Final Technical Report for DOE Award DE-SC0002763

DE-FG02-09ER64765

September 2013

Title: Collaborative Research: Using ARM Observations to Evaluate GCM Cloud Statistics for Development of Stochastic Cloud-Radiation Parameterizations

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Project ID: 0015146

Award Register#: ER64765

The long-range goal of several past and current projects in our DOE-supported research has been the development of new and improved parameterizations of cloud-radiation effects and related processes, using ARM data, and the implementation and testing of these parameterizations in global models. The main objective of the present project being reported on here has been to develop and apply advanced statistical techniques, including Bayesian posterior estimates, to diagnose and evaluate features of both observed and simulated clouds.

The research carried out under this project has been novel in two important ways. The first is that it is a key step in the development of practical stochastic cloud-radiation parameterizations, a new category of parameterizations that offers great promise for overcoming many shortcomings of conventional schemes. The second is that this work has brought powerful new tools to bear on the problem, because it has been an interdisciplinary collaboration between a meteorologist with long experience in ARM research (Somerville) and a mathematician who is an expert on a class of advanced statistical techniques that are well-suited for diagnosing model cloud simulations using ARM observations (Shen).

The motivation and long-term goal underlying this work is the utilization of stochastic radiative transfer theory (Lane-Veron and Somerville, 2004; Lane et al., 2002) to develop a new class of parametric representations of cloud-radiation interactions and closely related processes for atmospheric models. The theoretical advantage of the stochastic approach is that it can accurately calculate the radiative heating rates through a broken cloud layer without requiring an exact description of the cloud geometry.

Compared to the gridbox-averaged observations from the Oklahoma Mesonet, preliminary work shows that the stochastic model has great promise as a parameterization approach (Lane et al., 2002). Development of a practical stochastic algorithm entails empirically determining the statistical variability of cloud properties under varying circumstances, and making progress on this task has been a major objective of the current research project being reported on here.

We have developed and used advanced statistical techniques described in the attached publication. Our objective has been to provide results that will be useful for the development of stochastic cloud-radiation parameterizations and to estimate parameterization errors. This work will contribute to improving GCM realism and utility.

The research that we have carried out directly addresses the DOE Climate Change Research Division Long Term Measure (CCRD LTM) of Scientific Advancement to deliver improved scientific data and models about the potential response of the Earth's climate and terrestrial biosphere to increased greenhouse gas levels, to help enable policy makers to determine safe levels of greenhouse gases in the atmosphere. It does so by contributing to the specific ARM goal to improve the treatment of radiation and clouds in the GCMs used to predict future climate.

This research also directly addresses the DOE Biological and Environmental Research (BER)'s interests by focusing on developing innovative methods for data analysis and testing improved cloud-radiation parameterizations based on ARM observational data from all the ARM field sites. Cloud-radiation interactions are widely held to be the largest single source of uncertainty in climate model projections of future climate change due to anthropogenic increases in atmospheric greenhouse gas concentrations. By focusing on reducing this uncertainty through an integrated research program in which we develop and evaluate methods for characterizing the statistical variability of cloud populations, we explicitly support the BER-CCRD Long Term Measures.

The research we have carried out is motivated by the stochastic radiative transfer theory developed with ARM support by Lane-Veron and Somerville (2004). The research helps make it possible ultimately to develop a new class of parametric representations of cloud-radiation interactions and closely related processes for atmospheric models. The stochastic parameterization concept motivates our work. However, the research carried out under this award has been devoted entirely to cloud property diagnosis and evaluation using ARM observations.

A simple way to describe the stochastic concept is that, rather than predicting cloud fraction deterministically in a global climate model (GCM) and weighting clear and overcast radiative transfer calculations by a fraction, one instead transforms the problem and calculates the probability of cloud spacing (Lane-Veron and Somerville, 2004), and probability density function (pdf) of cloud parameters such as cloud size and liquid water content (McFarlane et al., 2002). Thus, the conventional deterministic approach is a limiting case of the more general stochastic approach.

