the strategy (shown in the manuscript)	309-628 m (Thick cloud), *H~369 m
8/10	Descent case solely based on the strategy. However the cloud was already precipitating when it was seeded.	286-553 m (low clouds) *H~367m
8/11	The seeding/sampling strategy was not an ideal. During the mid-and cloud-top legs (post-seeding flight), the seeded area was already advected far southeast. Only cloud-base legs were (barely) located	440-600 m (Two broken cloud layers)

	within the seeded area.	
8/12	The seeding/sampling strategy was not an ideal. Post-seeding cloud sampling leg on the cloud-base only (barely) sampled the seeded area (no sufficient data for the post-seeding legs).	278-578 m (Thick cloud layer)

*H (cloud thickness) is calculated from the vertical profile of LWC obtained from soundings on the day (time and location is shown in Fig. 4 in the manuscript (for 3 August 2011) and in Fig. 5 shown later in this response (for 10 August 2011).

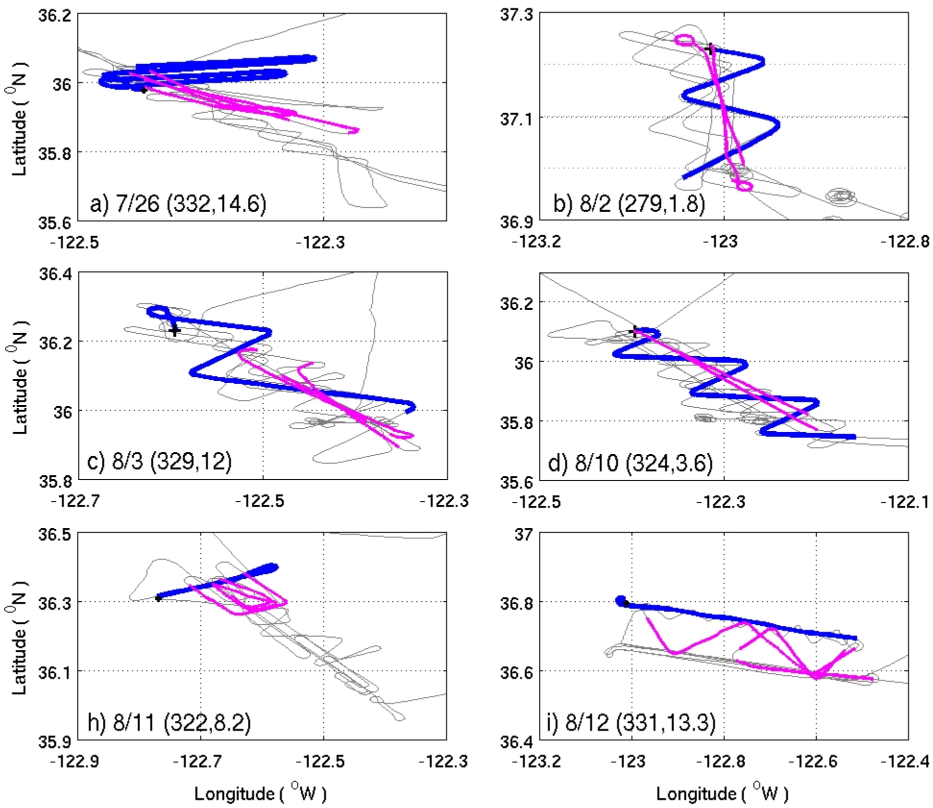

Fig. 1. Flight patterns during salt seeding (blue) and post-seeding cloud sampling legs (magenta) for some of the seeding flights. First and second numbers inside the parenthesis indicate the mean wind speed and wind direction during the salt-seeding leg.

In Fig. 1, the parallel post-seeding sampling with zigzag seeding pattern (c and d) was found to be the most effective flight pattern to capture the seeding effects. In contrast, the perpendicular patterns between the seeding and post-seeding patterns reduced the chance of proper sampling of a salted/seeded air mass during the post-seeding flights. In this case, there was no sufficient time for the seeded air mass to be sampled during the post-seeding sampling legs. Based on our analysis, the 3 August and 10 August cases were ideal when the seeding and sampling strategy alone was considered. However, the cloud deck on 10 August was already precipitating while the seeding was made (confirmed with radar reflectivity, not shown).

