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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 will be 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. 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. For all of our studies with the CIRPAS Twin Otter we have collaborated closely with Dr. Haf Jonson at the Naval Postgraduate School on the analyses of the aersol, cloud, and mean state observations.

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. 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 19 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.

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 aerosol and cloud properties demonstrate clear variations over this region during the study with accumulation mode aerosols in the boundary layer varying from 200 - 700 cm^{-3}. Aerosol number concentrations above the boundary layer were substantially smaller than those below (50 - 250 cm-3) except for a two cases where these values were elevated. Cloud droplet concentration varied from 50-400 cm^{-3} over the18 flights. Drizzle water content varies from 10-5 to 0.05 g m^{-3} and 6 flights out of 18 flights have mean drizzle water content larger than 0.0015 g m^{-3}. Since the boundary layer conditions at this fixed point are so steady, the observations provide a unique data set for the evaluation of models operating at a variety of scales—from LES to large scale.

The boundary layer structures observed on several of the VOCALS flights were remarkably similar, although the observed aerosol concentrations in the boundary layer and the cloud water content and the liquid water path of the clouds topping the boundary layer varied considerably (Fig 1). On 10 of the flight days, the boundary layer was well mixed, the clouds sampled were non-precipitating, and conditions at the top and the bottom of the mixed layer were very similar. Calculated boundary layer back trajectories for the 72 hours prior to the observations at 20^{o}N and 72^{o}W remained mostly over coastal ocean areas and indicate that advective effects were generally small during this time. Thus the boundary layer, cloud and aerosol structures sampled on the individual days were likely to be steady and close to equilibrium. Despite the constancy of the thermodynamic structures of the boundary layers studied on these 10 flights, the subcloud CCN varied substantially and was closely coupled to the cloud droplet concentrations as well. CCN in the boundary layer for these cases ranged from 180-580 cm^{-3} in the relatively thin capping clouds. The liquid water path in these clouds ranged from 22 to 73 gm^{-2} and was positively correlated with the aerosol and cloud droplet concentrations (Fig. 2) as described in a GRL paper (Zheng et al., 2010). Processes that may link the aerosol concentrations and the liquid water path and explain the observed positive correlation are currently under study.

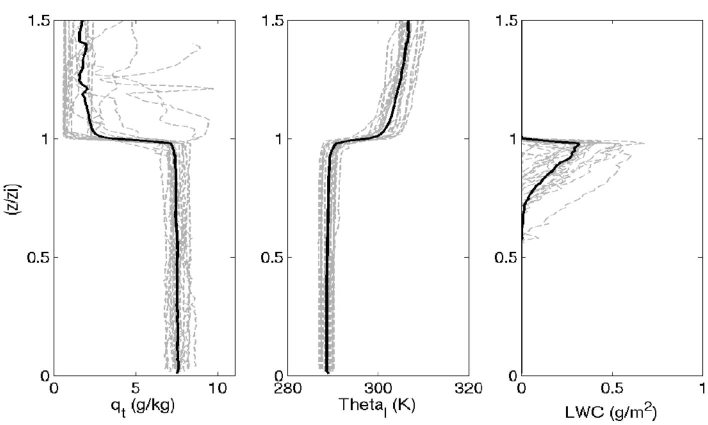

Figure 1. Profiles scaled by the PBL heights of a) total-water specific humidity (g/kg); b) liquid water potential temperature (K); and c) LWC (g m^{-2}) The gray lines arte for individual flights, and the black solid lines show the averaged soundings.

During BACEX the Twin Otter was able to sample many cumulus clouds in various phases of growth 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 principal variability in the background aerosols observed during these flights was associated with African dust above the boundary layer. On two days when convection was completely suppressed, an African dust event associated with near record 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 will be documented. Work is in progress to analyze the wealth of information collected on the flights flown during BACEX.

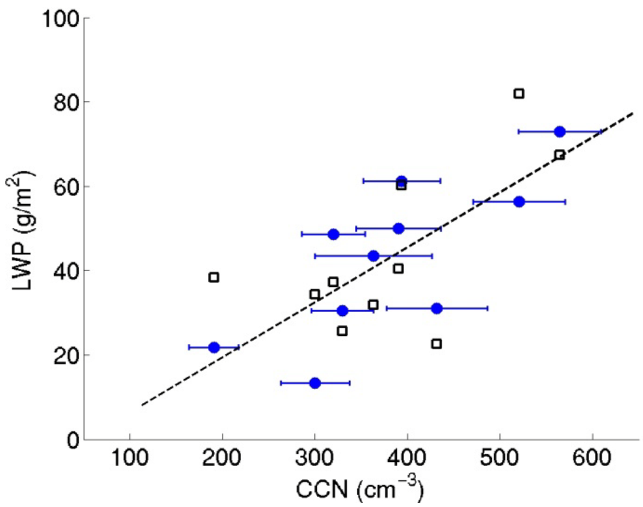

Figure 2. LWP as a function of sub-cloud CCN concentrations for selected 10 flights. Blue solid symbols are from aircraft profiles. The error bars through these symbols indicate the standard deviation of CCN. Open symbols are averages from GOES retrievals within radii of 20 km. Line is the best fit to the aircraft LWP estimates.