We find that data from the ARM CRF SGP site can be used to provide the necessary statistical information about the cloud field for input into radiation routines. However, there is still improvement needed in the processing of some observations, such as that of cloud fraction. In the research we have carried out, we have developed and exploited advanced statistical techniques, including Bayesian posterior estimation (BPE) to achieve the needed increase in accuracy. The BPE approach allows new observational data to update the prior knowledge via Bayes' conditional probability theorem.

Particular attention has been paid to the case that the prior distribution or the likelihood function is non-Gaussian. In this case, the conventional minimum mean square error approach will not lead to an optimal solution, and the statistical inference will need to be based on a credible set rather than the confidence interval for a symmetrical distribution.

We also use a maximum likelihood estimate to simplify the calculation. Our estimate output of a cloud parameter is thus a pdf rather than a deterministic value with an error bar. The pdf provides the range of the relevant radiation parameters in a GCM. The expected value and its uncertainty (i.e., error) are all described by the pdf.

We are encouraged by our finding that ARM observations can be processed to yield probability density functions of cloud parameters. This information is critical to the development of practical stochastic approaches to the cloud-radiation problem (Lane et al., 2002). Because of the pdf input to the GCM, an ensemble prediction of the future climate may be derived from multiple predictions guided by the input pdf ranges.

Because of nonlinearity, non-stationarity, and possible asymmetric pdf of input radiation parameterization, the predicted GCM climate will likely be non-Gaussian, and the ensemble prediction may need to be derived from the application of a series of BPEs: each new prediction updates the previous prediction. Our work provides guidance for selecting the range of parameters in GCM predictions, and it provides a foundation for future research on implementing the stochastic approach in GCMs.

Our work has been included in a Masters thesis by Velado (2013) and two papers (Shen et al., 2013a, b). Shen et al. (2013a) describes the Bayesian statistical work outlined above. Shen et al (2013b) describes the stochastic modeling of cloud base mass transport and its validation by ARM TWP-ICE (Tropical Warm Pool - International Cloud Experiment) water vapor data in 2006. Velado's thesis (2013) contains detailed Bayesian studies for the ARM SGP data of cloud fraction, water vapor, liquid water path and precipitation as well as the CAM5 data of cloud fractions.

Shen, S. S. P., M. Velado, R. C. J. Somerville, and G. J. Kooperman, 2013: Probabilistic assessment of cloud fraction using Bayesian blending of independent datasets: Feasibility study of a new method, *J. Geophys. Res. Atmos*., **118**, 4644–4656, doi:10.1002/jgrd.50408.

Shen, S.S.P., M. Velado, K. Leung, A. Subramanian, G.J. Zhang, and R.C.J. Somerville, 2013: TWP-ICE precipitation and water vapor data and their stochastic model simulations with a random trigger, *Geophys. Res. Lett.*, in preparation.

Velado, M., 2013: A feasible study of a probabilistic approach to analyzing cloud properties such as cloud fraction, liquid water path, and precipitable water vapor. Master of Science Thesis, San Diego State University, 100pp.

Copies of Shen et al. (2013a) and Velado (2013) are attached as appendixes to this Final Technical Report.

Shen et al. (2013a, b) acknowledge support under this DOE award DE-FG02-09ER64764.

We will notify DOE promptly of any additional publications appearing in the future, based on further developments of the research carried out under this award.

References:

Lane, D. E., K. Goris, and R. C. J. Somerville, 2002: Radiative transfer through broken clouds: Observations and model validation. *Journal of Climate*, **15**, 2921-2933.

Lane-Veron, D. E., and R. C. J. Somerville, 2004: Stochastic theory of radiative transfer through generalized cloud fields. *Journal of Geophysical Research*, **109**, D18113, doi:10.1029/2004JD004524, 1-14.

McFarlane, S.A., K.F. Evans, and A.S. Ackerman, 2002: A Bayesian algorithm for the retrieval of liquid water cloud properties from microwave radiometer and millimeter radar data. *Journal of Geophysical Research*, **107**, 4317, doi:10.1029/2001JD001011.