1. The critical case with adding anthropogenic aerosols, in this case GCCN, is to know or estimate the natural amount of aerosols (GCCN). This is not done here. The authors estimate concentrations of their added GCCN, although this is at best done in a very approximate way.

To estimate the natural amount of aerosols (GCCN), aerosol concentrations larger than D > 2µm, D > 10 µm, D >20 µm were obtained from CAS on non-cloudy level flight legs flown near the ocean surface (20-30 m; 12 minutes of duration) and above the cloud top (750 m; 3 minutes of duration) as summarized in the table below.

Table 2. GCCN concentrations obtained from CAS on 3 August 2011.

	Near ocean surface (leg b in Fig. 4a in the manuscript)	~750 m (~ 17 UTC)
Diameter (µm)	Concentrations (cm^{-3})	Concentrations (cm^{-3})
D > 2	1.89	5×10^{-2}
D > 10	5.4×10^{-2}	3×10^{-3}
D > 20	9.5×10^{-3}	-

Table 2 shows that the natural amount of GCCN (e.g., D > 10 µm) above the cloud layer (~750 m) is on the order of 10^{-3} cm^{-3} and, no GCCN larger than 20 µm are observed there. On the other hand, the natural amount of GCCN with D > 10 µm near the ocean surface (about 20-30 m above the sea level) is on the order of 10^{-2}-10^{-3} cm^{-3}, which is an order of magnitude larger than those above the cloud layer. Table 1 also shows that the concentrations that are estimated for the salt dispersed artificially are at the same order as the GCCN concentration in nature. But we do not have an estimate just below cloud base to determine if this same concentration is available to the cloud. Also, there are uncertainties in these observed GCCN concentrations due to the low concentrations and the relatively small sampling volume of the CAS probe. Further, we acknowledge that our estimates of the emitted aerosols are crude too. These points have been added and clarified in the manuscript.

2. There is no attempt at relating the injected concentrations of GCCN to drizzle drop concentrations larger that some critical size. Figure 7 shows an increase in the concentration of drizzle drops, but with tick marks as sparse as 5 orders of

magnitude, there is no real way of evaluating the concentration, let alone the increase in concentration, of drizzle drops. For instance, can the injected salt particles approximately explain the increase in drizzle drop concentrations, or are there so many more drizzle drops over such a large area that the injection of GCCN acted as a catalyst that initiated a subsequently much more efficient precipitation process in a cleaner environment?

To address this issue, we modified Figure 7 of the manuscript to include a y-axis with further resolution. In addition, we calculated total droplet number concentrations larger than different critical sizes (D > 50 µm, D > 100 µm, and D > 200 µm are used) to show the changes in drop number concentrations in these ranges before and after seeding and added these differences. The total droplet number concentrations for these calculations are obtained from CIP.

Table 3. Total droplets number concentrations larger than some critical sizes.

Diameter	**Total number concentration (cm^{-3}) obtained from CIP**		
D > 50 µm	**Before**	**After**	**Difference**
Cloud Top	0.81	1.26	0.45
mid-cloud	0.24	0.39	0.15
Cloud base	0.08	0.12	3.5×10^{-2}
D > 100 µm	**Before**	**After**	**Difference**
Cloud Top	2.7×10^{-2}	6.6×10^{-2}	3.9×10^{-2}
mid-cloud	1.2×10^{-2}	4.1×10^{-2}	2.9×10^{-2}
Cloud base	7.7×10^{-3}	3.4×10^{-2}	2.7×10^{-2}
D > 200 µm	**Before**	**After**	**Difference**
Cloud-top	3.3×10^{-4}	1.0×10^{-3}	7.1×10^{-4}
mid-cloud	2.9×10^{-4}	1.3×10^{-3}	1.6×10^{-4}
Cloud-base	3.1×10^{-4}	1.2×10^{-3}	1.6×10^{-4}

