RIMS Final Report – FG02-02ER63314

Application of Stochastic Radiative Transfer Theory to the ARM Cloud-Radiative Parameterization Problem

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SUMMARY

This project had two primary goals: 1) development of stochastic radiative transfer as a parameterization that could be employed in an AGCM environment, and 2) exploration of the stochastic approach as a means for representing shortwave radiative transfer through mixed-phase layer clouds. To achieve these goals, climatology of cloud properties was developed at the ARM CART sites, an analysis of the performance of the stochastic approach was performed, a simple stochastic cloud-radiation parameterization for an AGCM was developed and tested, a statistical description of Arctic mixed phase clouds was developed and the appropriateness of stochastic approach for representing radiative transfer through mixed-phase clouds was assessed. Significant progress has been made in all of these areas and is detailed below.

HISTORY

The period covered by this grant is from 11/15/2001 - 2/10/2006. In January of 2006, I moved from the Department of Environmental Sciences at Rutgers, The State University of New Jersey to the College of Marine Studies at the University of Delaware in Newark, DE. I requested that a portion of the funds, $123,179, be relinquished by Rutgers to the Department of Energy for redistribution to the University of Delaware. The research was continued as a project of the same title, "Application of Stochastic Radiative Transfer Theory to the ARM Cloud-Radiation Parameterization Problem", FG02-06ER64246. The final report for the entire project was submitted from the University of Delaware.

RESULTS

This document contains summary and final information for the portion of the project concluded at Rutgers, from 15 November 2001 to 10 February 2006.

The most notable achievements from this time period are:

- Development of a one-year cloud climatology at all three ARM CART sites.
- Extension of the cloud climatology for five years at Tropical Western Pacific site, and application of cluster analysis.
- Modification of the stochastic model for multilayer clouds, multiple cloud layers, and mixed-phase clouds, and application for all years covered by the climatologies
- Five manuscripts prepared, four of which were submitted, three of which are published and one is undergoing major revisions to be resubmitted.
- 12 conference proceedings, five invited talks, and 17 conference presentations also resulted from this period of work.

OVERVIEW

A stochastic shortwave cloud-radiation parameterization for use in modern Atmospheric General Circulation models is under development. The parameterization is based on results from stand-alone stochastic model simulations that use observed cloud field characteristics to force the model. The stochastic model employed for these calculations is DSTOC, an approximate cloud-radiation model that uses Markovian statistics to represent the macroscale geometry of the model cloud field (Lane-Veron and Somerville, 2004; Lane et al. 2002). Continuous measurements of the cloud fields present during the year 2000 at all three ARM CART sites have been analyzed on an hourly basis and used as input to DSTOC. This input includes the hourly mean cloud base height, cloud thickness, cloud horizontal scale, droplet effective radius, liquid water path and cloud fraction. The mean values are used to scale the assumed Markovian distribution of cloud characteristics. The impact of the stochastic approach to modeling cloud-radiation interactions on the atmospheric heating rates is currently being assessed using a version of the Scripps Single-column Model.

A one-year cloud climatology of cloud characteristics has been developed as part of this project. The cloud characteristics needed to force the stochastic model have been analyzed on an hourly basis and then averaged seasonally and annually for the three CART sites. The mean observed cloud characteristics are shown in Table 1. Continued analysis of the one-year cloud climatologies and stand-alone radiative transfer modeling runs indicated that deriving parameterizable relationships among atmospheric state variables and cloud field characteristics was a complex process. However, in the tropics, there is a strong relationship between model performance and cloud fraction (Figure 1), and in the Arctic there was a relationship between model predicted irradiance and observed liquid water path. However, the results from the SGP site were unclear.

	NSA	SGP	TWP
CBH (km)	4.01	4.79	6.35
Thickness (km)	1.84	1.84	1.88
Chord Length (km)	2.08	4.43	1.08
Fraction	0.8	0.71	0.79
Droplet Radius (um)	4.75	5.57	4.94
Optical Depth	17.58	11.41	17.03
LWP (g/m^3)	53.08	30.32	69.35

Table 1. Mean cloud properties at the three ARM CART sites for the year 2000.

A more sophisticated analysis was begun at the Tropical Western Pacific CART site using four years of cloud and radiation data from 2001-2004, and is described in Foster and Veron (2008a). The TWP site was chosen after preliminary analysis indicated that the probability distribution of cloud chord lengths derived from ground based observations at the TWP was closest to a Markovian distribution, which is employed by the stochastic model.

