Entrainment and Aerosol-Cloud-Precipitation Interactions in Marine Boundary Layer Clouds

Bruce Albrecht
University of Miami
Rosenstiel School of Marine and Atmospheric Sciences
4600 Rickenbacker Causeway
Miami, FL 33149-1031

Award Number: N000140810465

LONG-TERM GOALS

This study focuses on defining and explaining key processes associated with entrainment and aerosol-cloud-drizzle interactions in marine boundary layer clouds—stratocumulus and trade-wind cumulus. The long term-goal of this project is to provide an improved description and understanding of the effects of drizzle and entrainment in boundary layer clouds for the purpose of developing, improving, and evaluating cloud and boundary layer representations in LES, mesoscale and large-scale numerical models.

OBJECTIVES

The scientific objectives are to: 1) document the structure and characteristics of entrainment circulations and processes in marine stratocumulus and evaluate the role of vertical wind shear at cloud top in affecting these process, 2) investigate the relative role of cloud thickness, cloud turbulence intensity, and aerosols on precipitation production; and 3) examine the role of GCCN and cloud electrification on the observed rapid production of precipitation in marine boundary layer clouds. The drizzle-cloud-aerosol interaction components will be aimed at better understanding equilibrium cloud and aerosol states that appear to be due to natural processes, but can be modified inadvertently or intentionally by man-made aerosol sources.

APPROACH

The observations for this study are principally made using the CIRPAS Twin Otter (TO) research aircraft. A key observing system for this work is an FMCW Doppler cloud radar (operating at a wavelength of 3mm) tracks drizzle and cloud features as the aircraft makes simultaneous *in situ* measurements of aerosols, clouds, precipitation, and turbulence.

Innovative approaches are developed to advance are capability to study the dynamical and microphysical processes operating in boundary layer clouds. One technique developed uses radar chaff dispersed at cloud boundaries to track air motions and circulations in and around clouds using the FMCW cloud radar and the CIRPAS MWR-05-XP scanning phased array X-Band radar (operating at 3 cm). The scanning radar is located on-shore and tracks the temporal evolution of 3-D chaff clouds from chaff dispersed just above the top of coastal stratocumulus clouds and sampled by the FMCW cloud radar on the TO flying below the cloud top within the scan volume of the X-Band radar. A second technique used for this project was the seeding of clouds with salt powder to study the response of cloud and drizzle processes to the artificial introduction of giant cloud condensation nuclei (GCCN) under varying aerosol background conditions. Giant cloud condensation nuclei in the form of small salt particles are introduced artificially into stratocumulus clouds to study the effect of these particles on precipitation processes. A third technique developed and applied as part of this project was the use of field mills operating from the TO to examine the electric fields near and in shallow warm clouds. These observations are combined with the TO cloud radar and *in situ* measurements to evaluate the mechanisms and processes that can cause the rapid and relatively heavy precipitation development in small cumuli and stratocumulus clouds.

The observations used in this study were obtained during a number of past field campaigns that were planned and carried out by our research group in collaboration with Dr. Haf Jonson and his research and flight operations staff. These campaigns included the Barbados Aerosol Cloud Experiment (BACEX) 15 March to 15 April 2010 (Jung et al.,2013). The purpose of this field experiment was to observe the time evolution of the cloud and precipitation characteristics of individual oceanic cumulus clouds and to develop statistics on aerosol, cloud, and precipitation under varying aerosol conditions. CIRPAS Twin Otter observations made as part of the July-August 2011 Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 (Russell et al, 2012) cloud radar observations from the CIRPAS Twin Otter were made in stratocumulus clouds off the coast of California. A set of experiments from E-PEACE where giant (salt) nuclei where intentionally dispersed in solid stratocumulus clouds off the coast provide observations to examine the role of giant cloud condensation nuclei (GCCN) on precipitation formation. In another deployment, observations from 18 CIRPAS Twin Otter flights made during cumulus clouds observed from Key West Florida as part of the Key West Aerosol Cloud Experiment (KACEX) in April-May 2012 provided observations for our current studies of the processes responsible for the fast generation of precipitation and the high precipitation efficiency of these clouds. Two field mills operated on the TO were used to examine the e-fields near and in clouds. Our research group planned and carried out the Stratocumulus Entrainment and Precipitation Study (SEPS) in August-July of 2014. A total of 16 flights were made with the CIRPAS Twin Otter and an excellent data set of precipitating non-precipitating stratocumulus clouds was obtained. Cloud seeding, chaff, and electric field studies were all made during SEPS. In addition, during four of the flights, the CIRPAS MWR (scanning phased array X-Band) radar was used to track chaff releases made above the inversion capping the coastal stratocumulus decks sampled by the TO.