Table 3 shows the increase of GCCN number concentration by adding salt power. For instance, total number concentrations of GCCN larger than D > 50 µm increased by an order of 10^{-1} to 10^{-2} cm^{-3} in the cloud layer, and the largest increase is found at the cloud top height where the salt power is injected. The degree of increase in total number concentration decreases as the critical size increases, such as ~10^{-2} cm^{-3} increases for D > 100 µm and ~10^{-3} cm^{-3} to 10^{-4} cm^{-4} increase for D > 200 µm. These calculations show that the number of large droplets (e.g., D > 100 µm) does not exceed our crude estimates of the salt concentrations dispersed from the aircraft. We have included these changes in the large drop concentrations as Table 4 in the manuscript and have added a discussion of this point to the text.

3. The authors attribute the change in cloud to seeding with GCCN, but were there other changes in the conditions experienced during the flight? For instance, did the near-surface wind speed change dramatically, thus explaining a natural increase or decrease in production of GCCN? Was the near-surface horizontal wind speed sufficient to explain wave breaking (10-m altitude speed above approx. 7 m/s)? Did the sea-surface temperature (SST) change in a way that might increase or decrease the turn-over time (residence time of cloud particles in cloud)? The manuscript does not address these causes of natural variability.

The mean wind near the ocean surface (~20 m) was about 10 m/s on this flight , so we cannot exclude the possibility of the contribution from the wave breaking (Please note that the aerosol number concentration (e.g., D > 10 µm) obtained from near the ocean level leg is an order higher than aerosol number concentrations obtained from above the cloud layer in Table 2). However, the winds remained almost the same before and after seeding experiment (Figure below) and the SST shows no variations either. We have modified the text to clarify these points.

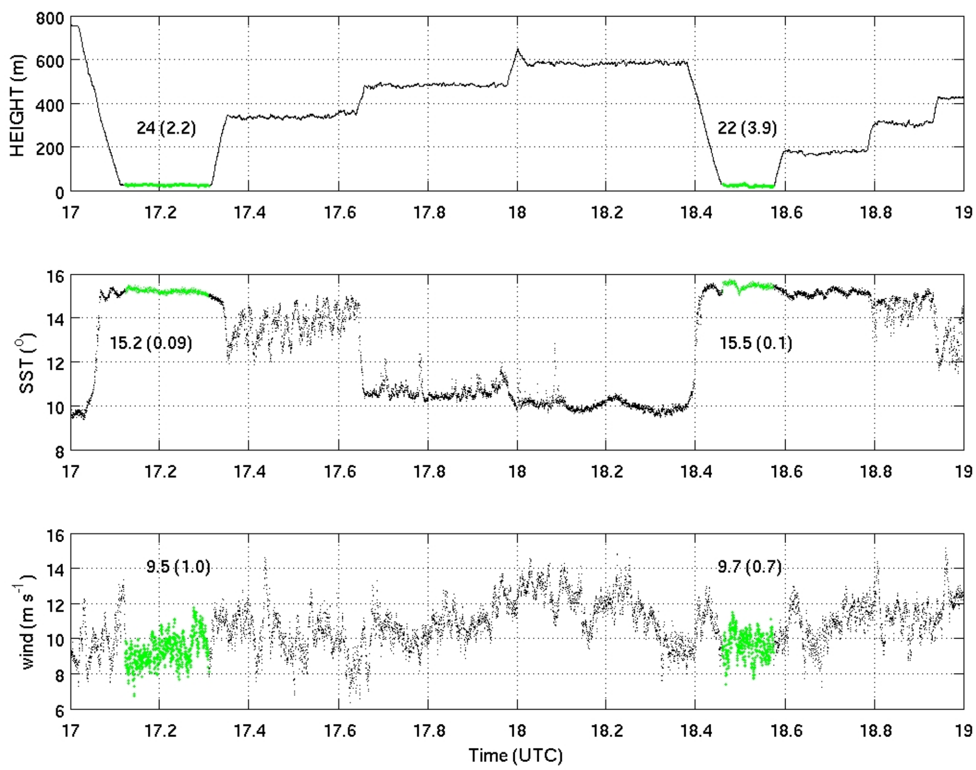

Fig. 3. Time-series of flight altitudes (upper), SST (middle), and wind speed (bottom) during the flight on 3 August 2011. Data obtained from TO flying the closest the ocean surface before and after seeding is shown as green. Numbers indicate the mean (standard deviation).

