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FY 2010 Fourth Quarter Report Evaluation of the Dependency of Drizzle Formation on Aerosol Properties

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1.0 Statement of the Metric

Metric for Quarter 4: Report results of implementation of composite parameterization in single-column model (SCM) to explore the dependency of drizzle formation on aerosol properties.
To better represent VOCALS conditions during a test flight, the Liu-Duam-McGraw (LDM) drizzle parameterization is implemented in the high-resolution Weather Research and Forecasting (WRF) model, as well as in the single-column Community Atmosphere Model (CAM), to explore this dependency.

2.0 Introduction

During October and November 2008, Brookhaven National Laboratory (BNL) participated in VOCALS (VAMOS Ocean-Cloud-Atmosphere Land Study), a multi-agency, multi-national atmospheric sampling field campaign conducted over the Pacific Ocean off the coast of Arica, Chile. Support for BNL came from the U.S. Department of Energy's (DOE) Atmospheric Science Program (ASP), which is now part of Atmospheric System Research (ASR) following its merger with DOE's Atmospheric Radiation Measurement (ARM) Program. A description of the VOCALS field campaign can be found at:

http://www.eol.ucar.edu/projects/vocals/

Archived data products are at:

ftp://ftp.asd.bnl.gov/pub/ASP%20Field%20Programs/2008VOCALS/Processed_Data/

The DOE's ARM Climate Research Facility (http://www.arm.gov) provides long-term observations for driving a hierarchy of modeling study and parameterization evaluation. Some selected forcing and model evaluation data are archived at http://faster.arm.gov/data/, extracted from ARM's Data Archive, and further processed and managed by the FASTER project at BNL.

The files used in the fourth-quarter metric report are listed in Table 1.

Table 1. Archived data used in Fourth Quarter Metric.

Data	Files	Last Modified
CCN Concentration	General	05/12/2009
SCM Forcing data	Variational Analysis Product	07/26/2010

2.1 Definition of the LDM Parameterization

The LDM parameterization is a new parameterization based on the idea that drizzle formation is a statistical barrier-crossing phenomenon that transforms cloud droplets to much larger drizzle size at a rate dependent on turbulent diffusion, droplet collection efficiency, and properties of the underlying cloud droplet size distribution. The complete derivation and description of the LDM parameterization is in Liu et al. (2005). Given cloud droplet number concentration N_D in 1/cm^3, and non-dimensional volume mixing ratio of cloud droplet L in cm^3/cm^3, the LDM parameterization defines the drizzle rate as

$$P = T_{LDM} \times \kappa\beta^6 N_D^{-1} L^3 \tag{1}$$

Where T_{LDM} is the threshold function having the form of

$$T_{LDM} = \frac{1}{2}(x_c^2 + 2x_c + 2)(1 + x_c)e^{-2x_c} \tag{2}$$

with x_c, the reduced critical mass as follows,

$$x_c = 9.7 \times 10^{-17} N_D^{3/2} L^{-2} \tag{3}$$

$\kappa = 1.1 \times 10^{10}$ g^{-2} cm^3 s^{-1}, and β depends on the relative dispersion of cloud droplet size distribution. In this report, for simplicity, the relative dispersion is not considered, hence β =1 is applied.

2.2 Implementation of the LDM Parameterization

The LDM parameterization focuses on the autoconversion of cloud water to form rain. The formulation requires the information about droplet number concentration N_D and volume fraction of cloud liquid water L. It is not directly responsible for the prediction of N_D or L. For this sake, the implementation of the LDM parameterization is realized by using an existing two-moment cloud microphysics in WRF or CAM as a shell. The shell scheme also handles the contribution due to macroscale condensation and evaporation. The implementation is accomplished by using the LDM parameterization to replace the Cohard and Pinty (2000) autoconversion formulation in WRF Double-Moment 5 class (WDM5, Lim and Hong 2010) scheme in the WRF model, and the Khairoutdinov and Kogan (2000) autoconversion in the Morrison and Gettelman two-moment scheme (Morrison and Gettelman 2008) used in the CAM model.