As part of an effort was made during the summer of 2015, the FMCW Doppler cloud radar was operated in conjunction with a ceilometer and microwave radiometer at a surface site near Marina California to examine the turbulence and turbulence dissipation rates in the entrainment zone at the tops of marine stratocumulus that move on shore. The high vertical resolution (10 m) of the FMCW radar will allow for an unprecedented opportunity to quantify the turbulence and entrainment processes near cloud top under varying wind shear conditions at cloud top.

WORK COMPLETED

Using BACEX observations, the circulations in and around shallow cumulus were studied using a newly-developed technique using an airborne cloud radar to track circulations in the clear air around and beneath the cloud using radar chaff. The chaff is used to track motions associated with entrainment and detrainment processes at the top and edges of cumulus clouds using the airborne FMCW 95 GHz Doppler radar on the Twin Otter. The chaff used for this experiment was pre-cut metallic coated fibers (cut to 1/2 of the wavelength of the radar for maximum response) that were dispersed from canisters carried in a pod beneath the wing of the CIRPAS Twin Otter. The chaff experiments were designed to examine entrainment-detrainment processes and the subsiding shells observed around small cumulus clouds. This work is described in recently publised paper in *Journal of Applied Meteorology and Climate* (Jung and Albrecht, 2014).

Using the E-PEACE observations, the effects of giant cloud condensation nuclei (GCCN) on precipitation processes in stratocumulus clouds were studied. One case has been studied in depth and the results have been published in *Atmospheric Chemistry and Physics* (Jung et al, 2015).

Mechanisms and processes associated with the rapid formation of precipitation in shallow clouds are still not fully understood. Mechanisms for the electrification of small cumuli and stratocumulus clouds were topics of discussion more than 40 years ago. In this same timeframe, research was done on how electrical fields in these clouds can influence collision and coalescence processes. But work on this topic during the two decades has been limited and there have been few direct observations to confirm various proposed cloud microphysical and electrification relationships in shallow clouds. We have revisited this topic in collaboration with Dr. Haf Jonson by using the KACEX observations are used to characterize the structure of clouds and precipitation streamers associated with fast precipitating clouds. The upward-facing FMCW Doppler radar mounted on the TO is used to characterize precipitation structures. Two field mills mounted on the aircraft were used to examine the electric fields in and near the clouds. In addition the FMCW radar

As part of SEPS 2014, a total 16 flights were made with the CIRPAS Twin Otter in July-August 2014. These flights were made with in collaboration with Research Scientist Dr. Virendra Ghate of the DOE Argonne National Laboratory and provided an excellent set of cases for studying precipitating and non-precipitating clouds. During these flights, several cloud seeding and chaff experiments were carried out. On some of the TO flights the CIRPAS MWR-05-XP scanning phased array X-Band radar was used to track chaff releases made above the inversion capping the coastal stratocumulus decks sampled by the TO. Following the chaff release, the TO flew below the top of the boundary layer so that the upward -ward pointing cloud radar could be used to sample the chaff as it is entrained into the boundary layer.

The CIRPAS FMCW Doppler cloud radar was operated from May-October 2015 with a Vaisalla ceilometer and a three-channel microwave radiometer (on loan from DOE ARM) were operated from a surface site located adjacent to the CIRPS aircraft hangar. These observations will be used with other remote sensing systems (ceilometer and microwave radiometer) at a surface site near Marina California to examine the turbulence and turbulence dissipation rates in the entrainment zone at the tops of marine stratocumulus that move on shore. The ceilometer provides an estimate of the cloud-base height, and the microwave radiometer provided the liquid water path. The high vertical resolution (10 m) of the FMCW radar will allow for an unprecedented opportunity to quantify the turbulence and entrainment processes near cloud top under varying wind shear conditions at cloud top using a technique described in Albrecht et al (2015).