Minor comments:

Page 57, line 13: "Typical time scale of 10-20 minutes." I think that is an underestimate, and anyway how was it determined? You have updraft and boundary-layer depths measurements to give much better estimates. My guess is that average updrafts were +0.4 m/s and average downdrafts were -0.4 m/s, which for a boundary-layer depth of 600 m would give t=2 x 600 / 0.4 = 3000 s or about 50 minutes.

We considered the cloud depth (H~300 m to 350 m) rather than the entire boundary layer depth since the salt power was injected at the cloud top, and updraft/downdraft ~ 0.5 m/s to 1 m/s; so t=2*300/0.5 ~ 20 minutes; t=2*350/1~10 minutes (~12 minutes for H=350 m, w=1 m/s; ~23 minutes for H=350, w=1 m/s.) We agree that the time underestimates the overturning time though the entire boundary layer. We recalculated the time by using cloud depth H~300-350m, vertical velocity w~0.35 (mean ranges from 0.3 to 0.4 (+0.2-0.3), and median values was about 0.3 m/s during the cloud layer). It gives t=2*350/0.35=33 minutes; t=2*300/0.35=29 minutes. We modified the manuscript accordingly from 10-20 minutes to 30 minutes and indicated that this is the overturning time within the cloud and may underestimate the overturning time through the depth of the boundary layer.

Page 58, line 7: "Appearance of a tail of large drops". Figure 7 does not show the generation of larger drops after seeding with GCCN; there is already a tail of large drops before seeding (all 3 boxes). However, the overall concentration of large drops certainly increases after the seeding.

Changes are made in the manuscript.

Page 73, figure 6 legend: If the CAS probe can measure drops in the size range 0-60 micron diameter, then average CAS observed diameters cannot exceed 60 micron, yet the plotted data show a significant number of mean diameters above 60 micron. I suspect that the mean is calculated from a combination of CAS and CIP data.

Changes are made in the manuscript

Interactive comment on "Precipitation effects of giant cloud condensation nuclei artificially introduced into stratocumulus clouds" by E. Jung et al.

Anonymous Referee #2
Received and published: 24 January 2015

General Comments:
The effects of giant CCN on cloud and precipitation has been an important issue in weather modification and climate change, but is still poorly understood, due mostly to the lack of observational evidence. This article presents aircraft measurements of the changes in microphysical properties of stratocumulus clouds induced by seeding giant salt particles. The results are interesting and are well presented. It should be publishable in ACP if the following specific issues could be considered in revision.

Specific Comments:
1) During the "post-seeding" flights, did the aircraft fly over some clouds which are not influenced by the seeding? It would be more convincing if some evidence are provided to show that the drop size and number concentration in the seeded area are really different from those in the nearby areas which are not clearly influenced by seeding.

During the post-seeding flight, we tried our best to track the seeded area to examine the effect of adding salt. As a result, unfortunately we did not sample outside the cloud purposely. To answer this question at our best, we checked the flight on this particular day. There were three soundings after seeding (between 19:30 and 20:00 UTC in Fig. 4a in manuscript). However, one of them was sampled above the boundary layer (no cloud layer), and the other two soundings that include the cloud decks were sampled farther northeast close to coast (located outside the domain shown in Fig. 4), which is not comparable with current case of seeded air mass since the air mass closer to the coast is more polluted consisting of numerous smaller droplets. The reviewer's point motivates us to modify future plans for the salt seeding experiment to include the measurements of upstream along with downstream (seeded area) since we did not consider this earlier.

