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Title: "Boundary Layer Cloudiness Parameterizations Using ARM Observations"

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This study used DOE ARM data and facilities to: 1) study macroscopic properties of continental stratus clouds at SGP and the factors controlling these properties, 2) develop a scientific basis for understanding the processes responsible for the formation of boundary layer clouds using ARM observations in conjunction with simple parametric models and LES, and 3) evaluate cumulus cloud characteristics retrieved from the MMCR operating at TWP-Nauru. In addition we have used high resolution 94 GHz observations of boundary layer clouds and precipitation to: 1) develop techniques for using high temporal resolution Doppler velocities to study large-eddy circulations and turbulence in boundary layer clouds and estimate the limitations of using current and past MMCR data for boundary layer cloud studies, 2) evaluate the capability and limitations of the current MMCR data for estimating reflectivity, vertical velocities, and spectral under low-signal-to-noise conditions associated with weak non-precipitating clouds, 3) develop possible sampling modes for the new MMCR processors to allow for adequate sampling of boundary layer clouds, and 4) retrieve updraft and downdraft structures under precipitating conditions.

A. *Stratus Cloud Climatology Statistics*

Observations from the Belfort ceilometer and the micro-pulse lidar were used to identify periods when boundary layer clouds are present over the SGP site from 1996 to present. Hourly statistics for this period provide cloud base height, lifting condensation level, surface meteorology, liquid water path, and surface fluxes of heat and moisture. Cloud-top height and cloud thickness have only been compiled for the late fall and winter months in 1997, since the detection of non-meteorological targets (NMT) by the MMCR complicate the retrieval of cloud top. All the cloud cases from 1997 were subjectively classified into synoptic classifications. These results indicate the seasonal variability and the wide-range of synoptic conditions, particularly in the wind profiles, associated with stratus clouds observed at the SGP site. A web page at the University of Miami designed specifically for the ARM project (http://orca.rsmas.miami.edu/arm/index.html) provides images for 1996-2001 products. The archive gives the research community access to more closely screened data sets (both processed data files and images) of individual stratus cloud cases. The archive also provides a subset of data for investigators who want to focus on stratus clouds for both process and modeling studies without having to search through all of the ARM data to identify these cases. A continental boundary layer cloud case study for the a model inter-comparison performed by the GCSS-WG1 [GEWEX (Global Water and Energy Experiment)] was selected from this ARM data set (Brown et al.,2001). Examples of some of the long-term cloud statistics from this data set are shown in Fig. 3 along with analyses from LES simulation applied to particular cases.

B. *Process Studies and Cumulus Parameterization*

Studies were made of the processes responsible for the formation of stratus clouds and the fractional amount of boundary layer clouds. These studies focus on formation of nocturnal stratus under stable conditions and the daytime development of boundary layer clouds under unstable conditions. For the nocturnal stratus the importance of wind shear for cloud formation is considered. For the daytime stratus studies, the focus is on the diurnal cycle and the coupling between the clouds and the LCL. These studies use case studies to demonstrate key processes that can then be used to develop strategies for developing more extensive statistical analyses

using the ARM data bases. The observations from the boundary, intermediate, and extended facilities surrounding the central SGP are used to define mesoscale variability for these studies. To further consider mesoscale effects and to study land-atmosphere interactions, the Regional Atmospheric Modeling System (RAMS) has been used to predict boundary layer cloud development using ARM data to initialize the model and evaluate the simulated cloud formation. Case studies made during clear and cloudy nighttime conditions have shown the role of wind shear on cloud formation. This work is described in Zhu and Albrecht (2001).

The utility of the ARM data for further study of daytime cases associated with boundary layer clouds has also been clearly demonstrated. A full characterization of the cloud and boundary layer evolution for the diurnal cases are being made for a wide range of cases. The validity of simple mixed layer theory for defining the evolution of the mean LCL and the boundary layer depth has been used to study the processes leading to cloud onset. The role of surface processes on the entrainment fluxes on development is considered in detail. This work is also part of Ping Zhu's dissertation research and is described in Zhu and Albrecht (2002). Further investigation of boundary layer cloud initiation and development has been made using SGP ARM observations in conjunction with large eddy simulations of fair-weather cumuli. These simulations indicate that the evolution of clouds is very sensitive to the initial vertical structure of moisture and the entrainment moisture fluxes. A new parameterization of boundary layer cloudiness for continental fair-weather cumuli has been developed (Zhu and Albrecht, 2003).

C. Large-Eddy Observations in Support of Large Eddy Simulations (LEO for LES)

Techniques were developed for examining the turbulence structure of stratus clouds and for testing simple mass flux representations of the vertical velocity fields in the clouds. As part of this, the turbulent-scale vertical velocity structure in a continental stratocumulus cloud (8 hours of 2-s data) was studied using a 3-mm wavelength Doppler radar operating in a vertically pointing mode. This study illustrated the use of cloud radar vertical velocities for comparing directly observed updraft fractional coverage and mass flux with those obtained from the bulk statistics. These comparisons are remarkably consistent with similar comparisons made using LES models. Decomposition of the variances has been used to examine the validity of mass flux representations that are used in some boundary layer parameterizations. This study further illustrates the utility of mm-wavelength radars for studying turbulence in boundary layer clouds and particularly in defining the vertical structure of coherent eddies (LEO) that can be compared with LES and CRMs. This work is described in Kollias and Albrecht (2000).

Observations have also been made in fair-weather cumuli sampled by the UM Radar during operations in South Florida. These detailed cloud radar observations (Kollias et al., 2001) demonstrate the utility of using high temporal resolution radar observations and demonstrate techniques for describing updraft-downdraft characteristics and turbulence structure in fair-weather cumuli including turbulence dissipation rates in updraft cores.

