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; and 5) explore mass, moisture, and aerosol transports across interfacial regions at cloud base and at the capping inversion.

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.

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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 rawindsonde 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 where 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.

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^{o} 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. Rapidly dissipating clouds (life-times of less than 10-15 minutes) were probed on several occasions by cloud penetrations starting from cloud top and working downward with time. The time evolution of these strongly precipitating clouds and the relative role of precipitation and evaporation (through entrainment) in explaining these results are under study. The observations have been used to develop a statistical description of the aerosol, cloud, and precipitation properties in the undisturbed trade-wind boundary layer. The relationship between the cloud droplet concentrations N_d and the updraft/downdraft velocities (w') at cloud base are shown in Fig. 2. The slope of N_d (as well as the subcloud layer cloud condensation nuclei (CCN)) as a function of updraft velocities (w'>0) varies by a factor of 2 between the pristine and the high aerosol cases studied. These relationships provide a means for evaluating and developing parameterizations for models that predict cloud microphysical processes.

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 days with non-precipitating or weakly precipitating clouds (<-20 dBz) tend to show higher reflectivity associated with updrafts with a relatively narrow range of reflectivity. 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.

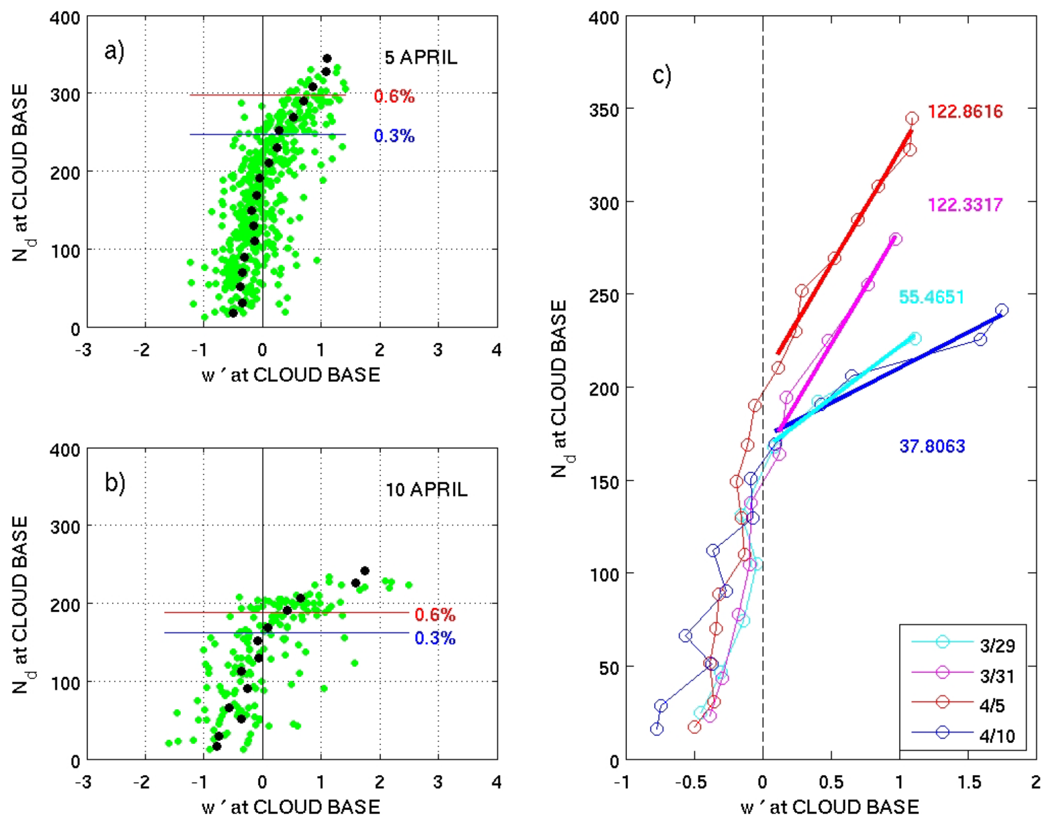

Figure 1.The N_d versus w′ at cloud base for (a) polluted (5 April) and (b) pristine (10 April) environments. Green dots in a) and b)indicate all the data points for the day. Cloud-base N_d is averaged for 20 cm^{-3}-interval and is shown as black dots. The mean values of sub-cloud CCNs (0.3 % and 0.6 %) are shown as horizontal lines with labeled accordingly. The mean profiles of N_d v.s. w′ for two pristine (29 March, 10 April) and dusty (31 March and 5 April) cases are shown in c) with slopes (dN_d/dw') estimated for the regime of w′ > 0.

