Final Scientific/Technical Report

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Project Title: Evaluation of GCM column radiation models under cloudy conditions with the ARM BBHRP Value Added Product

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Executive Summary

The overarching goal of the project was to improve the transfer of solar and thermal radiation in the most sophisticated computer tools that are currently available for climate studies, namely Global Climate Models (GCMs). This transfer can be conceptually separated into propagation of radiation under cloudy and under cloudless conditions. For cloudless conditions, the factors that affect radiation propagation are gaseous absorption and scattering, aerosol particle absorption and scattering and surface albedo and emissivity. For cloudy atmospheres the factors are the various cloud properties such as cloud fraction, amount of cloud condensate, the size of the cloud particles, and morphological cloud features such as cloud vertical location, cloud horizontal and vertical inhomogeneity and cloud shape and size. The project addressed various aspects of the influence of the above contributors to atmospheric radiative transfer variability. In particular, it examined: (a) the quality of radiative transfer for cloudless and non-complex cloudy conditions for a substantial number of radiation algorithms used in current GCMs; (b) the errors in radiative fluxes from neglecting the horizontal variabiity of cloud extinction; (c) the statistical properties of cloud horizontal and vertical cloud inhomogeneity that can be incorporated into radiative transfer codes; (d) the potential albedo effects of changes in the particle size of liquid clouds; (e) the gaseous radiative forcing in the presence of clouds; and (f) the relative contribution of clouds of different sizes to the reflectance of a cloud field. To conduct the research in the various facets of the project, data from both the DOE ARM project and other sources were used. The outcomes of the project will have tangible effects on how the calculation of radiative energy will be approached in future editions of GCMs. With better calculations of radiative energy in GCMs more reliable predictions of future climate states will be attainable, thus affecting public policy decisions with great impact to public life.

Comparison of the actual accomplishments with the goals and objectives of the project

The proposal originally submitted to DOE's ARM program aimed at the evaluation of the performance of the shortwave and longwave radiative transfer algorithms implemented in two of the US GCMs participating in IPCC activities, namely those of GFDL (AM2) and NCAR (CCM). The proposal stipulated that such an evaluation can be accomplished through the use of ARM's Broadband Heating Rate Profile evaluation product. While some of the objectives of the original proposal were accomplished (see description below), the project suffered from the inability of GFDL to provide a column radiation model to be used for the purposes of the effort (instead, the NASA-Goddard radiation package used in the GEOS-5 Large Scale Model was used). Moreover, while the CCM radiative transfer algorithm was indeed evaluated, during the period of funding it was replaced by a different package and became thus obsolete. Nevertheless, the project experienced a significant expansion in scope and accomplished the following:

- 26 radiative transfer codes were evaluated via the Continual Intercomparison of Radiation Codes (CIRC) endorsed by the GEWEX Radiation Panel and the International Radiation Commission using a reference dataset created from ARM data.

- The bias in the reflected solar flux by neglecting horizontal variation of cloud extinction was evaluated at global scales using satellite measurements.

- The theory and practical application of estimating the cloud albedo changes due to pre-defined changes in cloud particle number was developed.

- The horizontal and vertical variability (overlap) of condensate was determined from ARM observations and modeled with the aid of Cloud Resolving Model simulations using copula functions.

- The relationship between cloud size and reflectance distributions for fair weather cloud regimes was established using high resolution satellite measurements.

- The radiative forcing of tropospheric ozone and nitrogen dioxide was assessed under cloudless and cloudy conditions using satellite data.

Project Activities Summary

Research accomplishments for the duration of the project (including the no-cost extension period) are reported here in subsections covering distinct areas of scholarly activity. All research activities are closely related to ARM goals even in cases where no ARM datasets are involved.

