

Aerosol-Cloud-Drizzle-Turbulence Interactions in Boundary layer Clouds

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LONG-TERM GOALS

The long term-goal of this project is to provide an improved description and understanding of the effects of aerosol-cloud interactions and drizzle and entrainment processes in boundary layer clouds for the purpose of developing, improving, and evaluating cloud and boundary layer representations in LES, mesoscale and large-scale forecast models.

OBJECTIVES

The scientific objectives are to: 1) document the structure and characteristics of entrainment circulations in marine stratocumulus and fair-weather-cumuli, 2) characterize the vertical distribution of drizzle and how it relates to cloud and mesoscale circulations; 3) investigate the relative role of cloud thickness, cloud turbulence intensity, and aerosols on precipitation production; 4) study the processing of aerosols by cloud processes; 5) explore mass, moisture, and aerosol transports across interfacial regions at cloud base and at the capping inversion, and 6) examine the role of GCCN and cloud electrification on the observed rapid production of precipitation in marine boundary layer clouds.

APPROACH

The observations needed for this study are made using the NAVY CIRPAS Twin Otter research aircraft and includes the use of an FMCW cloud radar to track drizzle and cloud features while making simultaneous *in situ* measurements of aerosols and cloud characteristics. Further, we use the cloud radar with radar chaff to track air motions in and out of the clouds. Cloud seeding techniques demonstrated in an earlier ONR funded study are extended to study the response of cloud and drizzle processes to the artificial introduction of CCN and giant nuclei under differing aerosol backgrounds. In addition, a set of aerosol and cloud observations in trade wind cumulus clouds using the CIRPAS aircraft with the cloud radar was designed and carried out. The observational components of this study are made in environments where a strong-aerosol-cloud variability was observed. This included observations made during VOCALS (VAMOS Ocean Cloud Atmosphere Land Study) Regional Experiment off the coast of Chile (Oct.-Nov. 2008) where satellite observations indicate strong gradients in cloud properties off the coast. Further from the South Florida area of fair-weather cumulus clouds (Jan. 2008) where clouds with both marine and continental characteristics were observed. This was followed by a set of observations made in 2010 of cumulus clouds in off of Barbados and a more

recent set of observations April-May 2012) in marine cumulus clouds made from Key West Florida. These studies included the participation of a number of graduate students and a technician/data analyst. For the VOCALS study we collaborated with Dr. Carl Friehe and Djmal Khief (U. Calif. Irvine) on turbulence observations from the Twin Otter and with Dr. Patrick Chaung (U. Calif. Santa Cruz) on cloud physics measurements. Dr. Haflidi Jonsson, the chief scientist for the CIRPAS Twin Otter (TO), has been an integral collaborator in all projects involving this research aircraft. Related modeling studies involved collaborations with Dr. Shouping Wang of the Naval Research Laboratory Monterey.

WORK COMPLETED

As part of this research project the CIRPAS Twin Otter (TO) research aircraft was deployed for VAMOS Ocean-Cloud-Atmosphere-Land Study -Regional Experiment (VOCALS-REx) that was undertaken from October to November 2008 over the subtropical southeastern Pacific to investigate physical and chemical processes important for boundary layer and cloud processes in this region Wood et al., 2012). The CIRPAS Twin Otter aircraft made 19 research flights off the coast of Northern Chile during VOCALS-REx from Oct. 15 to Nov. 15. Cloud conditions were excellent during this deployment. The flight strategy involved operations at a fixed point (20 S; 72 W; reference point alpha) that allowed for a definition of the temporal evolution of boundary layer structures, aerosols, and cloud properties. Each flight included 3 to 4 soundings and near-surface, below-cloud, cloud base, in cloud, cloud top, and above inversion observations along fixed-height legs. This study used the aerosol, cloud, boundary-layer thermodynamics and turbulence data from those 18 flights to investigate the boundary layer, and aerosol-cloud-drizzle variations in this region.