Two new techniques for using an airborne cloud radar for probing air motions in precipitating clouds and tracking circulations 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 spectra. 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 (Kollias et al, 2002). 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 1-2 km), raindrops exceeding this diameter were observed on several occasions. Thus, although, this technique has been successfully demonstrated using surface-based radars, the BACEX cases represent the first-ever application of this technique from observations from aW-band radar operating on an aircraft.

After the W-band radar Doppler velocities are corrected for aircraft motions, the vertical air velocity can then be deduced from the difference between the terminal velocity of a raindrop with a diameter of 1.65 mm and the value of the observed first minimum in the Doppler spectrum. Results from a case study based on observations made during BACEX are shown in Figure 3. The Doppler spectrum shown in the first panel shows a cloud extending about 1 km above the level of the aircraft. The strong radar returns from the precipitation in the cloud shows two well-defined maxima separated by a minimum. A maximum associated with the weaker returns is also shown. The velocities at the spectral peaks and the minimum are shown in the second panel. Since the minimum is associated with a droplet of 1.65 mm with a known terminal velocity, the air velocity can be obtained as the difference between the velocity at the Mie minimum and the terminal velocity. The velocity retrieved in this case gives the updraft structure shown in the third panel. In this case, the spectral peak associated with the returns from the cloud droplets, which have a negligible fall velocity, give an air velocity that is very close to that retrieved from the Mie minimum and provides a confirmation that has not been possible from previous ground-based radar measurements. The air velocities from the Mie minimum, which are available when drops larger than 1.65 mm are present, have a temporal resolution of 0.33 seconds. Further the spectral power allows for a retrieval of the relative raindrop distribution at the same temporal resolution.

The second technique demonstrated during BACEX was the use of radar chaff to track motions associated with entrainment processes at the top and edges of cumulus clouds and at the top of the atmospheric mixed layer using the airborne FMXW 95 GHz Doppler radar on the Twin Otter. The chaff used for this experiment was pre-cut metallic coated fibers (cut to an optimum length 1/4 of the wavelength of the radar) that were dispersed from canisters carried in dispenser designed and built for mounting beneath the wing of the CIRPAS Twin Otter. The fibers have a terminal velocity of about 2 cm/s and closely track air motions. The chaff experiments were designed to examine two types of entrainment processes. In one, chaff was dispersed near the top and the edge of small cumulus clouds. After the chaff was dispensed, the aircraft made penetrations of the cloud at lower levels to observe the chaff clouds above with the radar. In the second approach, chaff was dispensed just above the top of the mixed layer with subsequent levels flown in the mixed layer to observe the time evolution of the chaff clouds. The possibilities for further extending and improving this technique for tracking air motions and studying entrainment circulations are being pursued.

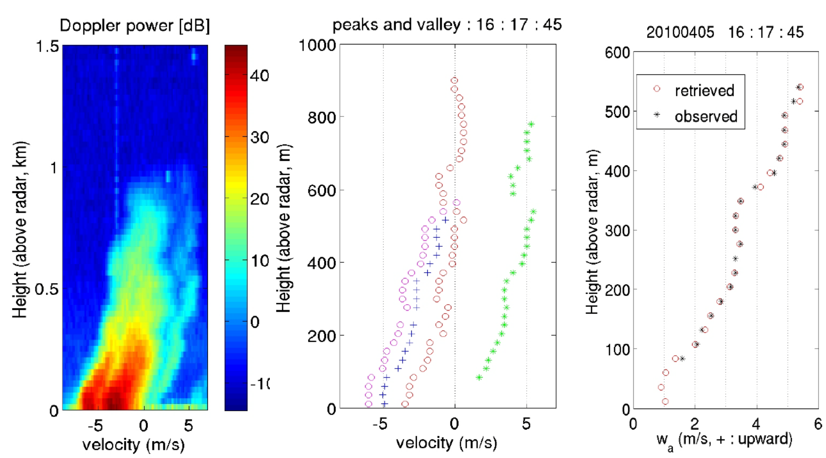

Figure 3: Vertical profiles of a) Doppler power; b) Mie peaks and minimum and cloud peak in the spectra, and c) retrieved air velocity fro the Mie minimum and that from the cloud peak (observed).

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 rang 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 NRL Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) was run by NRL scientists to provide real-time forecast for VOCALS-Rex from October 1 – November 30, 2009. One of the objectives of the real-time forecast is to comprehensively evaluate COAMPS's forecast of marine boundary layer structure. Twin-Otter research flights at "point alphat" (20S, 72W) provide excellent datasets for the COAMPS forecast evaluation. Shouping Wang at NRL at Monterey, working with the UM RSMAS team (Ph.D. student Xue Zheng), compared averaged COAMPS soundings with the Twin-Otter observations (Wang et al., 2010), as shown in Figure 4 where normalized thermal and wind profiles from both COAMPS and Twin-Otter are displayed. The results are follows: 1) The predicted temperature and moisture in the boundary layer are, in general, consistent with those from the observed; 2) Both COAMPS and observations show clear wind speed and directional shear across the inversion at the top of the PBL; 3) the COAMPS predicted PBL height (781 m) is considerably lower than that derived from the Twin-Otter soundings (1165 m), leading a significantly lower cloud water mixing ratio from COAMPS; and 4) the air above the inversion from COAMPS are cooler and more moist, in part, due to the lower PBL height. Currently, NRL scientists are looking into the issue of the underpredicted PBL height from COAMPS near the west coast of Chile (Wang et al., 2010). The Twin Otter observations at point alpha have also been integrated into the analyses obtained from other aircraft operating during VOCALS to provide a cross-section of the cloud aerosol, cloud, and boundary layer structures extending from point alpha westward at a latitude of 20°S (Bretherton et al., 2010).