BBHRP-based evaluation of GCM Column Radiation Models

The atmospheric and surface input datasets used for generating BBHRP radiative fluxes with the radiative transfer codes RRTM-SW and RRTM-LW were adapted for use in the GSFC and CCM GCM column radiation models. The GSFC radiation model was already available in stand-alone format, while the CCM algorithm was stripped from the full GCM package. We were then able to run these codes in “BBHRP mode” for BBHRP versions 1.4.1 (input and radiation runs available at the time of radiosonde launches) and 1.4.1tK (input and radiation runs generally available every hour). Overall statistics of radiative flux closure performance were produced for both algorithms and comparisons with standard BBHRP closure and for various classes of output (clear skies, overcast, partly cloudy, liquid, ice, mixed phase clouds, surface, top-of-the atmosphere, shortwave (SW) and longwave (LW) part of the spectrum). We found that (a) There is broad consistency between the BBHRP (RRTM) closure errors and those of the “shadow” dataset, pointing to the values or interpretations of the input as the major reason for existing radiative closure discrepancies; (b) Inter-model inconsistencies are greater for ice and mixed-phase clouds; (c) Many large SW surface closure errors are associated with very thick clouds while for thin clouds the models differ in the partitioning of total flux into direct and diffuse; (d) Overall, RRTM performs better than the other models; and (e) When all radiation budget components are accounted for (SW & LW, TOA and surface) the overall flux closure error is ~10%. This is driven largely by the LW, but is still remarkably good. During our investigation we also discovered that the CCM radiative transfer code produces spurious jumps in the LW downward flux profile immediately above the surface accompanied by overestimates in the surface flux. Further analysis revealed that the CAM radiation code sets the lowest interface (air) temperature equal to the ground (surface skin) temperature, which yields large errors when the surface-air temperature gradient is large. This restriction can be easily removed, yielding significant improvement in the downwelling LW fluxes.

As part of tests preceding the implementation of RRTMG SW/LW in the GEOS-5 modeling and assimilation system, these codes were run in "BBHRP mode" for BBHRP versions 1.4.1 and 1.4.1tK. The produced radiative fluxes showed excellent agreement with those calculated by the BBHRP algorithm which is based on the spectrally detailed multistream (for the SW) RRTM. Parallel runs of RRTMG were also conducted with the McICA method, assuming horizontally homogeneous clouds, in order to evaluate the ability of the method to reproduce the standard fluxes for different cloud fraction overlaps as function of the number of cloudy subcolumns. This is especially important for SW where RRTMG does not have a partial cloudiness formulation in non-McICA mode.

Overall, this part of the project has made important contributions to the understanding on how to use ARM data as a testbed for RT code performance, and the experience gained will hopefully assist in the design and optimization of the upcoming RIPBE VAP.

Continual Intercomparison of Radiation Codes (CIRC)

CIRC (http://circ.gsfc.nasa.gov) attracted 20 registered participants (9 USA, 2 Brazil, 2 France, 2 Russia, 1 Australia, 1 Canada, 1 UK, 1 Finland, 1 China). For Phase I results from 26 SW and LW radiative transfer codes incl. non-GCM) were submitted and are being currently evaluated as part of a paper under preparation. In addition, a BAMS article, a GEWEX newsletter and an IRS proceedings paper were published. Main findings from CIRC Phase I: (a)

Significant differences between the RT codes and deviations from LBL calculations were found; (b) LW is better simulated (LW downwelling to the surface is best quantity); (c) CO2 forcing needs to be improved, both in the longwave and shortwave parts of the spectrum; (d) The shortwave diffused downward flux can be far off, especially for 2-stream codes; (e) shortwave absorptance is another poorly simulated quantity: all codes underestimate it, some much more than others; (f) the wide-band average of spectral surface albedo is not an intrinsic surface property and the exact method of averaging can affect TOA flux by a few Wm^{-2}.

Shortwave cloud radiative forcing bias from MODIS observations

Solar radiative transfer is sensitive to horizontal cloud inhomogeneity. It is almost certain that a large contribution to the flux closure errors seen in BBHRP comes from ignoring or imperfectly accounting for horizontal cloud water variations (we limit the discussion here to non-3D effects). The global shortwave radiation impact of this inhomogeneity was examined during the project performance period with satellite observations. The study is directly relevant to ARM goals since it addresses the improvement of RT in GCMs where large errors are introduced by assuming homogeneous clouds. In a paper submitted during the reporting period, Oreopoulos et al. (2009) presented the global plane-parallel SW cloud radiative forcing (SWCRF) bias of liquid and ice clouds for four months of 2005 as inferred from global Collection 5 MODIS Terra and MODIS Aqua Level-3 datasets. We found that the absolute value of global SWCRF bias of liquid clouds at the top of the atmosphere is ~6 Wm^{-2} for MODIS overpass times, while the SWCRF bias for ice clouds is smaller in absolute terms by ~0.7 Wm^{-2}, but with stronger spatial variability. If effective radius variability is neglected (only optical thickness horizontal variations are accounted for), the absolute SWCRF biases increase by about 0.3-0.4 Wm^{-2} on average. Marine clouds of both phases exhibit greater (more negative) SWCRF biases than continental clouds. Finally, morning (Terra)–afternoon (Aqua) differences in SWCRF bias are much more pronounced for ice than liquid clouds, up to about ~15% (Aqua producing stronger negative bias) on global scales, with virtually all contribution to the difference coming from land areas. The substantial magnitude of the SWCRF bias, which for clouds of both phases is collectively about 4 Wm^{-2} for diurnal averages, should be a strong motivation to accelerate efforts that link cloud schemes accounting for subgrid condensate variability (such as the copula scheme described later) with appropriate radiative transfer schemes in global climate models.