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. An overview of the relationship between the mixing ratio and the aerosol structures for these two days are shown in Fig. 3. 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, 2012a).

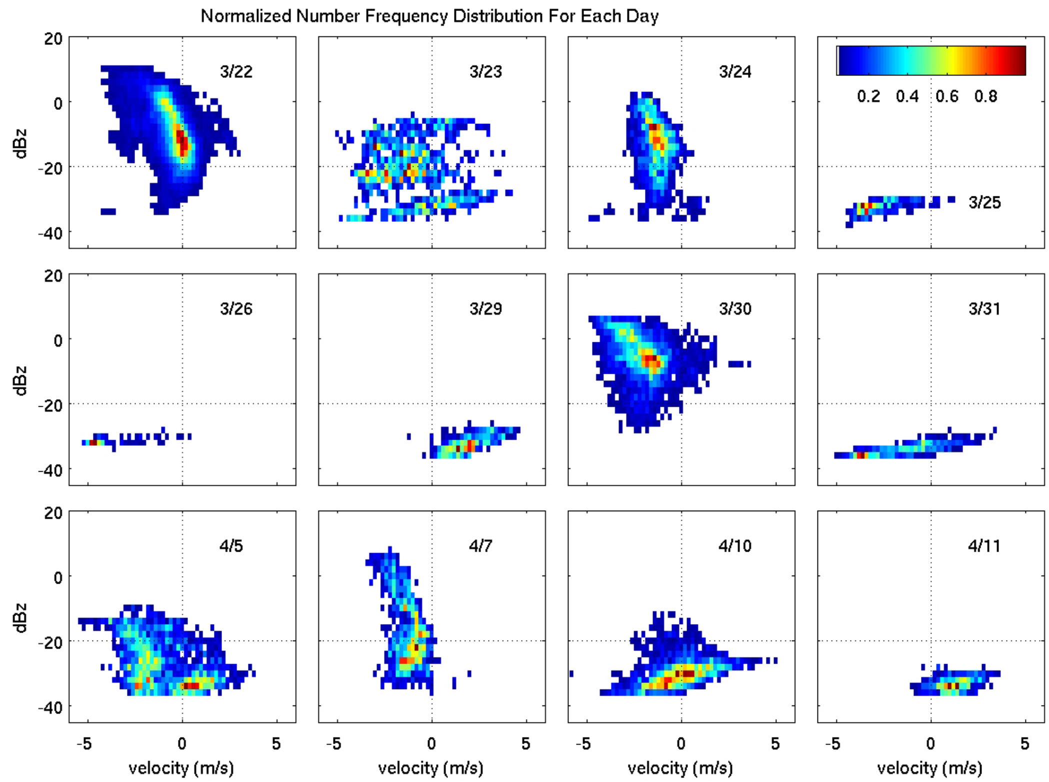

Fig. 2. Normalized velocity-reflectivity number frequency distribution on each day during BACEX. Color bar is shown in upper right corner. Reflectivity of -20 dBz and Doppler velocity of 0 m s^{-1} are denoted by dotted line. No clouds are observed on 1-2 April during the cloud-base level flights.

