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Parameterization of Cumulus Convective Cloud Systems in Mesoscale Forecast Models

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LONG-TERM GOALS

The development and improvement of the microphysics parameterization of cumulus convective clouds in mesoscale numerical weather prediction models

OBJECTIVES

Conduct detailed studies of cloud microphysical processes in order to develop a unified parameterization of boundary layer stratocumulus and trade wind cumulus convective clouds. Develop a parameterization of subgrid cloud variability that in combination with the parameterization of conversion/sedimentation rates will provide a complete formulation of microphysical processes in convective clouds for use in mesoscale forecast models. Test the parameterization using COAMPS model in simulations of convective cloud systems.

APPROACH

The research is based on the SAMEX large eddy simulation (LES) model with explicit formulation of aerosol and drop size-resolving microphysics. The LES simulations based on observations from field projects will provide datasets necessary for parameterization development. COAMPS simulations based on field projects data will test the parameterization.

WORK COMPLETED

1. A new three-moment parameterization of autoconversion has been developed. Compared to traditional two-moment formulation, it significantly reduces scatter and results in a more accurate precipitation forecast.
2. Joint PDFs for boundary layer stratocumulus clouds have been formulated.
3. New computationally efficient and easy to implement in mesoscale models PDF formulations for cumulus clouds have been developed and tested.
4. The shallow cumulus cloud microphysical parameterization was implemented into COAMPS model and tested against observations from the VOCALS field project.

RESULTS

1. A three moment formulation of autoconversion rates for shallow cumulus clouds

During the first years of the project we developed a new microphysical parameterization (Kogan 2013) which is valid for both shallow cumulus and boundary layer stratocumulus clouds (Fig.1). The new "Cu" parameterization eliminates the bias in shallow cumulus clouds evident when using the old "KK" parameterization. However, it is striking that while the accretion rates are uniquely defined by a function of two moments (right panels in Fig. 1), the autoconversion rates, however, still exhibit very large scatter when formulated as a function of two variables (left panels). This is true for both the old "KK" and the new "Cu" formulation, and clearly signifies that more than two moments are required to uniquely define the autoconversion rate.