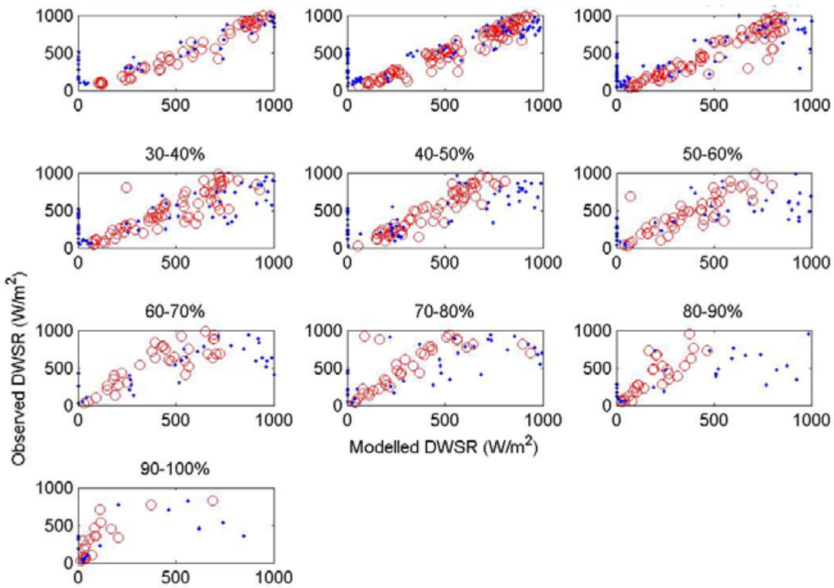

Figure 1. Modeled downwelling shortwave radiation relative to observed, binned by cloud fraction (in percent) for the TWP site.

All data used in this study were taken from observations and value added products (VAPs). Cloud amounts, base and top heights, liquid water path, downwelling diffuse and direct shortwave flux, cloud fraction, and cloud droplet effective radius and were averaged hourly, and then interpolated to thirty-two vertical layers. In order to complete the simulations described below, all input data from these diverse observations must be available and be able to meet certain criteria. Of the 35064 hours spanning from the beginning of 2001 to the end of 2004, 8408 of those hours were used in the simulations.

The stochastic model, DSTOC and the stand-alone CRM were initially compared for 241 hours during clear-sky conditions. Both models predicted downward solar surface irradiance (SSI), agreed within 1.2 ± 1.5%, a mean difference of 6 Wm^{-2} with a standard deviation of 8 Wm^{-2}. As closer agreement was anticipated, an analysis of 177 of these clear sky hours was done when Total Sky Imager (TSI) data were available. For most of these times the TSI indicated that opaque or thin clouds were present – missed by the upward looking instruments initially used. The mean opaque cloud fraction detected by the TSI over this period was 0.15 and the mean thin cloud fraction was 0.04.

The SSI calculated by DSTOC and CRM for cloudy conditions was analyzed on an hourly, daily and monthly basis. Both models perform well relative to observations from January to April, but their divergence from observations increases from April to September. DSTOC tends to overestimate when values of SSI are low, such as times when SZA is large or cloud amount very high, and improves as values of SSI increase. The opposite appears to be true for the CRM, plane-parallel results. In Figure 2, it can be seen that for SZA larger than 60 degrees the mean SSI difference from observations for the CRM is 4 Wm^{-2} while the difference between DSTOC SSI and observations is 16 Wm^{-2}. For SZA smaller than 60 degrees the mean difference from observations for the CRM is 29 Wm^{-2} while for DSTOC it is 7 Wm^{-2}. This result is not

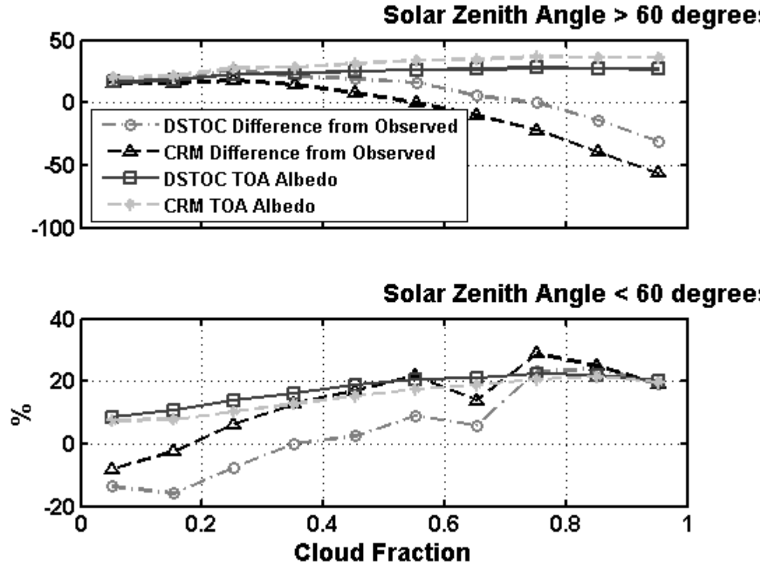

Figure 2. Model performance as a function of solar zenith angle.

