Using Cloud-Resolving Model Simulations of Deep Convection to Inform Cloud Parameterizations in Large-Scale Models

S. A. Klein
National Oceanic and Atmospheric Administration
Geophysical Fluid Dynamics Laboratory
Princeton, New Jersey

R. Pincus
National Oceanic and Atmospheric Administration
Cooperative Institute for Research in Environmental Science
Climate Diagnostics Center
Boulder, Colorado

K. -M. Xu
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Abstract

Cloud parameterizations in large-scale models struggle to address the significant non-linear effects of radiation and precipitation that arise from horizontal inhomogeneity in cloud properties at scales smaller than the grid box size of the large-scale models. Statistical cloud schemes provide an attractive framework to self-consistently predict the horizontal inhomogeneity in radiation and microphysics because the probability distribution function (PDF) of total water contained in the scheme can be used to calculate these nonlinear effects.

Statistical cloud schemes were originally developed for boundary layer studies so extending them to a global model with many different environments is not straightforward. For example, deep convection creates abundant cloudiness and yet little is known about how deep convection alters the PDF of total water or how to parameterize these impacts. These issues are explored with data from a 29-day simulation by a cloud-resolving model (CRM) of the July 1997 Atmospheric Radiation Measurement (ARM) intensive operational period (IOP) at the Southern Great Plains (SGP) site. The simulation is used to answer two questions:

1. How well can the beta distribution represent the PDFs of total water relative to saturation resolved by the CRM?

2. How can the effects of convection on the PDF be parameterized?

Besides answering these questions, additional sections more fully describe the proposed statistical cloud scheme and the CRM simulation and analysis methods.

A Statistical Cloud Scheme

Statistical cloud schemes provide an attractive framework to parameterize stratiform clouds in large-scale models because they self-consistently predict the PDF of water vapor and cloud condensate, which can subsequently be used to determine the non-linear effects of radiation and precipitation. Statistical cloud schemes were originally developed in the context of boundary layer studies (Sommeria and Deardorff 1977; Mellor 1977); hence their extension to the full atmosphere is non-trivial.

In a statistical cloud scheme, a mathematical PDF is assumed to adequately represent in each large-scale model grid box the horizontal subgrid scale PDF of the specific humidity of total water (vapor plus condensate) q_t relative to saturation specific humidity q_s. Once the particular shape of the PDF has been determined, cloud fraction is diagnosed as the probability that q_t exceeds q_s. The cloud condensate mean value and its PDF can also be diagnosed from the PDF of q_t relative to q_s.

The difficult part of the parameterization is adequately prognosing the mean, width, and asymmetry of the q_t PDF. Distributions in the boundary layer are usually symmetric, but the PDFs of q_t relative to saturation at the detrainment levels of deep convection are highly skewed. Inspired by Tompkins (2002), I propose a new parameterization that adds to the large-scale model prognostic equations for higher order moments of total water: the horizontal variance of total water and third moment or skewness of total water. These will be full prognostic quantities in that they are advected with the mean flow and have parameterized sources and sinks from the physical parameterizations.

CRM Simulation and Analysis Method

A 29-day simulation of the July 1997 IOP at the ARM SGP site in Oklahoma was performed by the University of California-Colorado State University two-dimensional (2D) CRM (Krueger 1988; Xu and Randall 1995). The characteristics of the model simulation include: 2 km horizontal resolution, 512 km total domain size, 34 vertical layers below 20 km on a stretched grid, a 5 category bulk microphysics scheme, a third order turbulence closure, and interactive radiation. The CRM is driven with the variational analysis developed by Minghua Zhang.

To analyze the CRM data, the model domain must be segregated into stratiform and convective regions so that the statistics used to assess the stratiform cloud scheme come from only the stratiform region. Convective regions are identified by searching for columns with high values of either surface precipitation rate or vertical velocity below the melting level (Xu 1995). The PDFs are constructed by aggregating the 2 km mean prognostic variables from 5-minute snapshots over a time-space scale typical of large-scale models used in climate simulations, 512 km by 1 hour.

For parameterizing the effects of convection on the PDF moments, it is necessary to compute among other things D, the rate at which mass is detrained from the convective region into the stratiform region and the mean $q_{t,c}$ of air being detrained. As per Siebesma (1998), these quantities are computed from line integrals on the boundaries between convective and stratiform regions. An algorithm has been devised for determining the horizontal velocity of the interface between convective and stratiform regions from the 5-minute model snapshots.

How Does the Beta Distribution Fit the CRM Data?

The beta distribution is an attractive candidate for the sub-grid scale distribution of total water since it has finite limits, eliminating the problem of negative or infinite total water, and can be skewed in both negative or positive directions, as appear needed from the CRM data. The disadvantages of this distribution include that the skewness range is limited to plus or minus 2, which is smaller than the range in the CRM data, and that transcendental functions such as the incomplete beta function must frequently be evaluated.