2.3 Model Configurations and Case Selection

Two modeling frameworks are used in this exploration: cloud-resolving simulation using multiple nesting of the WRF model, and single-column model simulation using the CAM model. The most recent releases of Advanced Research WRF version 3.2.1 (Shamarock et al. 2008) and CAM version 5 (Neale et al. 2010) are employed. CAM5 is the atmospheric model component of the Community Earth System Model (CESM). Both types of simulations are based on real-case settings, to couple as closely as possible with realistic meteorological conditions and lower boundary surface flux exchanges.

For WRF-based simulation, the multiple nesting to cloud-resolving resolution is the most feasible approach to realize the small-scale features embedded in the operational large-scale analysis through dynamical downscaling. These small-scale features may be the key ingredient that promotes the formation and growth of clouds and precipitation, but are observationally unavailable or perhaps even unobservable.

In the second quarter metric report, the measurements from the G-1 flight on October 28, 2008 during VOCALS field campaign were found to capture a cloudy day with drizzle condition (Figure 2, McGraw et al. 2010), in companion with a CCN gradient that gradually decreases away from the coast. The LDM threshold parameterization was also found to be a strong indicator for the intensity of drizzle. This case is an ideal fit for the current metric report to explore the effect of aerosol properties on drizzle formation.

A three-domain WRF model nesting (Figure 1) is configured to simulate this cloudy case with drizzle. The horizontal resolutions are 18 km, 6 km, and 2 km. Time step for the finest domain is 10 seconds. The horizontal span of the 2-km resolution domain closely matches the G-1 flight range. The NCEP FNL (Final) Operational Global Analysis data at 1°x1° resolution, available 6 hourly, are used to initialize the model and define the lateral and lower boundary conditions (e.g., skin temperature as SST in the WRF real case simulations). The FNL analysis data are obtained from the NCAR CISL (Computational and Information System laboratory) Research Data Archive.

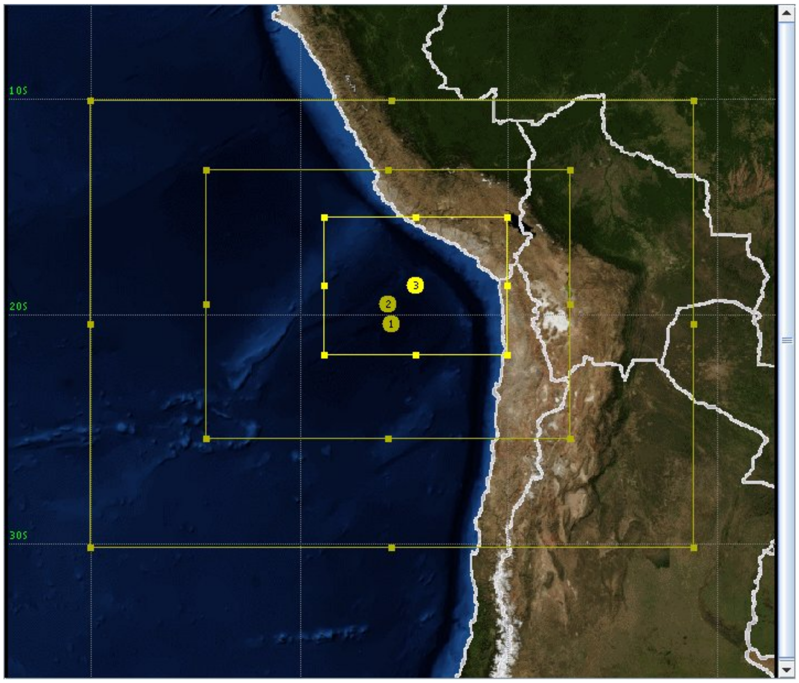

Figure 1. WRF 3-domain nesting configuration. The innermost domain has horizontal resolution at 2 km. The east-west span of the finest domain closely matches the October 28 G-1 flight range.