necessarily intuitive, as one might expect the closest approximation of a plane-parallel atmosphere to occur when the sun is directly overhead, or nearly so. However, when cumulus towers are frequently present, as is the case here, the large SZA case may more closely approximate a ‘plane-parallel’ situation.

Cluster analysis was explored as another method for objectively identifying circumstances where the stochastic approach to modeling shortwave cloud-radiation interactions would be appropriate in an AGCM environment. A k-means clustering algorithm is applied to ground-based cloud and radiation measurements taken from Nauru Island in the Tropical Western Pacific from the beginning of 2001 to the end of 2004 using liquid water path, cloud amount, and cloud top height. Four distinct cloud regimes were identified: including a convectively active optically thick cirrus regime with large coverage, a convectively active optically thin cirrus regime with relatively low coverage, a suppressed regime composed primarily of boundary layer clouds, and a convectively active very optically thick regime composed of multiple cloud types. Modeled SSI from DSTOC and CRM was used to indicate when cloud field geometry has a significant effect on domain-averaged shortwave radiative transfer. Characteristics of each cluster are shown in Table 2. It is found that cloud top height, mean wind shear between cloudy layers and mean vertical spacing between cloudy layers are correlated with both the structure of the cloud regimes and the performance of the stochastic model, while convective available potential temperature appears weakly if at all correlated with either cloud structure or and model performance.

The performance of the models varies greatly among the clusters. Large wind shear between cloudy layers, high cloud top heights and small spacing between cloudy layers all coincide with improved performance by the stochastic model. Intuitively these variables make sense, as together they generate cloud fields with large vertical extents with several intermittent cloudy layers both horizontally and vertically.

c	rfo	cloud amount		doppler (m/s)		diffuse/total		topheight (km)		thickness (km)		lwp (g/m^2)	
		median	*std*	*median*	*std*	*median*	*std*	*median*	*std*	*median*	*std*	*median*	*std*
1	0.15	0.74	0.15	0.37	0.35	0.73	0.18	12.74	2.23	1.76	1.71	22.70	28.87
2	0.13	0.39	0.15	0.16	0.38	0.42	0.27	13.52	2.79	0.91	1.94	12.40	21.38
3	0.18	0.30	0.11	-0.03	0.22	0.28	0.16	1.43	1.82	0.08	0.23	22.02	22.73
4	0.54	0.50	0.20	0.29	0.64	0.56	0.27	7.10	3.45	0.47	2.25	37.08	60.71

It should be noted that significant effort was invested in developing clusters at the Southern Great Plains CART site as well. This effort was focused on trying to clarify the modeling results from Veron et al. (2009). However, while it was possible to identify cloud regimes from the ground-based observations; the clusters were not useful in interpreting the model results.

Additionally, the stochastic model was coupled to the Scripps single-column model (Iacobellis and Somerville 1991 a, b) in a preliminary effort to assess the impact of the stochastic fluxes on model dynamics and on in cloud heating rates.

STATISTICAL ANALYSIS OF ARCTIC MIXED-PHASE CLOUDS AND STOCHASTIC MODELING

We investigated a stochastic approach to modeling shortwave cloud-radiation interactions in overcast mixed-phase clouds for several case studies during the SHEBA campaign. The stochastic mixed-phase cloud-radiation model, MX-STOC, is a significantly modified version of the stochastic model used in previous studies of inhomogeneous cloud fields. MX-STOC assumes a horizontal distribution of ice patches (i.e., different sizes and spacing) throughout the liquid cloud layer. MX-STOC produces the ensemble-averaged radiation field, averaged over a domain similar to many AGCMs. The cloud characteristics for ice and liquid phases (e.g., water content, horizontal fraction and patch size) are determined from observations. We compare all stochastic calculations to those from a typical stand-alone cloud-radiation model, SUNRAY (Fouqart and Bonnel 1980) and the CRM.