The Barbados Aerosol Cloud Experiment (BACEX) was planned by our research group and then carried out from 15 March to 15 April 2010. 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. The principal observing platform for the experiment was the CIRPAS TO that was equipped with aerosol, cloud, and precipitation probes and standard meteorological instrumentation for observing mean and turbulent thermodynamic and wind structures. The highlight of the TO observing package was an upward facing FMCW Doppler 95 GHz radar (designed and fabricated by ProSensing). The use of the FMCW radar, which has a dead zone of less than 50 m, allows for radar observation in close proximity to the *in situ* probe measurements. The Doppler spectra from the radar proved to be rich in structure that will help deconvolve the contributions to the radar returns from both cloud and rain. The aircraft was used to characterize the structure of shallow to moderately deep (cloud tops less than 2 km) and mostly precipitating marine cumulus clouds. A total of 15 aircraft flights were made just upstream from a point on the eastern shore of Barbados (Ragged Point) where surface aerosol measurements (Joe Prospero, University of Miami) were made along with aerosol characterizations from a NASA AERONET tracking sun photometer for aerosol optical depth (AOD) and a micro-pulse LIDAR. Routine rawinsonde observations made daily from the island (by Barbados Meteorological Service) and observations from an S-Band radar (by Caribbean Meteorological Organization) on Barbados were collected in support of BACEX.

Cloud radar observations from the CIRPAS Twin Otter were made in support of the TO operations made off the coast of California during July-August 2011 in support of The Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 that was led by Dr. Lynn Russell and with collaborators John Seinfeld and Armin Sorooshian. The observations from the FMCW radar that was operated by our group are being used to document the cloud structure observed on the flights flown during E-

PEACE. A set of experiments where giant (salt) nuclei were intentionally dispersed in solid stratocumulus clouds off the coast was executed. The giant nuclei released during these experiments were milled salt particles (about 3 μm) that were coated to prevent sticking. They were dispersed using a mechanism that auger fed particles into fluidized bed of grit before emitting them to the outside in a pressurized flow. After the particles were dispersed flights were made in the cloud at lower levels where the radar and the in situ probes sampled the air mass that was seeded with the salt particles to see how the cloud and precipitation characteristics of the cloud were modified (Russell et al, 2012).

Another set of observations (from 18 CIRPAS TO flights) was made in cumulus clouds observed from Key West Florida as part of the Key West Aerosol Cloud Experiment (KACEX) in April-May 2012. A total of 15 flights were flown and provided sampling over a wide range of aerosol, cloud and boundary layer conditions. The Twin Otter was used to study aerosols, cloud, precipitation and turbulence observations in conjunction with cloud radar observations. During VOCALS, BACEX, KACEX 6 University of Miami graduate students (two funded by this grant) and one undergraduate student participated in the aircraft field operations. Observations from KACEX are currently being analyzed.

RESULTS

The observations made during the VOCALS deployment provide a unique characterization of the cloud and aerosol variability in the coastal environment. The marine atmospheric boundary layer structures observed showed relatively little variability and indicated little influence from meso-scale and large-scale systems. The boundary layer, cloud and aerosol structures sampled on the individual days were likely to be steady and close to equilibrium. Most of the VOCALS analyses were completed and published during the past year (Zheng et al., 2010 and 2012). Further these observations were used with those from the other aircraft observations made during VOCALS to give a composite cloud and boundary layer structure along 20° S extending from near the coast (TO observations) to 1500 km to the west (Bretherton et al. 2011). The VOCALS TO observations have also played a major role in modeling studies headed by Dr. Shouping Wang (Wang et al, 20011 and 2012) of NRL Monterey.