For single-column CAM simulation, the key is to provide carefully constructed large-scale forcing conditions to allow model physics parameterizations to generate cloud and precipitation. Such forcing products are not available during the VOCALS period. Instead, we use an ARM IOP (intensive observation period) product at the Southern Great Plains (SGP) site. The SGP March 2000 Cloud IOP has well-established forcing products to drive single-column model simulation, and a period of non-precipitating shallow clouds was observed from March 12 to March 15 (http://faster.arm.gov/scm/exps/sgp/, subperiod D) that is appropriate for the study of aerosol effects on warm cloud formation and the autoconversion to rain.

3.0 Results

The data needed for the evaluation of the dependency of drizzle formation on aerosol properties are contained in the "General" files of the processed data. CCN3 from the column labeled as "CCN N_B," which is 10-second averaged CCN concentration at a supersaturation level close to 0.4%, is used to represent the overall aerosol properties relevant for cloud and drizzle formation. The results are displayed using the LDM diagram, which is designed to display the drizzle formation as a function of N_D and L together with contours of the threshold function. This diagram is also used and illustrated in greater detail in the second-quarter metric report (McGraw et al. 2010).

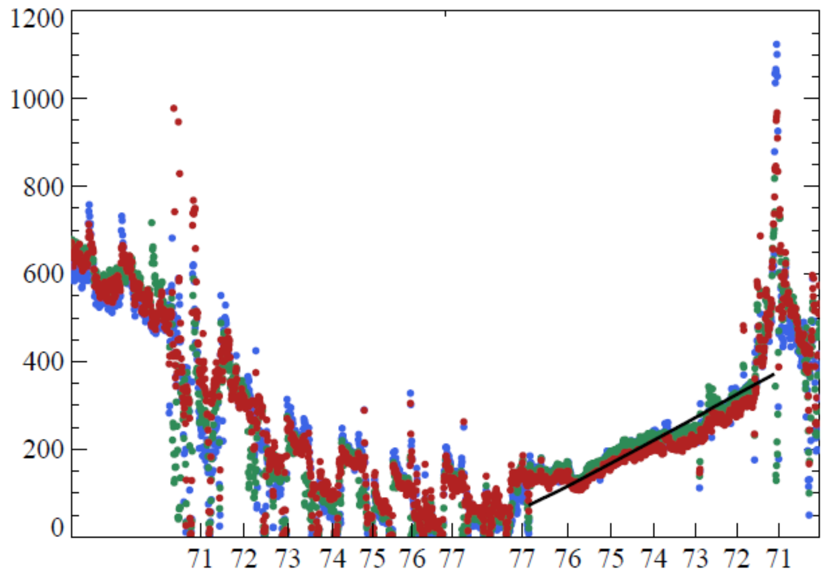

Figure 2. October 28 along flight CCN concentration (units cm^{-3}): Blue, green, and red for CCN1, CCN2, and CCN3, defined with respect to supersaturation levels of 0.2%, 0.28%, and 0.4%, respectively. Horizontal axis, longitudes in degrees west, tracks the progression of the flight. The CCN3 along the return track after the plane descended to sub-200 m altitudes represents the typical sub-cloud CCN concentration in the boundary layer. The linear regression of CCN3 against longitude, the black line, is used to prescribe the CCN gradient in the WRF model to investigate the aerosol effect on the formation of cloud droplets and drizzles. The cutoff value for CCN in WRF is 500 cm^{-3} near coast and 50 cm^{-3} towards open ocean.