2) The values shown in Table 2 should also include the standard deviations.
The standard deviations are given in the table (Table 3 in the modified manuscript).

3) In the caption of Figure 4, "Fig. 1f" should be "Fig. 4f"; the color "dark blue" is not really dark; other color curves are not clearly explained.
Changes are made in the manuscript.

Supplement to responses to Reviwer A---CASE OF 10 AUGUST 2011

(*please note that this part is not included in the modified manuscript)

Results form the case of 10 August 2011 are shown in Fig. 4 to Fig. 8. On 10 August 2011, the cloud depth are about 300-350 m, similar to that flown on 3 August, but the cloud base is lower on 10 August 2011. Accumulation mode aerosol concentration is about 200 cm^{-3} with little variability. The flight patterns (Fig. 5) are also similar to those flown on 3 August (Fig. 4 in the manuscript). Salt seeding is made during the cloud-top flights (shown as blue in Fig. 5f; 18:48-19:10 UTC), then the seeded area is sampled while the aircraft flies at cloud-base (g) and mid-cloud (h) heights from 19:30:37 to 19:53:23 UTC. On 10 August, no post-seeding cloud top legs are made. Figure 6 shows that the post-seeding cloud sampling area (red) is well located within the estimated post-seeding sampling area (shaded area), indicating that the seeded air-mass is properly sampled during the post-seeding legs. The size of cloud droplets for the day slightly increases after seeding (Fig. 7a), but the increase is insignificant compared with that observed on 3 August (Fig. 6a in the manuscript). Before seeding, cloud droplet number concentrations (Fig. 7b) are about 180-190 cm^{-3} through the cloud base to cloud top; they then decrease to 150-160 cm^{-3} after seeding. However, again, the decrease is not as significant as observed on 3 August. The mean precipitation rate (Fig. 7c) decreases after seeding, from 0.1-0.2 mm hr^{-1} to 0.1 mm hr^{-1}, though the median precipitation rate increases slightly from 0.04 mm hr^{-1} to 0.05-0.06 mm hr^{-1} (see Table 4).

Time series of radar reflectivity obtained from pre-seeding legs showed strong radar returns, confirming that the salt was injected to the cloud while it is precipitating (not shown). Changes in drop size distributions on 10 August, before and after seeding, are shown in Fig. 8. The different feature of DSD here, compared with that on 3 August 2011, is that there already are abundant large drops (e.g., D > 200 μm in Fig. 8a) prior to seeding at the level of cloud top where the salt seeding is made, which also reconfirm that seeding was made to the cloud that is already precipitating. After seeding, larger drops (in particular, D > 200 μm) are depleted significantly compared with those of pre-seeding condition in Fig. 8c. The rsults of 10 August is consistent with Feingold et al. (1999) in that seeding is not efficient for the precipitating cloud.

Table 4. As in Table 2 (in the manuscript), but for 10 August 2011. Median values of precipitation rate are denoted in the parenthesis.

8/10	D_e (μm)		N_d (cm^{-3})		R (mm hr^{-1})	
	Before	After	Before	After	Before	After
Top	19.3 (21.3)	-	181	-	0.15 (0.05)	-
Mid	17.5 (19.3)	17.7 (19.3)	193	147	0.19 (0.04)	0.08 (0.06)
Base	14.8 (16.7)	14.6 (17.6)	185	159	0.12 (0.04)	0.07 (0.05)