Input data for MX-STOC include liquid water path, ice water path, cloud base, cloud top, effective radius of liquid particles, effective radius of ice particles, ice fraction, and a characteristic scale of a horizontal ice patch, all of which are derived from observations. For all simulations performed in this experiment, the input data for the stochastic and plane-parallel models are derived from cloud observations made during the SHEBA campaign. The clouds used for this study are very thin, where the cloud is confined to one model layer, with cloud top and base occurring and model layer interfaces. Measurements of surface shortwave radiative fluxes are from four Eppley Precision Solar Pyranometers. Determination of ice fraction is done using the lidar data to indicate where in the cloud is liquid or ice (Figure 3). We calculate ice fraction by dividing the cloud ice amount by the total cloud amount for the hour.

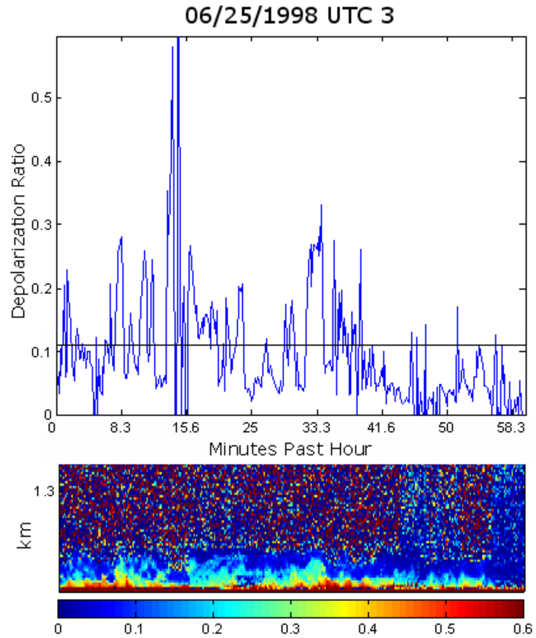

Figure 3. Lidar depolarization ratio for June 25th, showing relative frequency of ice and liquid patches in one hour.

Many Arctic mixed-phase clouds have a liquid layer near the cloud top. Due to the importance of liquid water amount in the cloudy layer seen in the first series of simulations, an additional series of runs were performed (MX-LIQ) where a liquid layer was inserted at the top of the mixed-phase cloud; a structure that is consistent with observations. With this more physically realistic representation of the mixed-phase clouds, MX-LIQ outperforms all other versions of the stochastic model and the plane-parallel model. In all runs, the stochastic model typically over predicts downward surface shortwave flux relative to those observed, while the plane-parallel model under predicts shortwave radiation. Both stochastic model versions consistently produce more realistic fluxes than the plane-parallel model, and MX-LIQ predicts downwelling fluxes that are closer to observations than those produced by MX-STOC.

These results indicate that it is equally important to include both water phases as well as the distribution of the phases within an overcast mixed-phase cloud. The improvement from the case studies in the radiative fluxes suggests that a larger data set should be investigated to determine the potential for the stochastic approach to be used as a mixed-phase cloud-radiation parameterization.

PUBLICATIONS:

Barton, N. P., and D. E. Veron, 2009: Modeling Radiative Transfer through Arctic Mixed-Phase Clouds Using Stochastic Techniques, Journal of Geophysical Research, withdrawn and under revision.

Foster, M. and D. E. Veron, 2008: Investigating the Shortwave Radiative Effects of Cloud Field Geometry in the Tropical Western Pacific, Journal of Geophysical Research, 113, D22205, doi:10.1029/2007JD009581.

Veron, D. E., M. Foster and J. Secora, 2004: Development of a shortwave stochastic parameterization based on observed cloud characteristics and model simulations. Journal of Geophysical Research, in preparation.

Lane-Veron, D. E., and R. C. J. Somerville, 2004: Stochastic Theory of Radiative Transfer Through Generalized Cloud Fields, *Journal of Geophysical Research*, 109, doi:10.1029/2004JD004524.

Lane, D. E., K. Goris, R. C. J. Somerville, 2002: Radiative transfer through broken cloud fields: Observations and model validation. *Journal of Climate*, 15(20), 2921-2933.

CONFERENCE PROCEEDINGS:

Veron, D. E., J. Secora, M. Foster, C. Weaver and F. Veron, 2005: Application of stochastic techniques to the ARM cloud-radiation parameterization problem, *Proceedings from the 2005 ARM Science Team Meeting*, Daytona Beach, FL, USA.