During BACEX the Twin Otter was able to sample many cumulus clouds in various phases of growth during BACEX and under different aerosol loading. Precipitation varied from light to heavy with the convection showing substantial meso-scale organization on several of the flights. The observations have been used to develop a statistical description of the aerosol, cloud, and precipitation properties in the undisturbed trade-wind boundary layer. Observations of the variability of the cloud and precipitation properties observed during BACEX from the cloud radar are shown in Fig. 3. Here normalized reflectivity-velocity number distributions are shown for all the days when clouds were observed. The precipitating clouds, however, show that precipitation fall velocities dominate as the reflectivity increases and show a much wider range of reflectivity. The characteristic patterns for clouds of different types are being studied to understand the processes and factors that control precipitation rates in the clouds observed. An overview of the aerosol-cloud-precipitation characteristics observed during BACEX is detailed in a manuscript that has been drafted.

The principal variability in the background aerosols observed during BACEX was associated with African dust above the boundary layer. On two days when convection was completely suppressed, an African dust event associated with record Aerosol Optical Depths (AODs) for Barbados during this time of the year was observed. The vertical structure of the aerosols and the boundary layer observed during these cases was documented. Aerosols in the near-surface mixed layer are relatively mixed with

height as are the aerosols in the Saharan Air Layer (SAL). The intermediate layer (IL) between the SAL and the sub-cloud layer (SCL) shows substantial variability in the thermodynamic and the aerosol structures. The observed variability in the structure is most likely linked to convective processing of the aerosol sometime in the history of the intermediate air mass as it moved across the Atlantic. This unique data set was used to study aerosol transports and processing during this major African dust event (Jung et al, 2013).

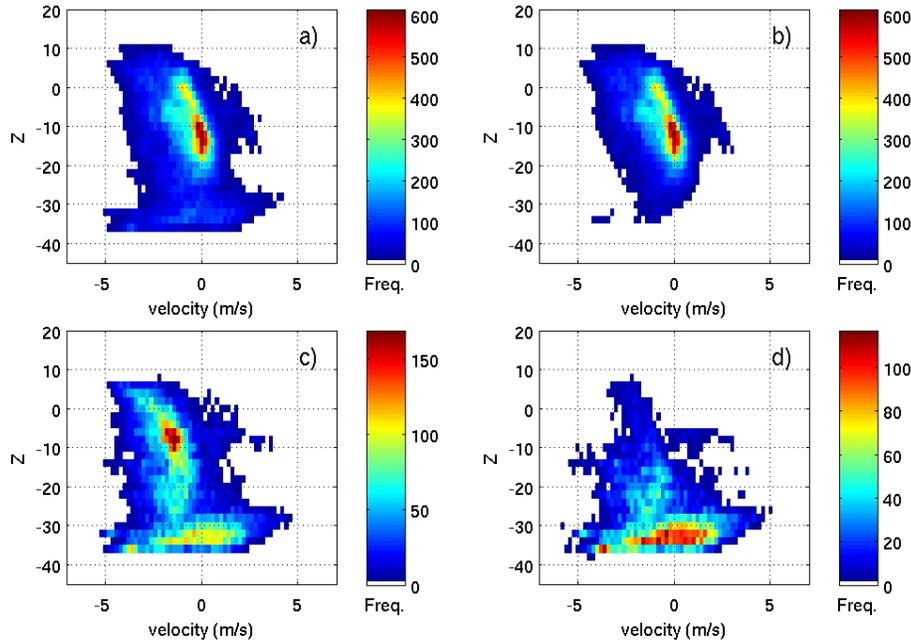


FIG 1. Cloud reflectivity and velocity distributions estimated from an average of all individual days (12 cases), (b) using three precipitating clouds days, (c) using 11 days but excluding one day with the strongest precipitating clouds, and (d) from non-precipitating and/or lightly precipitating clouds.

A new technique for using an airborne cloud radar to track circulations in the clear air around and beneath the cloud was demonstrated during BACEX 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) 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.