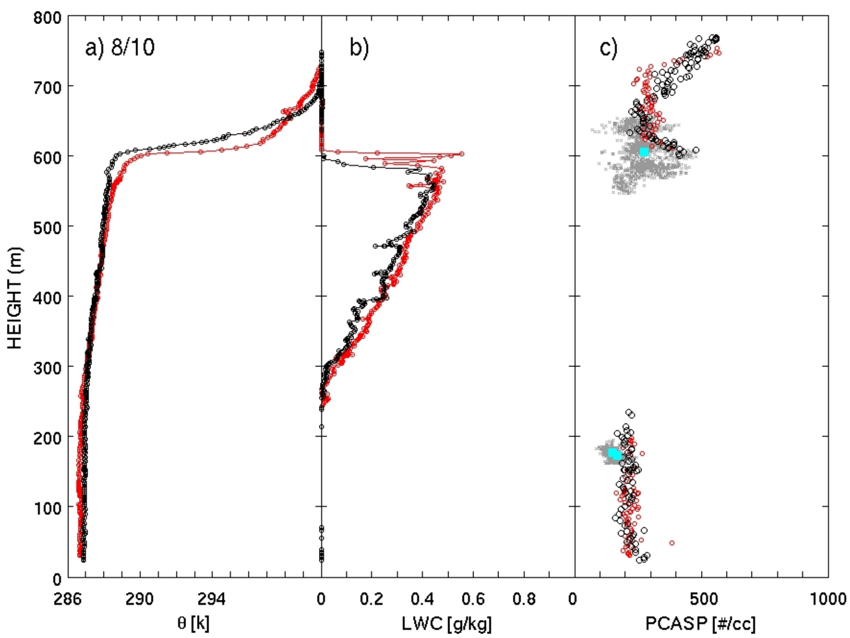

Fig. 4. As in Fig. 3 (in the manuscript), but for 10 August 2011.

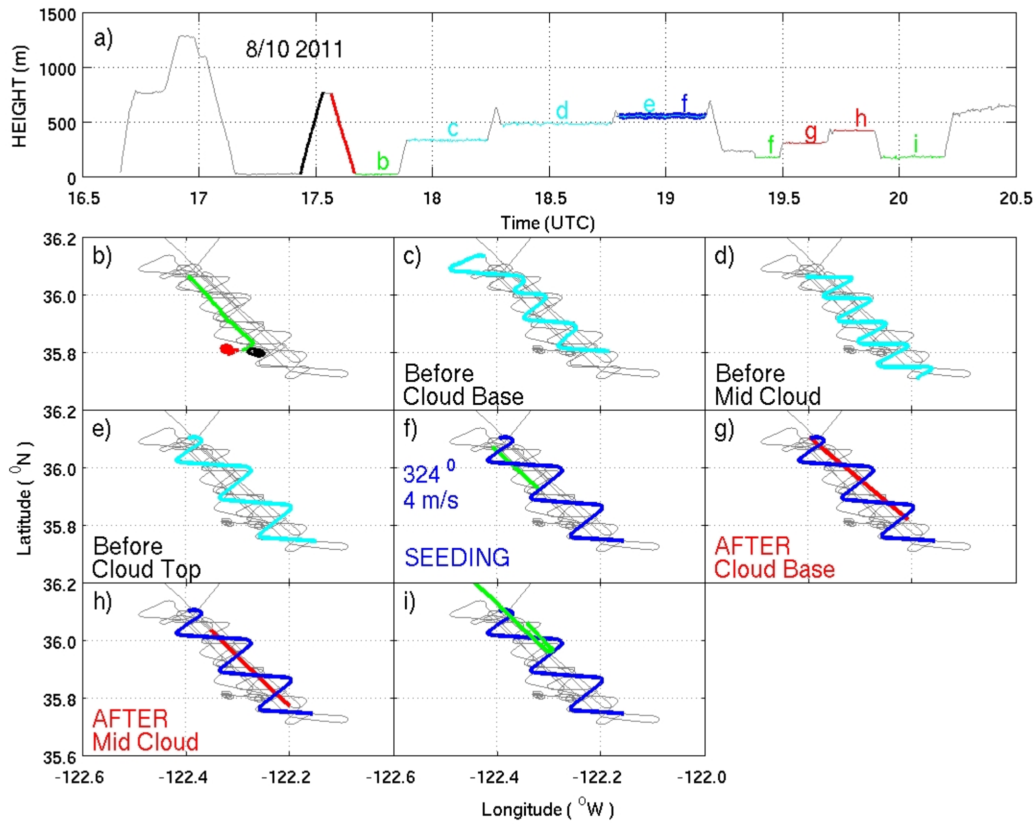

Fig. 5. As in Fig. 4 (in the manuscript), but for 10 August 2011.