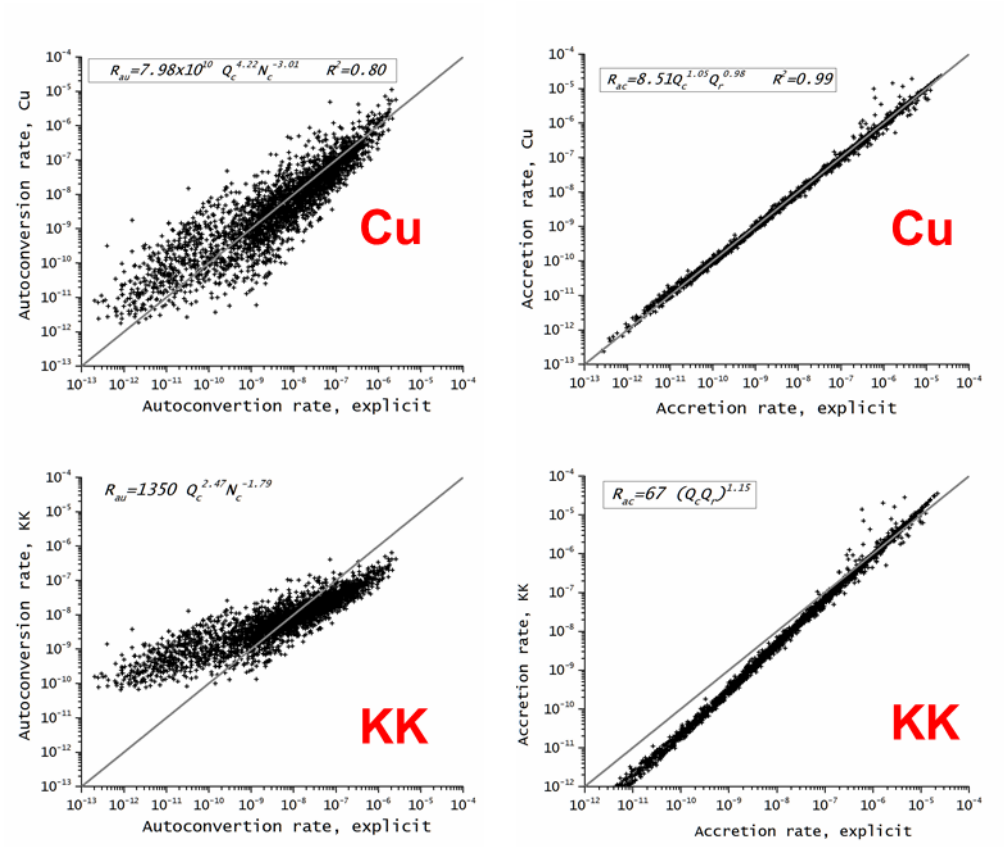

Figure 1. Scatter plots of autoconversion (left panels) and accretion (right panels) rates [s^{-1}] using Cu (top) and KK (bottom) formulation against explicit model values. [graph: The new Cu parameterization eliminates the bias shown when using the old KK parameterization. However, while the accretion rates show almost no scatter, the autoconversion rates are not uniquely defined by two variables and exhibit large scatter]

We developed and tested several formulations for autoconversion rates as a function of three moments. The dataset was obtained using simulations based on CIMMS LES model initialized with observations during the RICO (Rain In Cumulus over the Ocean) field project. The extra third moment (*mean*

radius r) can enter into formulation either explicitly as an additional power function, and in this case the formulation (*Au4*) will have four constant parameters (1). Or, alternatively, we can use the traditional formulation as a function of two moments, but the three parameters in this case will be functions of the third moment. Such formulations (Au_{3r} , Au_{3n}) are given by formulas (2)-(3).

$$Au_4 = \Delta q_c^{\alpha} n_c^{\beta} r_c^{\gamma} \tag{1}$$

$$Au_{3r} = \Delta(r) q_c^{\alpha(r)} n_c^{\beta(r)} \tag{2}$$

$$Au_{3n} = \Delta(n) q_c^{\alpha(n)} r_c^{\beta(n)} \tag{3}$$

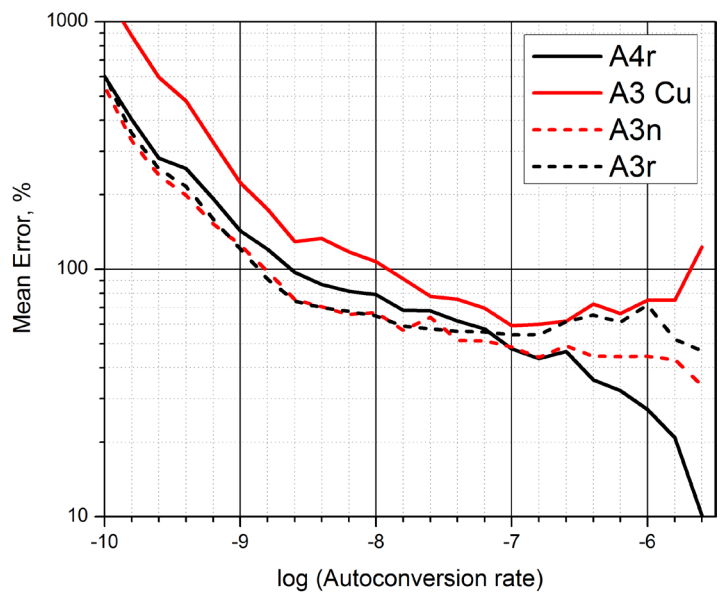

Figure 2. Comparison of errors in autoconversion rates when applying two and three moment formulation. [graph: The differences are significant for autoconversion rates, but less so for accretion]

We evaluated the mean errors of autoconversion rate for all different formulations and show them in Figure 2. Solid black curve corresponds to the case with three moments using four constant parameters according to (1); the solid red curve represent the two moment parameterization "Cu" with 3 constant parameters; the dashed black line corresponds to formulation (2) with three parameters which are functions of the *mean radius r*; and the dashed red line corresponds to formulation (3) with three parameters which are function of the *drop concentration n*. Results in Fig. 2 demonstrate that the smallest errors over the whole range of autoconversion rates are given by formulation (3), and that all three formulations decreased significantly the errors compared to original two moment formulation A3.