These high-resolution (2s) data from the stratus and the fair-weather cases were used to evaluate the potential of using the MMCRs to define the small-scale structure of boundary layer clouds. This was done by degrading the high-resolution data to the ARM MMCRs temporal-spatial resolution and comparing various statistically derived properties of the cloud structures (e.g.

cloud boundaries detail, vertical velocity variance, cloud reflectivity homogeneity). This evaluation indicates the inadequacies of using the old MMCR signal processing for detailed resolution of the internal circulations in fair-weather cumuli

A method for using 94 GHz Doppler observations in precipitating clouds for obtaining vertical air motions under precipitating conditions has been developed and demonstrated. This technique makes use of the Mie oscillations features in the backscattered signals associated with large raindrops. This technique also provides raindrop size distributions. It was demonstrated that high temporal resolution vertical velocities obtained in tropical stratiform rain are sufficiently accurate to define boundary layer turbulence. Although there are no immediate applications of this technique to the current ARM instruments, there are plans to operate a Doppler 94 GHz radar at the SGP site in the future. A review of this technique is provided in Kollias et al. (2002) additional results are shown in Kollias et al. (2003). Techniques have also been developed retrieving properties of mixed-phase clouds Shuoe et al.(2004).

D. Fair -Weather Cumulus Climatology at the TWP ARM Site.

Over two years of data from the MMCR, at the TWP-Nauru site (ARSCL VAP datafiles), are analyzed to provide a statistical description of the fields of fair weather cumuli observed at this site. In addition, sounding and surface meteorology data from both the Manus and Nauru sites were analyzed and used to classify tropical boundary layer structures as a function of simple stability criteria. Furthermore we investigated the island effect (e.g. enhance cloud cover fraction) by partitioning the data for different wind conditions (onshore-offshore). Statistics on cloud thickness, fractional coverage, updraft-downdraft magnitudes and cloud reflectivity are estimated for four classes of fair weather cumuli. Seasonal patterns are identified and their relationship to the thermodynamic structure of the boundary layer (wet-dry periods, available buoyancy and wind direction) is investigated. This study provides an observational data set appropriate for testing fair weather cumulus fractional coverage parameterizations in numerical models. Results were presented at the 2002 ARM meeting.   Examples of the mean cloud statistics from this study are shown in Fig. 2. The daily fractional coverage of fair-weather cumulus over the ARM-TWP site is around 0.30-0.35 without any significant seasonal variation. The diurnal cycle of fractional coverage exhibits a maximum of 0.4 around local noon and a minimum of 0.3 during the nighttime. The cycle indicates a possible enhancement of the day-time cloudiness due to island heating.

E. MMCR Evaluations and Recommendations for Boundary Layer Studies

The study of fair weather cumuli clouds at the TWP-Nauru site was used to evaluate the performance of the ARM mm-wavelength cloud radar (MMCRs). Fair weather cumuli are relatively small, weak radar targets. Despite their excellent sensitivity, the ARM MMCRs have difficulties observing these clouds. Another factor that complicates the detection of low-level broken cloud field by the MMCRs is the necessity for different modes of operations that allow for measurements in all types of clouds.

Comprehensive evaluation of the broken cloud observations from the Nauru MMCR indicates that under low Signal-to-Noise conditions, large errors are introduced in the Doppler moments

(e.g. 3-6 dB uncertainty for the reflectivity). At these conditions it is important to quantify the error bars in the Doppler moment estimates, especially the cloud reflectivity that is often used for cloud properties retrievals. Observations from all the ARM sites were analyzed to quantify how often and for what type of clouds the MMCRs observed weak returns (low SNR) from clouds. Doppler signal simulations and theoretical studies on the performance of the Doppler moment estimator at low SNR were used to evaluate the error bars of the Doppler estimates as a function of the SNR (Kollias et al., 2004a).

"Anomalous" behavior of the receiver noise variance is shown in Fig 2. When the cloud return is strong, variations of the instrument noise do not affect the Doppler moment estimates. However, at low SNR the noise variance is a large source of uncertainty especially since the analog-digital transfer function relating input SNR to cloud reflectivity is very sensitive to small fluctuations of the noise at low SNRs. In addition to the coarse sampling, the narrow Nyquist boundaries introduced by signal coherent integration introduces bias of the Doppler moments and filters out a small but important fraction of observations.

Using high-resolution data collected by the Univ. of Miami 94-GHz cloud radar for a variety of clouds, we evaluated the performance of the current operating modes for cloud detection, cloud boundaries, microphysical/optical and turbulence retrievals. This evaluation served as the basis for the design of a new set of operational modes for use with the new Digital Signal Processor (faster with more memory than its preprocessor) that that are being implemented at the ARM sites. These modes are currently proposed to the Cloud Properties Working Group (ARM Science meeting, 2002) and being evaluated for implementation by the instrument mentors (Kollias et al. 2004 b).

Another important issue is the development of a new merging radar mode data for the next generation of the Active Remote Sensing of Clouds (ARSCL) product. The merging of the modes to a 10 sec data product is a monumental task. Despite its sophisticated structure, the ARSCL merging algorithm cannot eliminate the Doppler moment errors introduced at low SNR or through the interpolation of the 10-20 sec temporal resolution data due to the highly variable in-cloud structure. The new merging strategy will take advantage of the higher temporal sampling, will introduce a QC based on radar noise, SNR, and higher Doppler moments and will include error estimates for all three estimates

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