Final Scientific/Technical Report

Project Title: Collaborative Research: ARM Observations for the Development and Evaluation of Models and Parameterization; DOE No: DE-SC0000777

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This is a collaborative project with Dr. Ping Zhu at Florida International University. It was designed to address key issues regarding the treatment of boundary layer cloud processes in climate models with UM's research focusing on the analyses of ARM cloud radar observations from MMCR and WACR and FIU's research focusing on numerical simulations of boundary layer clouds. This project capitalized on recent advancements in the ARM Millimeter Cloud Radar (MMCR) processing and the development of the WACR (at the SGP) to provide high temporal and spatial resolution Doppler cloud radar measurements for characterizing in-cloud turbulence, large-eddy circulations, and high resolution cloud structures of direct relevance to high resolution numerical modeling studies. The principal focus of the observational component of this collaborative study during this funding period was on stratocumulus clouds over the SGP site and fair-weather cumuli over the Nauru site. The statistical descriptions of the vertical velocity structures in continental stratocumulus clouds and in the Nauru shallow cumuli that are part of this study represents the most comprehensive observations of the vertical velocities in boundary layer clouds to date and were done in collaboration with Drs. Virendra Ghate and Pavlos Kollias.

1) *Continental Stratocumulus Vertical Velocity Statistics:*

Continental boundary layer (BL) stratocumulus clouds affect the local weather by modulating the surface energy and moisture budgets and are also intimately tied to the diurnal cycle of the turbulence in the BL. Vertical velocity structures of these clouds were studied using data from the Atmospheric Radiation Measurements (ARM) Southern Great Plains (SGP) observing facility located near Lamont, Oklahoma. Data from the vertically pointing cloud radar from eleven cases of non-precipitating BL stratocumulus clouds (70 hours of observations) were used to obtain half hourly values of in-cloud vertical velocity variance, skewness, updraft fraction, downdraft fraction and mass-fluxes. Vertically coherent structures spanning through the entire cloud layer were identified and the mass fluxes associated with these structures were compared with the mass fluxes associated with temporally coherent structures. These temporally coherent structures eddies were found to contribute substantially to the mass fluxes at different updraft and downdraft velocities and had a greater contribution than those associated with vertically coherent eddies. Vertical velocity statistics were composited for cases associated with high and low surface buoyancy fluxes and comparisons of these composite statistics were made for these cases. The observations generated provide a means for evaluating cloud vertical velocity statistics generated by LES under different forcing conditions and for considering the effects that vertical velocity variability has on cloud nucleation processes in model parameterizations. This work is described in Ghate et al (2010) in *JGR.*

2) *Multi-scale Simulations of Continental Stratocumulus:*

This collaborative study with Dr. Ping Zhu introduces a flexible multiple nested modeling framework developed from the Weather Research & Forecasting (WRF) model for boundary layer cloud research. It features a nested large eddy simulation (LES) in a hindcasting mode that allows a direct comparison of simulations with high resolution remote sensing measurements, such as cloud radar observations. Using this approach, we simulated two stratocumulus cases observed in the southern Great Plains (SGP). The simulation-observation comparisons demonstrate that the multiple scale WRF not only captures the large-scale low cloud geographic distribution derived from the satellite observations but also well reproduces the cloud radar detected cloud properties and vertical velocity fields. The simulations show that (1) the cloud fields can be strongly modulated by mesoscale organizations; (2) the vertical velocity variance and skewness in the boundary layer have well-defined diurnal variations and are strongly dependent on the external forcings. But the in-cloud turbulent statistics appears to be more controlled by the internal turbulent processes; (3) the organized updraft-downdraft pairs of stratocumulus are only slightly skewed, which is consistent with the cloud radar observations that the updraft fraction and downdraft fraction are close to 50%; and (4) the vertical distribution of mean cloud water content and the associated high-order moments depend strongly on the vertical profiles of the mean mixing ratio. This study suggests that the multiple scale WRF modeling system has a potential to be developed into a stand-alone parameterization testbed in a weather hindcasting mode that can be used to address various issues regarding the parameterization of boundary layer clouds. This work is reported in Zhu et al (2010) in JGR.