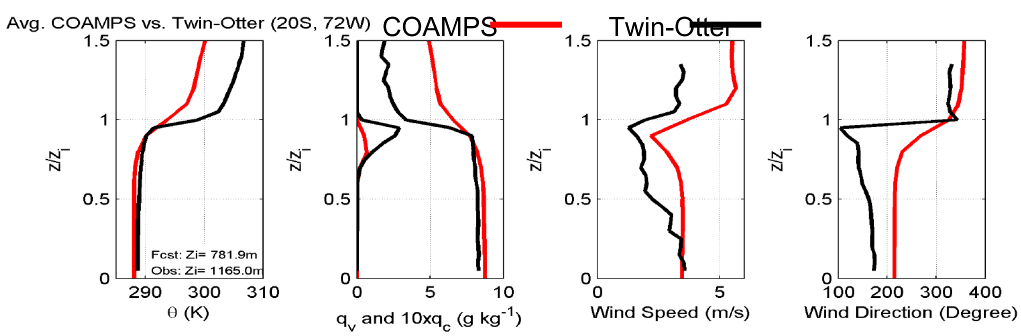

Figure 4. Evaluation of COAMPS real-time forecast using Twin-Otter soundings from VOCALS.

The results from the NRL COAMPS real-time mesoscale simulations are also being used with the Twin Otter analyses to use LES to unravel the possible effects of aerosol and synoptic-scale variability on the aerosol-liquid water path correlation. On the basis of the aircraft-COAMPS comparison, boundary layer structures are modified and used as initial conditions for LES simulations that will be made at points along boundary layer back trajectories. The LES results can then be compared with the aircraft observations to evaluate the validity of the simulations. An example from a sensitivity test made with an LES to examine the sensitivity of the solutions to the conditions at the top of the inversion is shown in Figure 5. The total water flux and the vertical velocity variance from the Twin Otter observations are compared with the simulations.

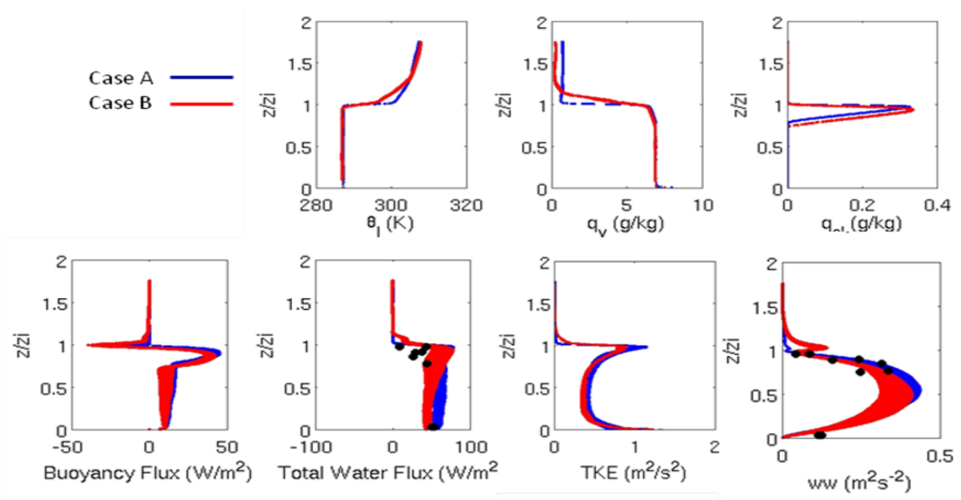

Figure 5. LES profile of mean state; (top), buoyancy flux, the total water flux, the turbulence kinetic energy (TKE) and the vertical velocity variance from the LES cases during the 4th hour bottom). The total water flux and the vertical velocity variance calculated from aircraft observations are marked as black dots.

The air velocity (Mie minimum) retrieval technique that was demonstrated from the BACEX observations has important implications for future observational studies using airbore cloud radars. Using a downward looking cloud radar (95 GHz), for example, the updraft and downdraft structures in tropical cyclone rainbands in radar samplingvolumes extending from the aircraft to the ocean surface could be retrieved. A radar designed to operate at a shorter wavelength (e.g. 1 mm) could be used for retrieving air motions in rain with raindrops smaller that 1 mm.

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HONORS/AWARDS/PRIZES

Elected Fellow of the American Meteorological Society, 2010