To evaluate how well the beta distribution is able to match the CRM data, the predictions of cloud fraction and cloud condensate mean, variance, and skewness from the beta distribution are compared to the CRM values. To determine the parameters of the beta distribution at each level and time, the values of the mean, variance, and third moment of q_t from the beta distribution are set to match the values from the CRM. In determining the cloud fraction and condensate, the liquid-ice water temperature, which is conserved under phase changes at constant pressure, is assumed to be constant in the horizontal and specified from the CRM.

If the PDF of cloud condensate from the statistical cloud scheme is to be used in radiation and microphysical calculations then the variance and skewness of the condensate PDF should compare well to that from the CRM. This is true from the vertical profiles of these quantities averaged over the 29-day length of the CRM simulation (not shown).

Parameterization of Convective Sources of Variance and Skewness

The difficult part of using a statistical cloud scheme is the parameterization of the PDF width and asymmetry. In this parameterization, these will be determined from a prognostic equation for the variance and third moment of total water. The scheme requires source and sink terms for these higher order moments from each parameterized physical process in the model. Statistical cloud schemes were developed for the boundary layer, so the sources and sinks due to boundary layer turbulence are well established. The sources and sinks due to parameterized convection, though, are not. I have derived the convective sources and sinks by asking how these moments in the stratiform area of the grid box change when air with specified properties is detrained from the convective regions. The convective source of variance, for example, is:

$$D(q_{t,c} - q_t)^2 + D(\mathrm{var}(q_{t,c}) - \mathrm{var}(q_t)) - gM_c d(\mathrm{var}(q_t))/dp.$$

Here D is the detrainment rate of mass from the convective areas to the stratiform areas, $q_{t,c}$ is the mean total water of the detrained air and $\mathrm{var}(q_{t,c})$ is the variance of total water within the detrained air. The first term says that variance in the stratiform areas increases if the total water being detrained has a different mean total water than is present in the stratiform area. The second term says that if the variance within the detrained air exceeds the variance of the stratiform area then the variance in the stratiform area will increase. The third term says that the variance in the stratiform area is advected downwards by the 'compensating subsidence' that accompanies the cumulus mass flux M_c. A similar derivation leads to the convective source of the third moment of total water (not shown).

The variance and skewness in the stratiform areas of the CRM domain have been calculated (not shown). Whenever intense convection occurs, the variance of q_t increases. In the upper troposphere, the skewness increases along with the cloud fraction and condensate at times of convection. This arises primarily because convection detrains air with total water higher than the stratiform environment into the upper troposphere. In the lower troposphere, negative skewness of total water occurs with convection as a result of downdrafts detraining air with total water lower than that present in the stratiform areas of the boundary layer.

The first two terms of the parameterization of convective effects on variance have been calculated (not shown). The first term is always positive and has large values at precisely the same times and heights where the skewness and variance are increasing significantly. The second term can be both positive and negative. The fact that it is negative in many places indicates that the variance of total water in the air being detrained is less than that in the stratiform environment. A difficulty with this term is that var($q_{t,c}$) is not generally available from convection schemes. Potential parameterization for this term are being explored.

Conclusions

Concepts for a new statistical cloud scheme have been explored with the aid of CRM data forced with ARM observations. A distinguishing feature of this cloud scheme is that the variance and skewness of total water will be prognostic variables of the large-scale model; thus they will be advected by the large-scale flow and have parameterized sources and sinks from the parameterized physics of the model.

Because the cloud scheme only represents the variability in the stratiform area of the grid box, parameterizations for the very large effects of convection on the higher order moments have been developed. These parameterized sources and sinks will be computed by the parameterized convection scheme in the large-scale model.

Corresponding Author

S. A. Klein, sak@gfd1.noaa.gov, (609) 452-6523

References

Krueger, S. K., 1988: Numerical simulation of tropical cumulus clouds and their interaction with the subcloud layer. *J. Atmos. Sci.*, **45**, 2221-2250.

Mellor, G. L., 1977: The Gaussian cloud model relations. *J. Atmos. Sci.*, **34**, 356-358.

Siebesma, A. P., 1998: Shallow cumulus convection. Buoyant convection in Geophysical Flows, E. J. Plate, E. E. Fedorovich, D. X. Viegas and J. C. Wyngaard, Eds., Kluwer Academic Publishers, 441-486.

Sommeria, G. and J. W. Deardorff, 1977: Subgrid-scale condensation in models of nonprecipitating clouds. *J. Atmos. Sci*., **34**, 344-355.

Tompkins, A. M., 2002: A prognostic parameterization for the subgrid-scale variability of water vapor and clouds in large-scale models and its use to diagnose cloud cover. *J. Atmos. Sci*., in press.

Xu, K. -M., 1995: Partitioning mass, heat, and moisture budgets of explicitly simulated cumulus ensembles into convective and stratiform components. *J. Atmos. Sci*., **52**, 551-573.

Xu, K. -M. and D. A. Randall, 1995: Impact of interactive radiative transfer on the macroscopic behavior of cumulus ensembles. Part I: Radiation parameterization and sensitivity test. *J. Atmos. Sci*., **52**, 785-799.