3) Turbulence Dissipation Rates in Continental Stratocumulus Clouds:

A method for retrieving turbulence dissipation rates in a stratocumulus clouds using the Doppler spectral width is developed and evaluated using 16 consecutive hours of stratocumulus clouds observed at the SGP. In this case, the latent and virtual sensible heat fluxes at the surface and the cloud top radiative cooling at cloud top exhibit a strong diurnal cycle and mid level clouds present during other periods also reduce the cloud-top cooling. The signatures of these forcings are found in the resolvable scale turbulence and the dissipation rates for three different time periods (Fig. 1). The vertical integral length scale (an important parameter for the parmeterization of turbulence effects in models) is found to be smaller at night when the convection is mainly driven by cloud-top cooling. The strongest in-cloud turbulence appears around noon and the weakest turbulence appears around sunset when a mid-level cloud also reduces the long-wave cooling at cloud top. Also in the normalized coordinate system, the averaged coherent structure of updrafts is characterized by low energy dissipation rate (EDR) in the updraft core and higher EDR values surround the updraft core at the top and along the edges. In contrast to that in the updraft, EDR is higher inside the downdraft core. Compared with the updraft, the downdraft core is more turbulent. For both updrafts and downdrafts, the maximum EDR occurs at 0.8 of the cloud depth where the maximum reflectivity and air accelerations or decelerations are observed. Resolved turbulence dominates near cloud base whereas unresolved turbulence dominates near cloud top. This study illustrates the utility of using Doppler spectrum width from millimeter wavelength radars to provide high temporal resolution EDR in non-precipitating clouds. This work is described in two manuscripts that have been submitted (Fang et al., 2012 a,b) to *Bound. Layer Meteor.*

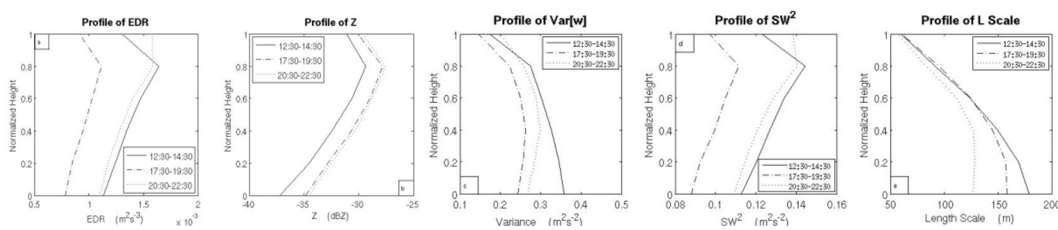

Figure 1. Profiles of eddy dissipation rates, cloud reflectivity, vertical velocity variance, square of the spectrum width, and the vertical integral length scale at different periods of the 16 hours of observations (on 26 March 2005) used for the dissipation rate studies. During the day-time period (12:30-14:30) turbulence is generated by surface buoyancy fluxes and cloud-top cooling is reduced by solar heating. During the night-time period 20:30-22:30) turbulence is generated by cloud top radiaitve cooling.

Fair-Weather Cumuli Vertical Velocity Statistics:

Fair-weather cumuli are fundamental in regulating the vertical structure of water vapor and entropy in the lowest 2-3 km of the Earth's atmosphere over vast areas of the oceans. In this study, a long record of profiling cloud radar observations at the Atmospheric Radiation Program (ARM) Climate Research Facility (ACRF) at Nauru Island is used to investigate cloud vertical air motion statistics over an 8 year observing period. Appropriate processing of the observed low radar reflectivities provides radar volume samples that contain only small cloud droplets; thus the Doppler velocities are used as air motion tracers. The technique is applied to shallow boundary layer clouds (less than 1000 m thick) observed from 1999-2007 when radar data are available. Using the boundary layer winds from the soundings obtained at the Nauru ACRF, the fair-weather cumuli fields are classified into easterly and westerly boundary layer wind regimes. This distinction is necessary to separate marine forced (westerlies) from land forced (easterlies) shallow clouds due to a well-studied island effect at the Nauru ACRF. The two regimes exhibit large diurnal difference in cloud fraction and cloud dynamics as manifested by the analysis of the hourly-averaged vertical air motion statistics. The fair weather cumuli fields associated with easterlies exhibit a strong diurnal cycle in cloud fraction and updraft strength and fraction indicating a strong influence of land-forced clouds. In contrast over the fair-weather cumuli with oceanic origin are characterized by uniform diurnal cloudiness and persistent updrafts at the cloud base level. This study provides a unique observational data set appropriate for testing fair weather cumulus mass flux and turbulence parameterizations in numerical models. This work is described in Kollias and Albrecht (2010) in *Journal of Climate.*