The CCN concentrations that are used for the model simulations are derived from the G-1 flight measurements on October 28, 2008. Figure 2 shows the along-track CCN distribution as a function of flight time (or longitude, as the flight mostly traveled east-west). The fluctuation in the first half of the data is due to periodic penetration of the plane into clouds. The return flight is mostly below the clouds, and the CCN gradient increasing towards the coast is more clearly defined. The linear regression of the CCN3 data collected during the return flight at sub-200 m altitudes, as a function of longitude, is used to prescribe the pre-cloud CCN gradient in the WRF real-case simulation. The cutoff value in the linear regression is 50 cm^{-3} towards open ocean and 500 cm^{-3} near the coast. To show the strong impact of aerosol properties on drizzle formation, simulations with constant values of pre-cloud CCN throughout the model domain at levels of 50 cm^{-3} and 500 cm^{-3} are also presented.

3.1 WRF Simulations with Constant CCN

In this set of experiments, the two extreme values of CCN concentration as derived from the linearly regressed CCN gradient in Figure 2, namely 50 cm^{-3} and 500 cm^{-3}, are used to define the initial pre-cloud CCN concentration throughout the domain. The simulation is initialized at 12 UTC. The cloud and drizzle parameters at 15 UTC along the east-west cross section at 18.5°S are plotted in LDM diagram format in Figure 3. It is noted that the WDM5 microphysics scheme does not have a drizzle class. The model drizzle number concentration in the figure is actually the number concentration for all warm rain particles. However, based on the number density and volume fraction of rain, it is found that the mean radius for the rain is a few tens of microns. This is well within the drizzle spectrum for the VOCALS measurements as reported in the second quarter metric.

The contrast between the two experiments in Figure 3 clearly shows that higher initial CCN concentration leads to higher cloud droplet number concentration, but essentially shuts down all drizzle formation. In both cases, the LDM threshold function is a good predictor for drizzle formation across and beyond the threshold zone.

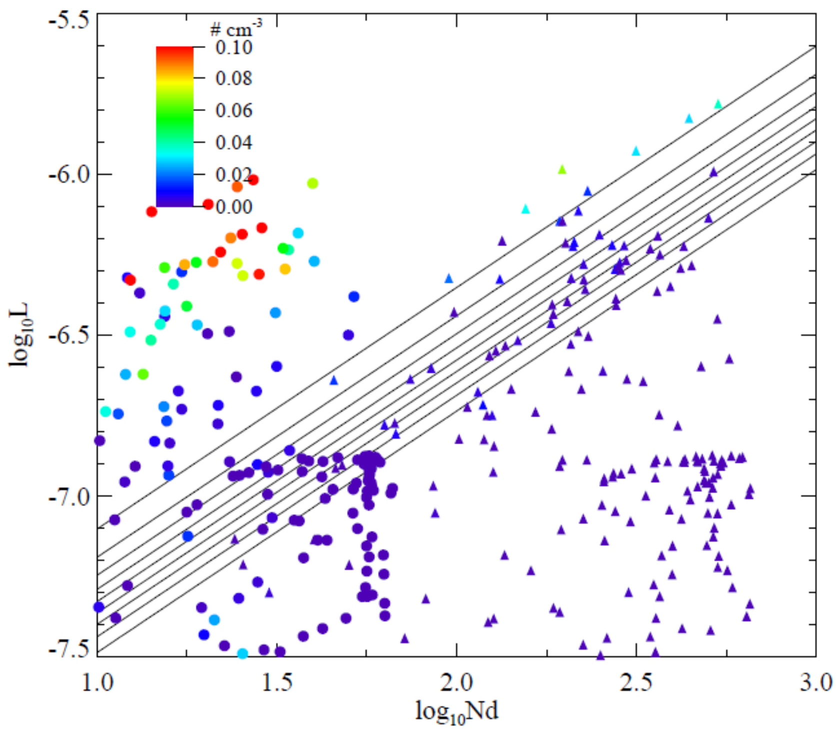

Figure 3. LDM diagram for WRF Simulation with LDM autoconversion in the WDM5 scheme and constant pre-cloud CCN concentration. Circles for pre-cloud CCN concentration at 50 cm^{-3} and triangle for 500 cm^{-3}. The black lines are LDM thresholds (upward from 0.1 to 0.9) for autoconversion. The color for the symbols indicates the drizzle number concentration. The points in the plot represent cloudy grids from all model levels below 1000 m altitude.