RESULTS

Using the E-Peace observations, the effects of giant cloud condensation nuclei (GCCN) on precipitation processes in stratocumulus clouds was studied. Salt particles of 1-10 µm diameter were released from the Twin Otter while flying near cloud top on 3 August 2011 off the central coast of

California. The seeded area was subsequently sampled from the CIRPAS TO using aerosol, cloud, and precipitation probes and an upward-facing cloud radar. During post-seeding sampling, made 30-60 minutes after seeding, the mean cloud droplet size increased, the droplet number concentration decreased, and large drop (e.g., diameter larger than 10μm) concentration increased. Average drizzle rates increased from about 0.05 mm hr^{-1} to 0.20 mm hr^{-1}, and cloud liquid water path decreased from about 52 g m^{-2} to 43 g m^{-2}. 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 a depletion of the cloud water due to rainout.

Mechanisms and processes associated with the rapid formation of precipitation in shallow clouds are being studied with the KACEX (Key West) observations. Analyses of a case study for May 22, 2012 focus on the microphysical, dynamical, and electric field structure associated with shallow cumulus clouds less than 2.5 km deep that rapidly precipitate. The clouds were observed over the open waters south of Key West Florida.

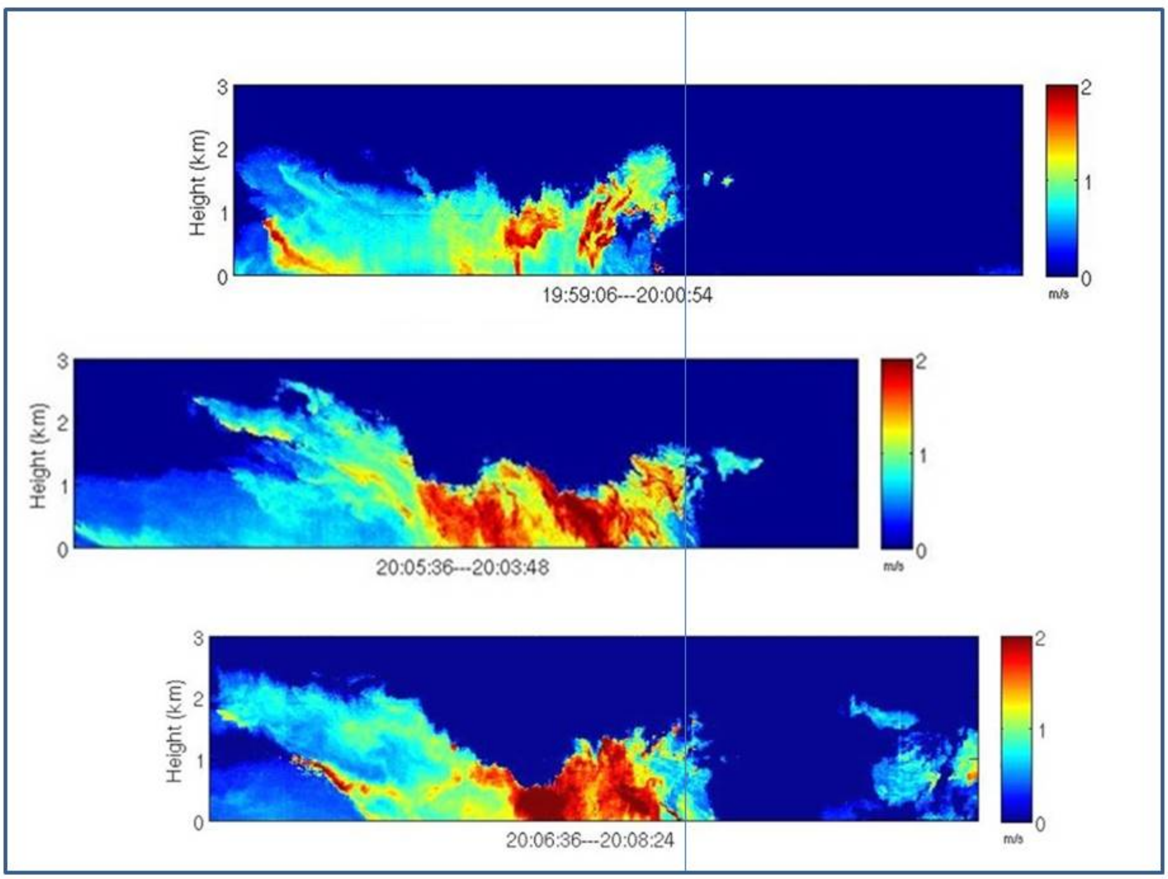

FIG 1. Spectrum width (indicator of droplet size) from the upward-facing cloud radar on a flight leg made near the cloud base through a complex of fast-precipitating clouds less than 3 km in depth observed during KACEX. Each panel corresponds to a separate pass through the line of convection. The time in the second panel has been reversed so that an east-west orientation of the passes can be visualized. In addition the panels have been aligned so that there is some alignment of the cloud features. The thin blue line indicates the right (east) edge of the cloud feature. The bright red ares show the areas of large drizzle droplets (greater than 1.5 mm diameter)