Figure 3 shows evolution of surface precipitation in simulations using different autoconversion formulation compared to the benchmark simulation (solid black line) obtained from LES model with explicit microphysics. The solid red line shows the original two moment (three-parameter) formulation, the dashed black line corresponds to 4-parameter formulation (1). The red dashed line which corresponds to formulation given by formula (3) provides the best precipitation forecast among all three autoconversion formulations over the whole 36 hour simulation.

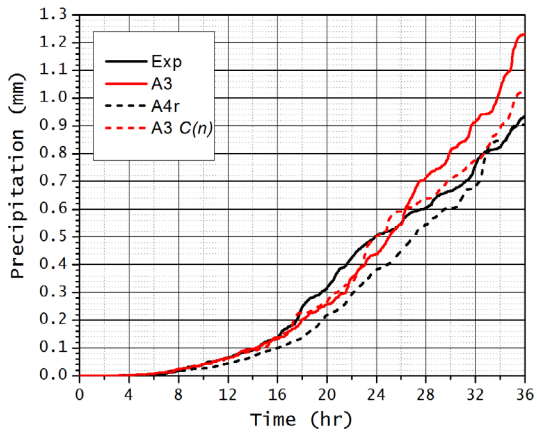

Figure 3. Comparison of surface precipitation evolution using different formulations of autoconversion rates. [graph: The most accurate surface precipitation prediction is produced by autoconversion formulation (3)-red dashed line]

2. Formulation of joint PDFs for boundary layer stratocumulus clouds

In previous years we formulated joint PDFs for cases of cumulus convection based on the shallow Cu case observed during RICO campaign and the congestus cumulus case based on observations during TOGA campaign. In the last year we have expanded the PDF formulation to the case of boundary layer stratocumulus using data from VOCALS observations.

Figure 4 shows isoline plots of the 2D PDF Ω (q_c, n_c) for all three cases. Clearly substantial differences exist between the three cloud regimes which include differences in vertical variation, shape of the PDF, and the slope of the isolines alignment. This leads us to conclude that a "universal" PDF formulation for various cloud types may not be possible, which is unfortunate given the appeal of unified physical parameterizations and the simplicity of their implementation. We surmise that future "smart" mesoscale models will be able to diagnose the cloud type system at each grid point based on criteria using stratification and instability (e.g., CAPE) parameters and, thus, determine which PDF formulation to apply at a particular location.