3.2 WRF Simulations with Gradient CCN from VOCALS

The simulation is initialized at 12 UTC as in Section 3.1. The pre-cloud CCN concentration is prescribed based on the linear regression defined in Figure 2. This simulation represents the most realistic setting in terms of both meteorological conditions and aerosol loadings. The cloud and drizzle parameters at 15 UTC along 18.5°S are displayed in Figure 4. The distinct drizzle characteristics from low to high LDM threshold values, corresponding to low to high drizzling rate, are qualitatively comparable to the observed cloud properties in Figure 2 of the second quarter metric report (McGraw et al. 2010).

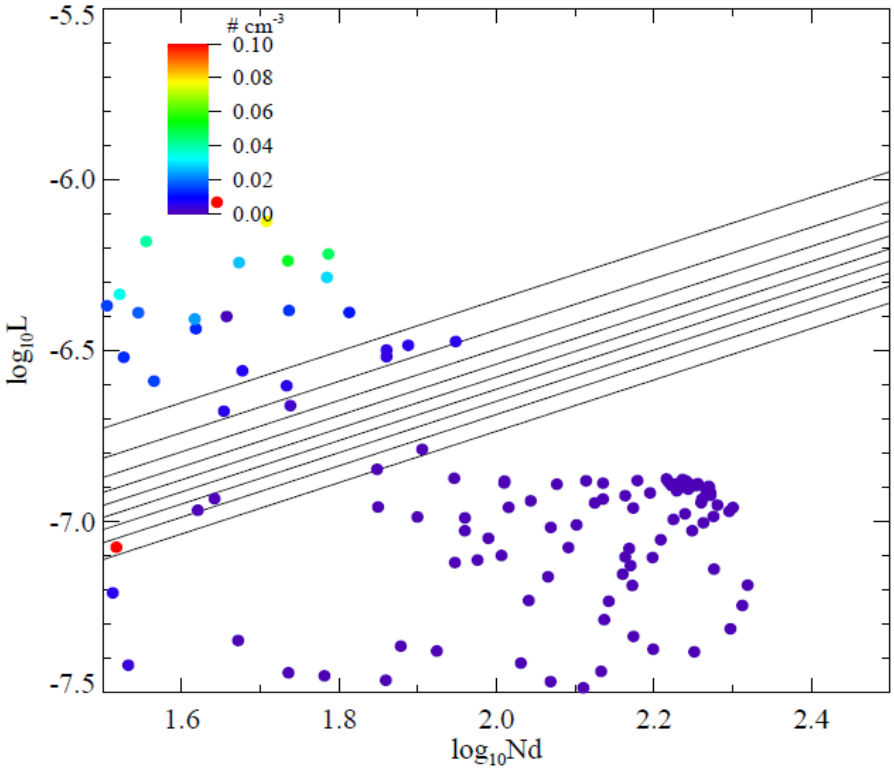

Figure 4. Same as Figure 3 except for prescribed CCN gradient.

3.3 Single-column Model CAM simulation with Constant Droplet Concentration

As indicated in Section 2.3, the case selected for single-column CAM simulation is from an ARM IOP at the SGP site. The simulations start at 00 UTC, March 12 and end at 12 UTC, March 15. The cloud droplet number concentrations are prescribed at 50 cm^{-3} or 500 cm^{-3} throughout the period when clouds are present. Qualitatively, this is equivalent to prescribing pre-cloud CCN concentration. Turbulence heat and moisture fluxes from the lower boundary are prescribed using IOP observations. Temperature and moisture profiles are relaxed towards observations with a three-hour time scale. The large scale advective forcings use the ARM variational product by Zhang et al. (2001). Such experimental settings are to minimize the impact due to non-cloud related processes.

