# Final report for grant DE-FG02-03ER63561
## *Accounting for unresolved variability in clouds and water vapor*
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This report summarizes a decade's worth of work including three cycles of funding from the ARM program.

This project focused on the variability of clouds that is present across a wide range of scales ranging from the synoptic to the millimeter. In particular, there is substantial variability in cloud properties at scales smaller than the grid spacing of models used to make climate projections (GCMs) and weather forecasts. These models represent clouds and other small-scale processes with parameterizations that describe how those processes respond to and feed back on the large-scale state of the atmosphere. When this project was initiated in 2000 essentially every model ignored all but the simplest small-scale variability in clouds: clouds were allowed to partially fill grid cells but were assumed to be internally homogeneous.

The problem with this assumption is that it introduces errors into any calculation that depends non-linearly on cloud properties. This problem was first identified for radiative fluxes by Cahalan et al. (1994), who showed that inhomogeneous clouds were less reflective than homogeneous clouds with the same mean optical thickness, and that this explained why models had to arbitrarily reduce cloud water contents before computing optical thickness if they were to produce radiative balance. Steve Klein and I showed that this problem also existed for microphysical calculations in large-scale models (Pincus and Klein, 2000). We proposed, as a solution, following work by Tompkins (2000) and building a cloud parameterization that assumed a flexible probability distribution (PDF) of cloud water content whose parameters would evolve in response to physical processes in the model. Some of the work we pursued in subsequent years concerned how processes like convection should affect the distribution of cloud water (Klein et al., 2005). Generally speaking, it was Dr. Klein's task to implement the overall assumed PDF scheme and my task to determine how to compute process rates given a PDF of cloud water.

Our largest success was a new method for computing radiative fluxes in the presence of subgrid-scale variability. This problem is especially hard because it is non-local, in that the radiative fluxes depend not just on the distribution of cloud properties within a grid cell but also on the way these properties are aligned vertically. The problem arises even in homogenous columns when each layer may have fractional cloudiness. In 2003 there were two approaches to dealing with this "cloud overlap." One was to make analytic changes to the radiative transfer equations, though this was known to be incorrect when compared to benchmarks (Barker et al., 2003). The other was to enumerate all possible configurations of cloudiness within each column, compute radiative fluxes within each, and weight the results appropriately (Stubenrauch et al., 1997; Collins, 2001), which was very computationally expensive.

Diagnostic calculations developed around this time (e.g. the "ISCCP simulator" of Klein and Jakob, 1999) introduced the idea of using samples from the distribution of cloudiness. These

samples were constructed randomly such that a large number would reproduce the fractional cloudiness in each layer and any overlap assumptions used. We realized that this approach could be extended to include any PDF of cloud properties within cloud layers, though this would require new methods for treating cloud vertical structure.

The problem of computing broadband fluxes over a distribution of cloud properties can be viewed as a integral requiring sums over cloud properties in one dimension and intervals in the electromagnetic spectrum in a second dimension; the latter sum typically requires many hundreds of intervals. Our insight was to realize that each spectral interval could be associated with a different random sample from the cloud distribution. This amounts to a Monte Carlo sample of the two-dimensional integral and gives the algorithm its name ("Monte Carlo Independent Column Approximation," or McICA; Pincus et al., 2003). McICA is nearly as efficient as a single radiative transfer in homogeneous clouds but is unbiased and works equally well with any distribution of cloud properties or any overlap assumption. Like all Monte Carlo methods it introduces some sampling noise, but testing across a wide range of global models (Barker et al., 2008; Morcrette et al., 2008) indicates that it does not affect model evolution.

If the goal of ARM is to improve the parameterizations in climate models McICA has been a resounding success. We got a big boost when the ARM-funded developers of the RRTMG package chose to use McICA as the only treatment of cloud overlap in their widely-used codes but many other modeling centers worldwide (including both major US climate models and the world's premier weather forecasting center) have adopted the technique.

In order to make McICA work with assumed-PDF cloud schemes we had to generalize the idea of overlap to include clouds with internal variability. This was most naturally done by examining the variability of total water content (the variable in which assumed-PDF scheme are formulated). This quantity is very hard to observe, though, so we looked at the variability in lengthy cloud-resolving model simulations at the ARM SGP site (Pincus et al., 2005). We found that the rank correlation of total water content in any two layers moved from perfectly correlated to perfectly uncorrelated roughly exponentially as the distance between the layers increased (a model inspired by the observations of Hogan and Illingworth, 2000). This allowed us to build an overlap parameterization that was insensitive to the resolution of the host model. We also extended the sampling methodology (Pincus et al., 2006) to include multiple species of clouds (e.g. "convective" and "stratiform" clouds) as are often produced by different schemes in global models.

Work on the assumed-PDF scheme slowed significantly when my collaborator Steve Klein left the GFDL modeling center to work at PCDMI. By this time, however, we had both become interested in how one might use ARM observations to evaluate models at all scales. In particular, we wanted to understand how the time-varying vertically-pointing observations from the showpiece active sensors at the central facility could be used to evaluate models on greatly different scales. One thread of research involved assessing the utility of the frozen turbulence assumption in which time averages of the observations and spatial averages from model domains are considered comparable (Jakob et al, 2004). Along the way we learned that cloud-resolving models were reasonably skilled at producing observed cloud fields when the large-scale environment is consistent with observations, but that the thermodynamic state in at least some

models drifts quickly away from reality when driven with time tendencies from the variational analysis (Henderson and Pincus, 2009). A second, more specialized thread found that three-dimensional radiative transfer effects were underestimated when vertically-pointing observations were used to characterize the cloud field (Pincus et al, 2005a) since one entire dimension of variability must be ignored. (ARM funding also supported the development of three-dimensional radiative transfer tools; see Pincus and Evans, 2009). Experience with using ARM observations to evaluate models fed efforts to develop tools for evaluating the clouds produced by global models (Zhang et al., 2005; Pincus et al, 2008); these efforts are now formally part of a WCRP panel on "metrics for the evaluation of climate models."

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