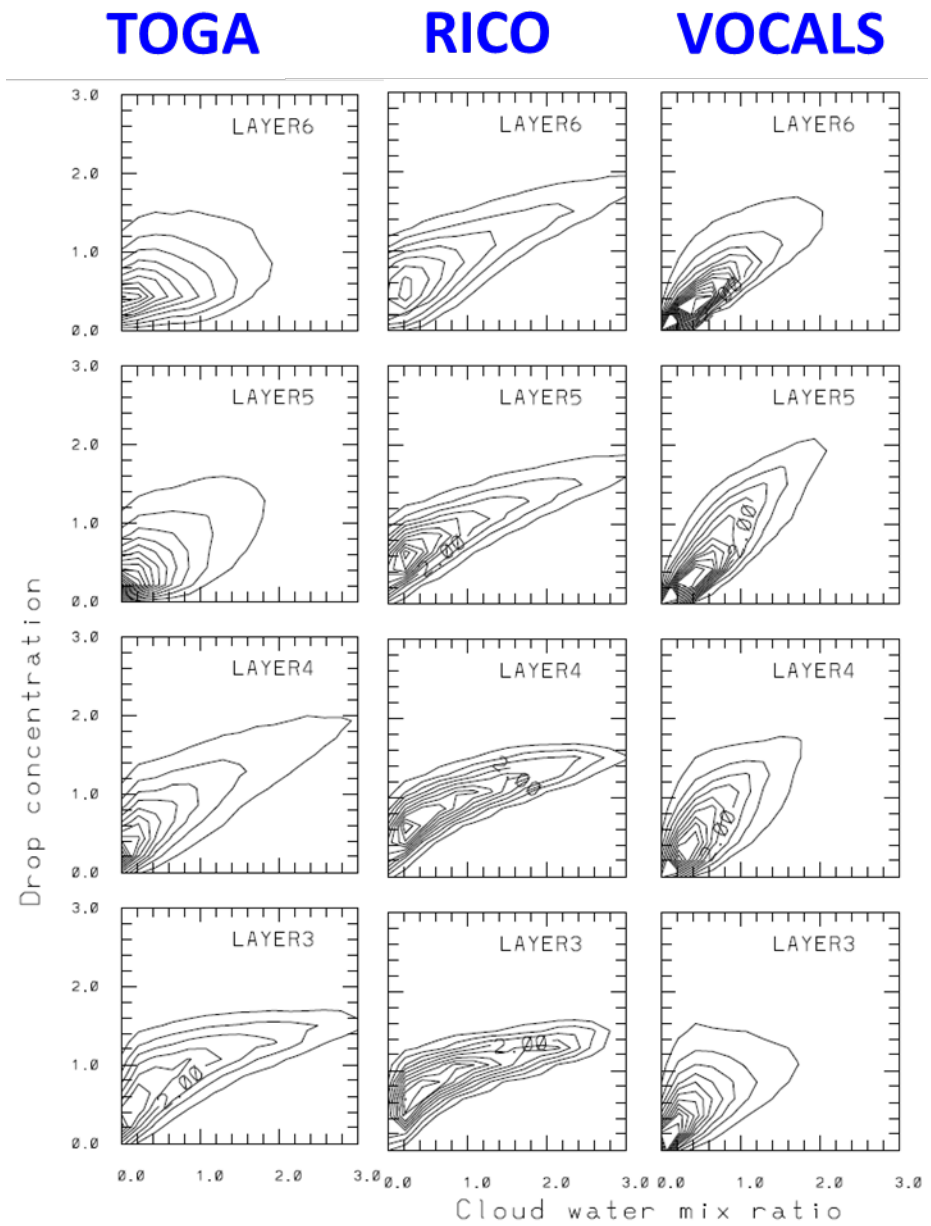

Figure 4. Isolines of the joint 2D PDF Ω (q_c, n_c) (in %) at indicated layers for the TOGA, RICO, and VOCALS simulations. [graph: Substantial differences between PDFs for different cloud regimes exist, signifying the need for cloud type specific PDF formulation in NWP models]

3. Computationally efficient formulation of PDFs for cumulus convective clouds

Our tests of the accuracy of different PDF formulation showed that the use of time- and group-dependent JPDF will result in the most accurate values for conversion rates. However, such a formulation where the shape of a PDF is dependent on time (hence layer-mean variables), and on cloud group (i.e. cloud top height) is difficult to obtain. In addition, the sub-grid information on cloud top heights inside a mesoscale model grid is in principle not available. We therefore tested feasibility of two simplified approximations, both using JPDFs obtained for the whole dataset that do not depend on layer-mean variables. In the first test, we use separate JPDFs for each of the three cloud groups

(*AU2DvarG*, magenta curve), while in the second test (*AU2DfxG4*, red curve) we use only one JPDF derived for G4 clouds (i.e. with tops higher than 2.7 km).

Figure 5 shows cumulative errors of such simplified approximations. For reference we also show curves for the most accurate, time- and group-dependent formulation (black curve *AU2D*) and the formulation neglecting SGS variability using only layer-mean variables (blue curve *AUmean*). The simplified formulations substantially degrade the accuracy: the case *AU2DvarG* for autoconversion rate has mean errors of 21.4% ± 25.8%, while the case *AC2DvarG* for accretion rate has mean errors of 14.4% ± 10.4%. A further simplification using the JPDFs from only the G4 group results in even larger errors, though the additional increase in error is less dramatic than that exhibited by *AU2DvarG* and *AC2DvarG*. In the case *AU2DfxG4* the autoconversion rate mean errors are 26.6% ± 27.8%, while in the case *AC2DfxG4* the accretion rate mean errors are 17.4% ± 11.2%. For comparison, the "true" formulations *AU2D* and *AC2D* have mean errors of the order of 12%, and the cases *AUmean* and *ACmean* have mean errors of 73.8% ± 10.7% and 21.9% ± 17.8%, respectively. We conclude that even using highly simplified formulations of JPDFs significantly reduce the errors in conversion rate calculations.