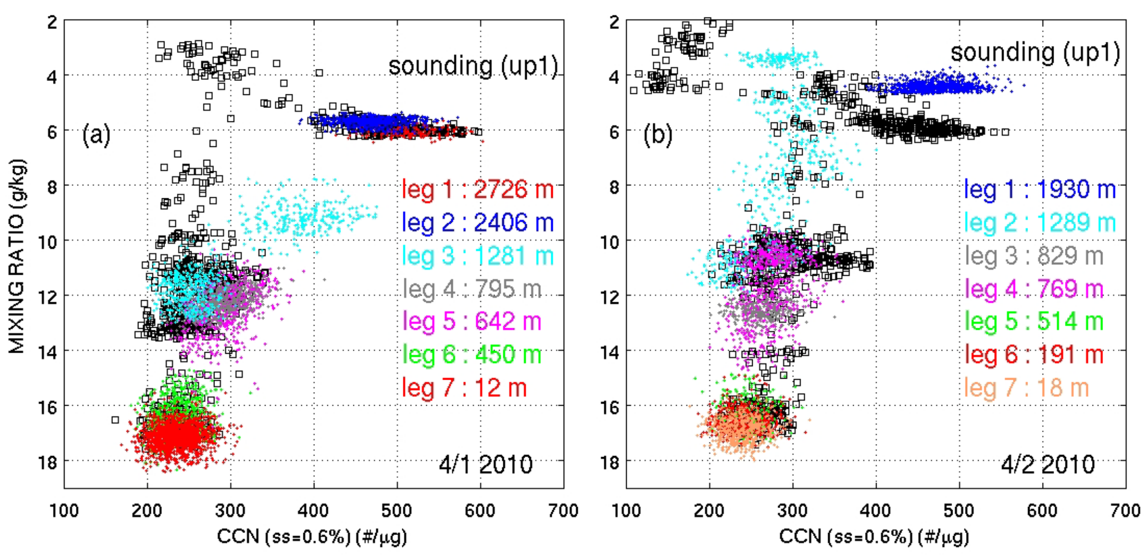

Fig3. Mixing diagram of cloud condensation nuclei CCN (0.6 %) per mass (µg^{-1}) and mixing ratio (g kg^{-1}) on (a) 1 April and (b) 2 April, 2010. Black squares are obtained from the ascent environmental soundings and colored dots are obtained from each level run. (a): leg 1(above SAL), leg 2 (SAL), legs 3-5 (IL), legs 6-7 (SCL), (b): leg 1 (SAL), legs 2-4 (IL), legs 5-7 (SCL).

Two new techniques for using an airborne cloud radar for probing air motions in precipitating clouds and tracking circulation in the clear air around and beneath the cloud were demonstrated during BACEX. The first is based on a technique that allows for the retrieval of vertical air motion from an airborne W-Band radar using Mie scattering thumbprints in the radar Doppler spectrum. In cases where raindrops have diameters comparable to the wavelength (3.2 mm) of the 95-GHz radar, Mie scattering explains the oscillation of the backscattering cross section between successive peaks and valleys as a function of the raindrop diameter. The minimum in the Doppler spectrum can then be used to determine the air vertical velocity (Kollias et al., 2003). At radar wavelengths of 3 mm, the first minimum in the backscattering cross section occurs at a raindrop diameter equal to 1.65 mm. Despite the relatively shallow nature of the convection observed on the BACEX flights (tops at 1.5-2 km), raindrops exceeding this diameter were observed on several occasions and allowed us to make a first-ever successful test of this technique from an aircraft. Further demonstration of this technique was made from observations made in precipitating cumulus clouds observed during KWACEX. The work completed on Mie technique from BACEX is described in a manuscript submitted to the *J. Appl. Meteor. and Climate* (Jung et al., 2012b).

The second technique demonstrated was the use of radar chaff to track motions associated with entrainment and detrainment processes at the top and edges of cumulus clouds 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 1/4 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. After the chaff was dispensed near cloud top, the aircraft made penetrations of the cloud at lower levels to observe the chaff clouds above with the radar. This technique also 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. This work is described in a manuscript submitted to *J. Appl. Meteor. and Climate* (Jung et al., 2012 c).

IMPACT/APPLICATIONS

The results from these studies are intended to provide an improved understanding of the physical processes associated with cloud-aerosol-drizzle-turbulence interaction that will lead the way to improved representation of the processes in models operating over a wide range of scale and particularly for mesoscale and large-scale forecast models used in coastal and marine environments. The successful completion of the VOCALS Twin Otter observational period has already produced results that show a positive correlation in the CCN concentration in the boundary layer with the observed LWP. The variations are substantial and the reasons for these changes are under study. The aircraft observations that were obtained during VOCALS have been used for evaluation of the COAMPS real-time forecast (Wang et al., 2011) and for investigating the role of shear in the boundary layer on the cloud and boundary layer structure (Wang et al, 2012).

The air velocity (Mie minimum) retrieval technique that was demonstrated from the BACEX observations has important implications for future observational studies. Using a downward looking cloud radar (95 GHz) one could, for example, retrieve the updraft and downdraft structures in tropical cyclone rainbands in radar sampling volumes extending from the aircraft to the ocean surface. A radar designed to operate at a shorter wavelength (e.g. 1 mm) could be used for retrieving air motion associated with smaller raindrops. The demonstration of the use of radar chaff optimally cut for use with a cloud radar provide a unique observational technique for understanding the flows in and around boundary layer clouds small cumulus and stratocumulus) and sets the way for future observational studies using this technique. If scanning cloud radars with differential polarization capabilities were used, the returns from cloud and chaff could be separated.

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