The chaff experiments were designed to examine entrainment-detrainment processes and the subsiding shells observed around small cumulus clouds. The radar chaff elements used for this experiment are fibers that are cut to a length of about 1/2 of the radar wavelength to maximize radar returns by serving as dipole antennae. The fibers are packed in fiber tubes and are mounted in a dispenser, beneath the wing of the aircraft. The chaff is released near the tops and edges of growing small cumulus clouds. Then the aircraft made penetrations of the cloud at lower levels to observe the chaff signals above the aircraft with a zenith pointing cloud radar. This technique provides a more complete picture of the entrainment and in-cloud flow patterns that have been hypothesized in previous studies and is the first-ever use of a cloud radar to track radar chaff flows in and around cumulus clouds from an aircraft. The idealized circulations around cumulus clouds that were tracked with chaff during BACEX is shown in

Fig. 2. This work is described in a manuscript submitted to *Journal of Applied Meteorology and Climate* (Jung et al., 2013).

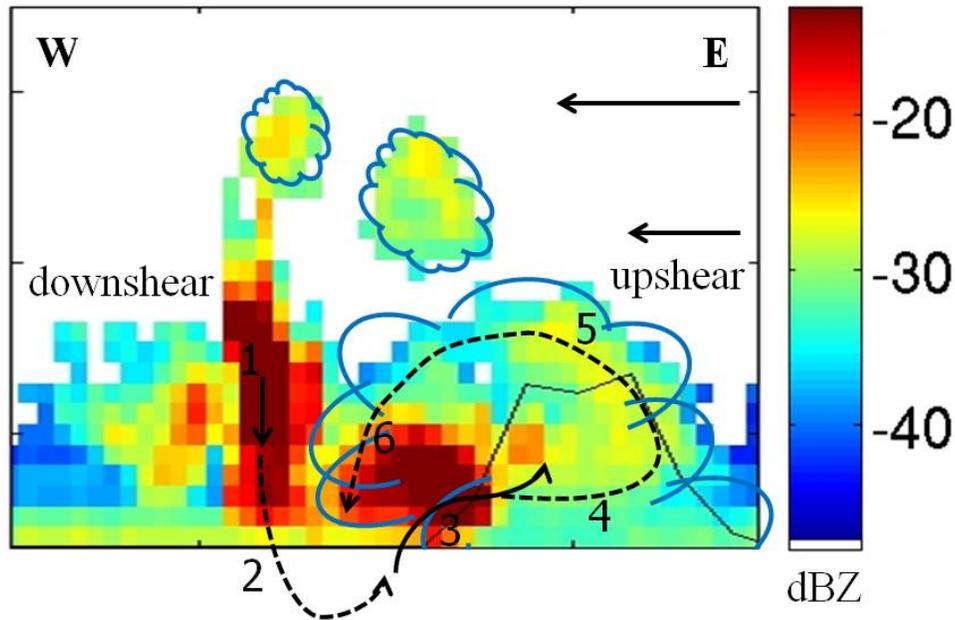


FIG.2. Schematic of the entrainment processes and in-cloud flow pattern for a shallow marine cumulus cloud, overlaid is the radar reflectivity field observed on aircraft leg flown below the level where chaff was released. Chaff areas are indicated by the high reflectivity areas (shaded red). Cloud boundaries are shown as blue solid lines, chaff movements and in-cloud flow patterns are denoted as black solid and dashed lines, respectively. Background winds are denoted as arrows to show the upshear/downshear direction. The letters 'E' and 'W' in the upper corners indicate east and west. A 1-Hz resolution of liquid water contents (LWC) are added as a thin black solid line. The z-axis spans about 0.5 km with cloud top heights are at 1.5 km.

Giant CCN (GCCN) can play an important role in warm rain initiation. To study the effects of GCCN on precipitation, we released milled salt particles of 5- μm diameter from an aircraft flown in stratocumulus clouds observed off the central coast of California during July and August 2011 during E-PEACE. After the GCCN are introduced to a solid cloud, the aircraft samples the seeded air mass downstream from the seeding area with *in situ* measurements and with an airborne cloud radar.