4) ***Fair-Weather Cumulus Cloudiness:***

The night-time cumulus mass fluxes and cloud draft statistics for 1999-2000 (an undisturbed period with little precipitation) of the Nauru study are used to evaluate the observed cloudiness and cloud-base mass flux distributions from a simple mixed layer formulation of the sub-cloud layer. This mixed layer model is found to be a very good representation of the convective-radiative equilibrium state of the sucloud layer on monthly time scales. The convective velocity scale and the static stability at cloud base from the mixed layer model and observed thermodynamic profiles are used to estimate cloud base mass fluxes with different parameterizations for comparison with the radar observed cloud base mass fluxes. Figure 2 shows the monthly observed fractional cloudiness from the ceilometers as a function of the convective velocity scale w* and the cumulus cloud base mass flux. The decrease of the fractional cloudiness is counter intuitive and work is in progress to understand what factors control the fractional cloudiness. LES radiative-convective equilibrium case studies during selected times of the 1999-2000 Nauru observations will be developed to allow for a full comparison of LES cloud statistics with cloud statistics from the radar under different large-scale conditions. This work is described in two manuscripts under preparation (Albrecht and Ghate, 2012 and Albrecht et al, 2012) for submission to *J. Climate*.

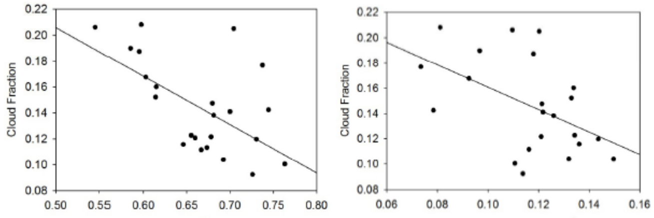

Figure 2: Monthly fractional cloudiness from Nauru ceilometers for the period 1999-2001as a function of the mixed layer convective velocity w and the cumulus cloud base mass flux.*

Publications supported under grant:

Zhu, P., B. A. Albrecht, V. P. Ghate and Z-D. Zhu, 2010: Multiple scale simulations of stratocumulus clouds. *J. Geophys. Res*., **115**, D23201, doi:10.1029/2010JD014400

Ghate, V. P., B. A. Albrecht and P. Kollias, 2010: Vertical velocity structure of non-precipitating continental boundary layer stratocumulus clouds. *J. Geophys. Res*., **115**, D13204, doi:10.1029/2009JD013091M.

Fang, B. Albrecht, V. Ghate, P. Kollias, 2012a: Turbulence in Continental Stratocumulus Part I: External Forcings and Turbulence Structures. *Bound. Layer Meteor.* (accepted subject to revision)

M. Fang, B. Albrecht, V. Ghate, P. Kollias, 2012b: Turbulence in Continental Stratocumulus Part II: Eddy Dissipation Rates and Large Eddy Coherent Structures *Bound. Layer Meteor.* (accepted subject to revision)

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Albrecht, B. and V. Ghate, 2012a: Radiative-convective equilibrium in the tropical marine atmospheric mixed layer capped by small cumuli. Part I: Fluxes and temperature and moisture coupling. *J. Climate* (to be submitted)

Albrecht B., V. Ghate, and P. Kollias 2012b: Radiative-convective equilibrium in the marine atmospheric mixed layer capped by small cumuli. Part II: Links to cloudiness and cumulus mass fluxes. *J. Climate* (to be submitted)