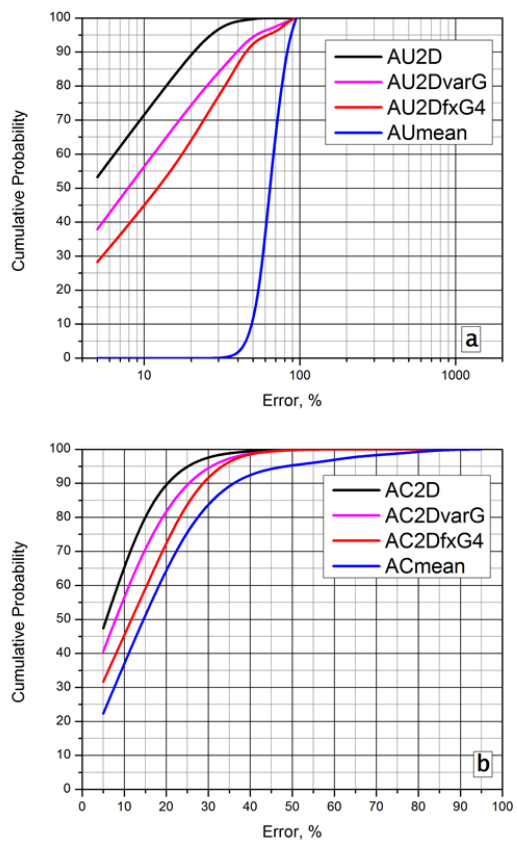

Figure 5. Cumulative distribution of errors in autoconversion (a) and accretion (b) rates calculated using various approximations for 2D JPDFs. The black line corresponds to the most accurate time- and height-dependent JPDF; the magenta line corresponds to a fixed-in-time but height-dependent JPDF; the red line corresponds to a JPDF fixed-in-time and obtained for clouds in the G4 group only. For comparison the blue line shows errors in case when only layer-mean variables are accounted and no PDFs are applied. [graph: Simplified, but computationally efficient PDF formulations still significantly reduce errors compared to neglect of sub-grid variability altogether]

4. The implementation and testing of the shallow cumulus cloud microphysical parameterization into COAMPS model

This work was performed by MS student Kevin Nelson under the advisement of David Mechem (Nelson et al, 2015). The shallow cumulus microphysical parameterization (Kogan 2013) have been implemented and tested in the COAMPS model. Cloud properties from a large suite of simulations using different parameterizations and concentrations of cloud condensation nuclei were compared to ship-based observations from the VOCALS-REx field campaign conducted over the southeastern Pacific (SEP). In addition to direct comparisons with the observations, the internal microphysical consistency of simulated MBL cloud properties was assessed by comparing simulation output to a number of observationally and theoretically derived scalings for precipitation and coalescence scavenging. Simulation results were broadly consistent with these scalings, suggesting COAMPS is behaving in a microphysically consistent fashion.

IMPACT

The improved parameterization of the physical processes in convective cloud systems will lead to more accurate numerical weather predictions for Navy operations.

TRANSITIONS

Our results have been accepted for publication in the two leading meteorological scientific journals (Journal of Atmospheric Sciences and Monthly Weather Review).

PUBLICATIONS

Kogan, Y. L., D. B. Mechem, 2015: A PDF based microphysics parameterization for shallow cumulus clouds. *J. Atmos. Sci.*, in press. [refereed]

Nelson, K. J., D. B. Mechem and Y. L. Kogan, 2015: Evaluation of warm-rain microphysical parameterizations in mesoscale simulations of the cloudy marine boundary layer. *Mon. Wea. Rev.*, accepted [refereed]

Kogan, Y. L., 2015: LES based approach to parameterization of cumulus convective cloud systems, Scientific Workshop on ONR DRI "Unified Parameterization for Extended Range Prediction", NRL-Monterey, August, 2015.

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Kogan Y.L., 2013: A Cumulus Cloud Microphysics Parameterization for Cloud-Resolving Models. J. Atmos. Sci., 70, 1423-1436.

Nelson, K. J., D. B. Mechem and Y. L. Kogan, 2015: Evaluation of warm-rain microphysical parameterizations in mesoscale simulations of the cloudy marine boundary layer. *Mon. Wea. Rev*.