This study shows that after seeding, the mean size of droplets increases, the number concentrations decrease and a tail of large droplets on the upper end of the cloud droplet size distribution appear. In contrast, in a case where a cloud is already precipitating, the effects of adding GCCN to the cloud is insignificant. The vertical distribution of the atmospheric aerosol for the days that seeding effects are visible shows slightly higher aerosol concentrations through out the boundary layer. The utility of the 95 GHz cloud radar observations in detecting drizzle stimulated by the addition of GCCN is shown in Fig. 3.

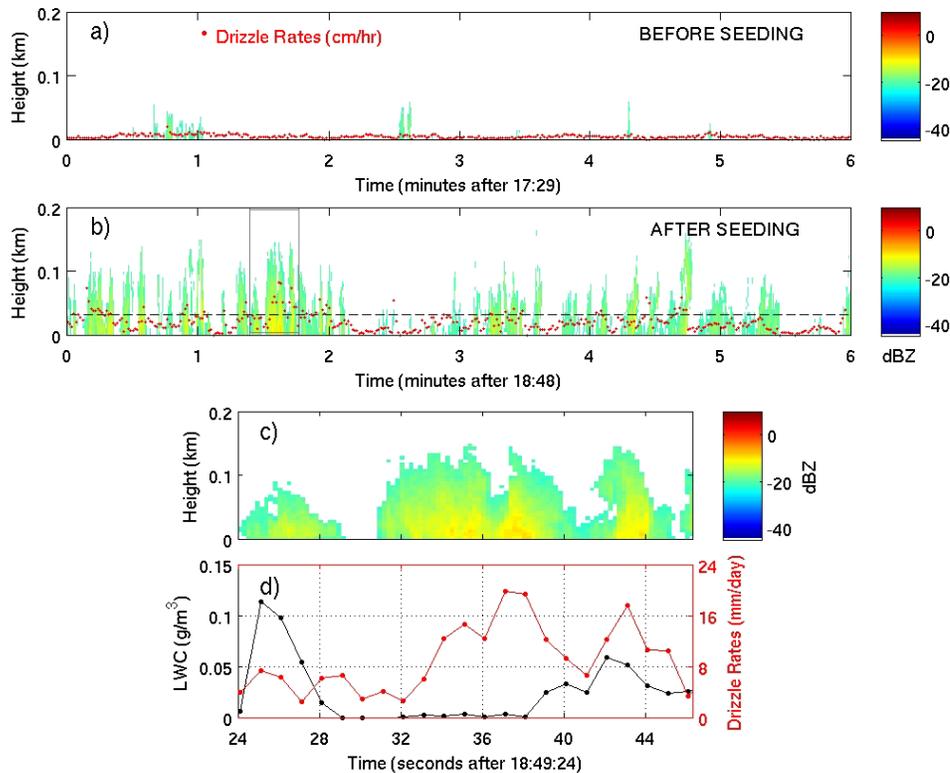


FIG. 3. (a) The radar reflectivity (in dBz, reflectivity Z is proportional to D^6 of droplet diameters) shows precipitation above the flight level from an upward facing 95-GHz cloud radar mounted on top of CIRPAS Twin Otter in (a) an area of cloud sampled before seeding (flight level 339 m) and (b) same air mass sampled after seeding (flight level 307 m). The drizzle rates (cm hr⁻¹) in (a) and (b) are estimated from the flight-level precipitation (CIP) probe. The outlined box in panel (b) indicates where a detailed analysis is made for (c) the radar reflectivity and (d) precipitation rate (from CIP) in mm/day and the cloud liquid water content (from PVM-100) in gm⁻³.

IMPACT/APPLICATIONS

Some innovative applications of a cloud radar that have developed under ONR support have been used to advance observational techniques for studying cloud processes and aerosol-cloud interactions. These techniques have the potential for further applications for studying clear air circulations in and around clouds. The chaff studies point to the potential of using shortwave-length scanning radars to track three-dimensional air motions in and around clouds time and to tag and track movements of air masses of interest.

PUBLICATIONS

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HONORS/AWARDS/PRIZES

2013 -- American Meteorological Society Teaching Excellence Award