Hourly mean cloud and drizzle properties below 800 mb for the last two and half days of the simulations are plotted in Figure 5. Note that for each of the cluster in Figure 5, there should only be a single x-coordinate. Solely for illustration purpose, the x-coordinate for each data point is randomly displaced by up to ± 0.1 in log scale to avoid neighboring data points being overlaid on each other. The results show that when cloud droplet number concentration (or equivalently CCN) is high (the cluster to the right), all data points are below the LDM threshold barrier and drizzle is shut down. In contrast, the left cluster appears at much higher LDM threshold, and a large fraction of the data points experience noticeable drizzle conditions.

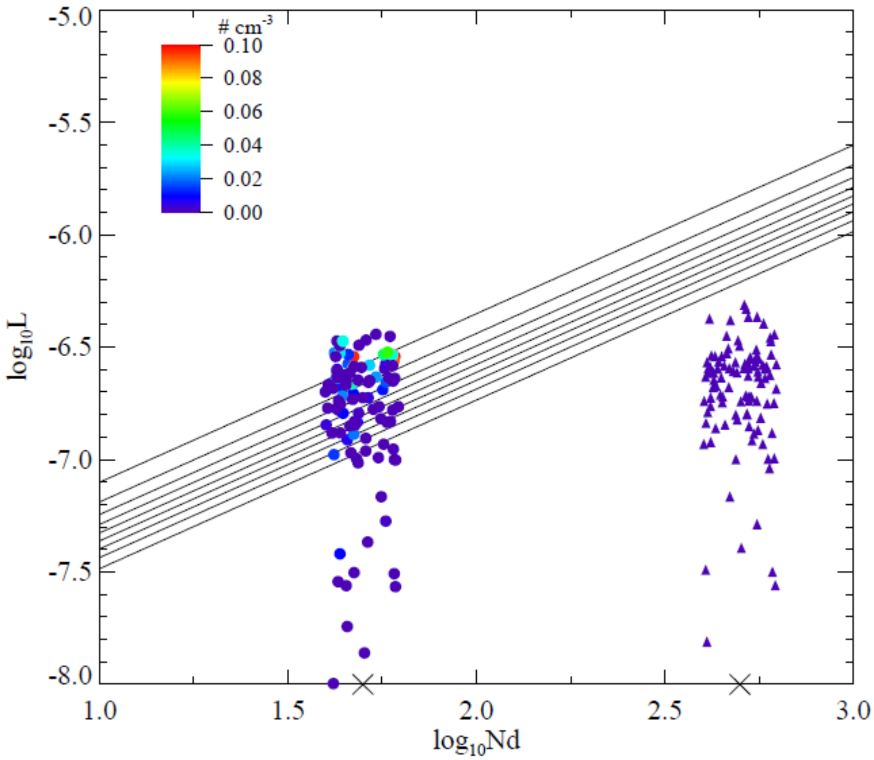

Figure 5. LDM diagram for single-column CESM/CAM5 simulation of March 2000 SGP IOP shallow cloud period of March 12 through March 15. The two clusters for different prescribed N_D at 50 cm^{-3} (circle) and 500 cm^{-3} (triangle), respectively. The x-coordinate for each point is randomly displaced by up to ±0.1 in log scale to avoid points being overlaid on each other. The actual x-coordinate for the two clusters are marked by 'X' on the x-axis.

4.0 Summary

The LDM drizzle parameterization is implemented to explore the dependency of drizzle formation on aerosol properties in shallow boundary-layer cloud conditions, using WRF and single-column CAM models. A cloudy case with drizzle from VOCALS field campaign in 2008 and a period from the ARM SGP March 2000 IOP are selected for the modeling study. The results show that the abundance of CCN can completely alter the properties of cloud and precipitation/drizzle. This may be particularly important for clouds that are not strongly driven by large-scale dynamical processes, such as the marine or continental boundary-layer clouds studied in this report. The LDM parameterization is found to be able to produce consistent results in both cloud-resolving models and coarse-resolution climate models, and agree reasonably with the observations. The LDM barrier crossing behavior for drizzle formation also proves to be sound in the two distinct modeling frameworks.

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