To characterize the evolution of the rapidly precipitating clouds observed on this case, we use the spectra from the FMCW Doppler radar. When large drizzle-sized droplets are observed, the velocity spectra show well-defined minimum associated with droplets of about 1.65 mm. This structure is associated with Mie effects (Kollias et al, 2002) and the spectra in these cases can be used to retrieve the air vertical velocity and the relative droplet distribution. In general, spectrum widths from the radar observations provide an effective way to identify areas of precipitation in the clouds. The spectrum widths for the May 22 KACEX case are shown in Fig. 1 and show the evolution of the precipitation areas within the cloud complex studied along three passes of the TO during a nine-minute period. There is a substantial expansion of the precipitation area in only 5 minutes. Work is in progress to explore the mechanisms responsible for this observed rapid production of precipitation. This work focuses on the role of turbulence (from radar observations) and electric field perturbations associated with warm cloud processes. Resolvable-scale turbulence in the form of fluctuations in the vertical velocity have been verified by applying Mie-technique to the Doppler spectra (Fang and Albrecht; 2015) for this case. The electric field from the field mils shows a large positive perturbation associated with the heavier precipitation areas and a negative perturbation on the west side of the main area of precipitation. Our preliminary analysis indicates that electric field perturbations of 100V/m and higher--well within the range where these fields may affect collision and coalescence processes—are consistently observed in and around the cloud system studied. However, further analysis is needed to determine if the electric field perturbations are real, or if they are affected by artifacts due to charging of the aircraft etc. Further, analysis is in progress to examine the possible effects of turbulence in enhancing the precipitation effects using the Doppler velocities from the cloud radar.

During SEPS, the radar chaff technique demonstrated during BACEX (Jung and Albrecht, 2014) was used to examine entrainment processes at the top of stratocumulus clouds using the TO FMCW (W-Band) cloud radar. The chaff used in these studies was pre-cut metallic coated fibers (cut to 1/2 the wavelength of the W-Band radar; 1.5 mm) that were dispersed from canisters carried in a pod beneath the wing of the CIRPAS Twin Otter. The fibers have a terminal velocity of about 2 cm/s and follow air motions. Here chaff was released just above the cloud top and then the TO made penetrations of the cloud at lower levels to observe the chaff signals above the aircraft with the zenith pointing cloud radar. In addition chaff cut to optimize returns from the MWR W-band scanning radar (15 mm) was dispensed from the TO using the same dispenser system. These large fibers fall more quickly than the smaller W-band chaff and may not effectively track vertical motions, but do track the horizontal motions.

This radar chaff study was made in collaboration with Research Scientist Virendra Ghate of the DOE Argonne National Laboratory. On four days the WXR scanning phased array X-Band radar was used to track chaff releases made above the inversion capping the coastal stratocumulus decks sampled by the TO (Fig. 2). During these cases the MWR made volume scans with a 45^{o} azimuth sweep and 0-55^{o} elevation scan in about 10 seconds. The radar was located at an overlook area on California Route 1 just north of the Point Sur Naval Facility at Hurricane Point. The MWR was on site and coordinated with the TO flights that were flown in the scan volume MWR. On 7 August the scanning radar was able to track the X-Band chaff releases for over an hour. In this case canisters of chaff were emptied along three legs flown parallel to the wind at a distance of about 2 km apart n two different chaff releases. The reflectivity returns for these chaff release are shown at three different times in Fig. 3. The three lines of the initial release of these are clearly shown in the 1641 UTC panel. The evolution of these three chaff tracks is clearly shown in the last two panels. The second release is shown in the 1730 UTC panel. Dr. Virendra Ghate has taken the lead in analyzing the MWR data and publishing the results.