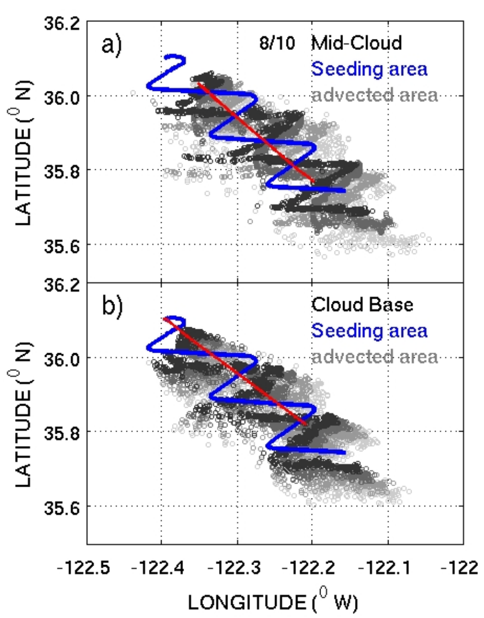

Fig. 6. As in Fig. 5, but for 10 August 2011.

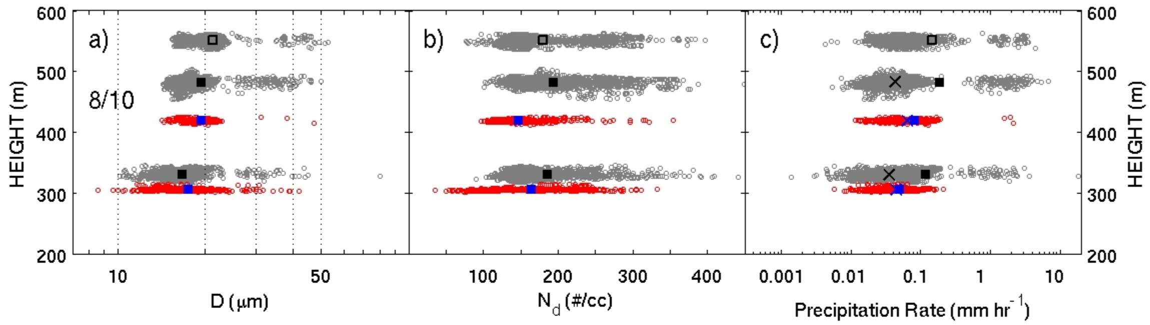

Fig. 7. As in Fig. 9 (in the manuscript).

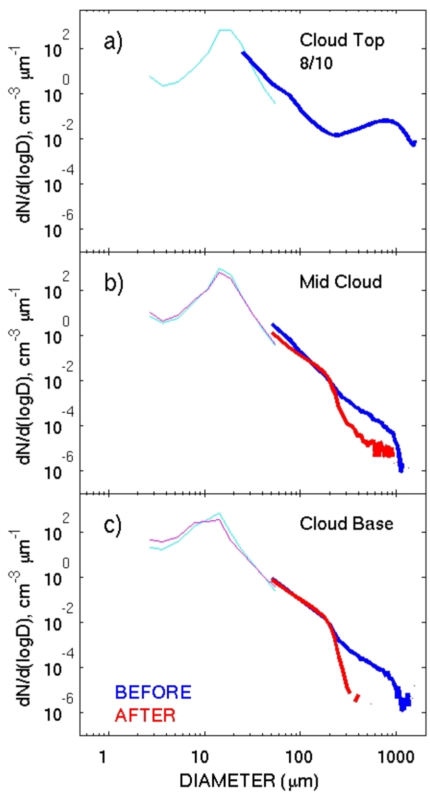

Fig. 8. As in Fig. 7 (in the manuscript), but for 10 August 2011.