Brodie, J. F., and D. E. Veron, 2005: Application of a stochastic cloud model to mixed phase arctic clouds: an overview. *Preprint from the Eighth Conference on Polar Meteorology and Oceanography*, San Diego, CA, USA.

Veron, D. E., J. Secora and M. Foster, 2005: Investigation of shortwave radiative transfer at the arm cart sites using a multiple layer stochastic model. *Preprint from the Sixteenth Symposium on Global Change and Climate Variations*, San Diego, CA, USA.

Brodie, J. and D. E. Veron, 2004: Stochastic Radiative Transfer in Polar Mixed Phase Clouds, *EOS Trans. American Geophysical Union*, 85(47), Fall Meet. Suppl., Abstract GC51D-1070, San Francisco, CA, USA.

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Lane, D. E., R. C. J. Somerville and S. F. Iacobellis, 2003: Development of a Stochastic Cloud Parameterization. *Preprint from the Fourteenth Symposium on Global Change and Climate Variations*, Long Beach, CA, USA.

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Lane, D. E., J. O. Pinto, and J. A. Curry, 2002: Evaluation of AGCM Radiation Parameterizations in the Arctic. *Proceedings of the Pan-GEWEX Cloud System Studies Workshop*, Kananaskis, Alberta, Canada.

INVITED TALKS:

Veron, D. E., 2005: Modeling interactions between radiation and clouds using stochastic transfer theory, Gordon Research Conference on Radiation and Climate, Colby College, Waterville, ME.

Veron, D. E., 2005: Improving the representation of cloud-radiation interactions in climate models, University of Delaware, Newark, DE.

Veron, D. E., 2003: Cloud-aerosol-radiation interactions and their impact on climate. State University of New York, College at Geneseo, Geneseo, NY.

Veron, D. E., 2002: Development of a stochastic cloud-radiation parameterization. Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ.

Lane, D. E., 2002: Development of shortwave stochastic cloud-radiation parameterization. Institute for Marine and Coastal Studies, Rutgers University, New Brunswick, NJ.

CONFERENCE PRESENTATIONS:

Foster, M., D. E. Veron and J. Secora, 2005: A Cloud Shortwave Parameterization Developed Using a Stochastic Model, Gordon Research Conference on Radiation and Climate, Colby College, Waterville, ME, USA.

Veron, D. E., J. Secora, M. Foster, C. Weaver and F. Veron, 2005: Application of stochastic techniques to the ARM cloud-radiation parameterization problem, Atmospheric Radiation Measurement Program's Science Team Meeting, Daytona Beach, FL, USA.

Brodie, J. F. and D. E. Veron, 2005: Application of a stochastic cloud model to mixed phase arctic clouds: an overview, Eighth Conference on Polar Meteorology and Oceanography, San Diego, CA, USA.

Veron, D. E., J. Secora and M. Foster, 2005: Investigation of shortwave radiative transfer at the ARM CART sites using a multiple layer stochastic model, Sixteenth Symposium on Global Change and Climate Variations, San Diego, CA, USA.

Foster, M. and D. E. Veron, 2005: Modeling interactions between radiation and cloud using stochastic transfer theory, Atmospheric Radiation Measurement Program's Cloud Parameterization Meeting, Stony Brook, NY, USA.

Foster M. and D. E. Veron, 2005: A Cloud Shortwave Parameterization Developed Using a Stochastic Model, Gordon Research Conference on Radiation and Climate, Colby College, ME, USA.

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Lane, D. E., R. C. J. Somerville and S. F. Iacobellis, 2003: Development of a Stochastic Cloud Parameterization. Fourteenth Symposium on Global Change and Climate Variations, Long Beach, CA, USA.

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Lane-Veron, D. E., J. O. Pinto, and J. A. Curry, 2003: Comparison and evaluation of AGCM Radiation Parameterizations in the Arctic, Seventh Conference on Polar Meteorology and Oceanography, Hyannis, MA.

Lane-Veron, D. E., J. Secora and R. C. J. Somerville, 2003: Observations and Stochastic Modeling of Shortwave Radiative Transfer at the ARM CART Sites, American Geophysical Union Annual Fall Meeting, San Francisco, CA, USA.

Lane, D. E., R. C. J. Somerville and S. F. Iacobellis, 2002: Development of a Stochastic Cloud Parameterization, American Geophysical Union Annual Fall Meeting, San Francisco, CA, USA.

Lane, D. E., 2002: Development of a Stochastic Cloud Parameterization, Atmospheric Radiation Measurement Program's Science Team Meeting, St. Petersburg, FL, USA.