FIG.2. Photos of the CIRPAS Twin Otter research aircraft and the CIRPAS MWR-05-XP scanning phased array X-Band located at Hurricane Point (just north of Point Sur). Satellite image is a visible image of stratocumulus cloud studied on 7 August 2014. The blue circle on the image shows the specific area studied.

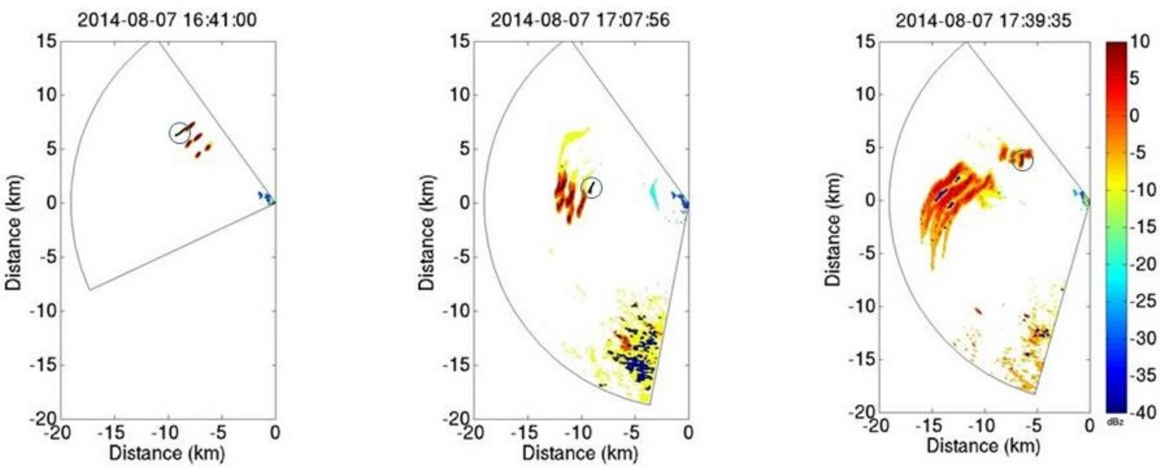

FIG. 3. Radar reflectivity from scans made with the MWR (scanning X-Band radar) located at Hurricane Point showing the evolution of the chaff clouds that were made from releases from the CIRPAS Twin Otter. The grid is oriented E-W and N-S. The blue circles indicate the location of the TO during the scans.

In this case, the chaff distribution observed about 40 minutes after the W-band chaff is dispensed above a stratocumulus cloud is shown in Fig. 4 for the August 7, 2014 case. The observations shown in this figure were made from a leg flown about 200 m below cloud top. The higher reflectivity returns within the boundary layer shown in Fig. 4 shows chaff returns that are tagging air entrained into the boundary layer. The chaff return features above the cloud top reflect the wind shear observed at this level. There is a region just above the clouds were there is a layer of chaff (15-30 seconds; about 1 km horizontally) that resides just on the top of the cloud. The entrained chaff in the boundary is associated with horizontal scales of about 200-400 m. Several other chaff cases were obtained during SEPS, and these will be included with the current case to further the structure of the entrainment events. These chaff traces provide a first ever 2-D look at cloud-top entrainment processes. The tracking of the chaff with the MWR provides a horizontal mapping context for the observations. These cases will also be prime candidates for simulations with Large Eddy Simulation (LES) models where tracers mimicking the dispersed chaff can be used in the simulations.

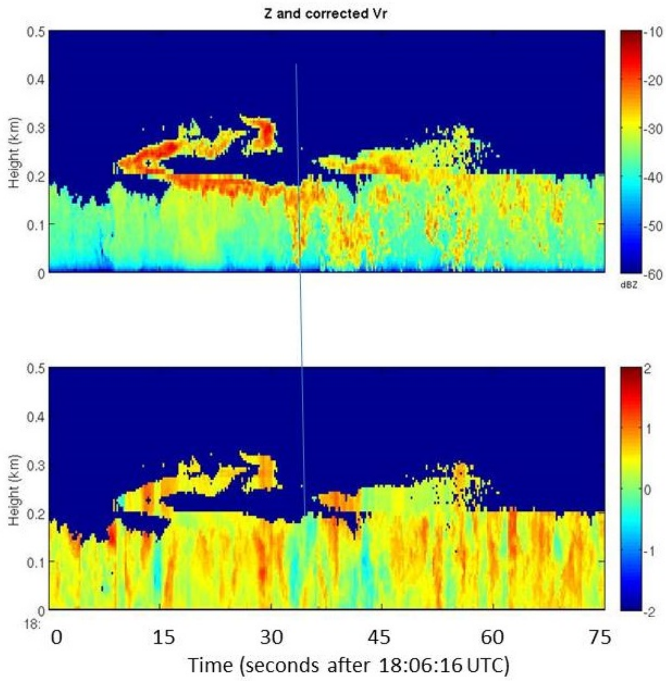

FIG 4. Refectivity returns from Twin Otter FMCW radar flying 200 m below the top of the stratocumulus cloud deck where chaff was released about 100 meters above the cloud about 40 minutes prior to 18 UTC on 7 August 2014. This 75-second time height section corresponds to horizontal distance of about 4 km. The chaff returns in the radar reflectivity (top panel) are shown by orange-red contours, while the cloud returns are from the light green and blue contours. The radar Doppler velocities (lower panel) show up and down circulations. The thin blue line marks an entrainment event shown in both the reflectivity and the verticsl velocity.

IMPACT/APPLICATIONS

Some innovative applications of a cloud radar that were developed under ONR support have been used to advance observational techniques for studying cloud processes and aerosol-cloud-precipitation interactions. These techniques have the potential for further applications in studying clear air circulations in and around cumulus clouds and cloud-top entrainment in stratocumulus clouds. The chaff studies point to the potential of using scanning radars to track three-dimensional air motions in and around clouds time and to tag and track movements of air masses of interest in and above the boundary layer. Although the work on the possible effects of warm-cloud electrification on the fast generation of precipitation are preliminary, if these effects are valid, major revision in how precipitation is parameterized in models operating at many scale will have to be made.

REFERENCES

Albrecht, B., Fang, M., and V. Ghate, 2015: Exploring Stratocumulus Cloud-Top Entrainment Processes and Parameterizations by Using Doppler Cloud Radar Observations. *J. Atmos. Sci.* (In Press).

Fang, M. and B. Albrecht, 2015: High Resolution Airborne FMCW Radar Reveals the Well-Known Puzzle of Warm Rain Formation in a Small Cumulus. 37th radar conference on meteorology, American Meteorological Society, Norma, OK, 275859.

Jung, E., B. Albrecht, J. M. Prospero, H. J. Jonsson, and S. M. Kreidenweis, 2013: Vertical Structure of Aerosols, Temperature and Moisture Associated with an Intense African Dust Event Observed over the Eastern Caribbean. *J. Geophy. Res. 118,4623–4643, doi:10.1002/jgrd.50352.*

Kollias, P., B.A. Albrecht, and F. Marks Jr., 2002: Why Mie? Accurate observations of vertical air velocities and raindrops using a cloud radar. *Amer. Meteor. Soc.,* 1471-1481.

Russell,L., A. Sorooshian, J. Seinfeld, B. Albrecht, A. Nenes, L. Ahlm, Y-C Chen, M. Coggon, J. Craven, R. Flagan, A. Frossard, H. Jonsson, E. Jung, J. Lin, A. Metcalf, R. Modini, J. Mülmenstädt, G. Robert, T. Shingler, S. Song, Z. Wang, A. Wonaschütz, 2012: Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE), *Bull. Am. Meteo. Soc. Bull. Amer. Meteor. Soc.*, **94**, 709–729.doi: http://dx.doi.org/10.1175/BAMS-D-12-00015.1

Wang, S., Zheng, X., and Jiang, Q.: Strongly sheared stratocumulus convection: an observationally based large-eddy simulation study, *Atmos. Chem. Phys.*, 12, 5223-5235, doi:10.5194/acp-12-5223-2012, 2012.

PUBLICATIONS

Jung, E., and B. Albrecht, 2014: Use of Radar Chaff for Studying Circulations in and around Shallow Cumulus Clouds. *J. Appl. Meteor. Climatol.*, **53**, 2058–2071. [referred, published]

Jung, E, Albrecht BA, Jonsson HH, Chen YC, Seinfeld JH, Sorooshian A, Metcalf AR, Song S, Fang M, Russell LM. 2015. Precipitation effects of giant cloud condensation nuclei artificially introduced into stratocumulus clouds. *Atmos. Chem. and Phy*. 15:5645-5658. 10.5194/acp-15-5645-201. [referred, published]