Theoretical analysis and MODIS-based global estimates of cloud susceptibility

The indirect effect of aerosols on clouds is a research topic of great interest to ARM and could potentially be studied with ARM ground based measurements when reliable algorithms of effective cloud particle size become available. A fact often ignored in indirect effect studies is that the extent of the radiative influence of aerosol-modified clouds depends on the properties of the unperturbed cloud. This dependence is captured by the concept of “cloud susceptibility” which is essentially the sensitivity of cloud broadband SW radiative fluxes to small perturbations in the cloud droplet number concentration (CDNC) under constant condensate, water path and cloud geometrical thickness conditions. Susceptibility quantifies the aerosol indirect effect sensitivity in a way that can be easily computed from model fields. In two recent JGR publications (Platnick and Oreopoulos, 2008 and Oreopoulos and Platnick, 2008), two approaches to study this sensitivity were adopted: absolute increases in CDNC for which the radiative response is referred to as “absolute cloud susceptibility”, and relative increases in CDNC or “relative cloud susceptibility”. Absolute cloud susceptibility has a strong non-linear dependence on droplet effective radius, while relative cloud susceptibility is primarily dependent on optical thickness. Both assume maximum values for CLOWD type of clouds, i.e., optical thickness approximately between 7 and 10 and receive 15-20% percent contributions from single scattering albedo and asymmetry factor perturbations that occur in addition to cloud extinction perturbations when CDNC changes. Global distributions of liquid water cloud albedo susceptibility were estimated for four months in 2005 of MODIS Terra and Aqua Collection 5 gridded data. Geographical distributions of absolute and relative susceptibility were markedly different indicating that the detailed nature of the cloud microphysical perturbation is important for determining the radiative forcing associated with the first indirect aerosol effect. Our realistic yet moderate CDNC perturbations (10% increase) yielded “susceptibility” forcings on the order of 1-2 Wm^{-2} for the cloud optical property distributions and land surface spectral albedos observed by MODIS.

Cloud water subgrid variability analysis for GCM parameterizations

Radiative transfer in SW and LW GCM column radiation models depends among other factors on the vertical correlations of cloud fraction and water content. In Norris et al. (2008) it was shown that a general representation of GCM column cloud fraction within the PDF-based statistical cloud parameterization context can be obtained by the use of statistical functions called copulas that encapsulate the dependence structure of rank statistics in a multivariate system. Using this theory and a cloud resolving model simulation for guidance, a new formulation of GCM cloud fraction and condensate overlap was obtained. We found that a Gaussian copula with Generalized Extreme Value (GEV) marginal distributions provides estimates of column cloud fraction for a 12-layer test case using synthetic data from a Goddard Cumulus Ensemble ARM-IOP simulation that improve values of total cloud fraction and liquid water path variability obtained with a number of alternate overlap schemes. As a result, the simulation of radiative transfer also improved: Gaussian copula Monte-Carlo estimates of the SW transmittance and reflectance and the LW surface downwelling and TOA outgoing radiation showed significant improvement over other cloud generators including exact overlap methods with mean or randomized horizontal condensate distributions. Although the work addresses subgrid scale variability in both moisture and temperature, we found that as long as cloud locations are determined from the full temperature and humidity field, temperature variability can be ignored for condensate amount calculations, resulting in simpler moisture-only copulas.

During the no-cost extension, this aspect of the project was refined as follows:

(1) *The form of horizontal moisture subgrid-scale variability was further investigated*: various moisture probability density functions (PDFs) that permit both positive and negative skewness were studied. The GEV and its reverse distribution were found to give the best overall representation of horizontal moisture variability in cloud resolving model (CRM) output. Specifically, it was found, by examining 20 days of three hourly CRM output centered over the ARM Southern Great Plains site, that a skewed GEV fit provided a significant improvement over a symmetric Gaussian fit in a majority of cases. It was also shown that the occurrence of significantly skewed moisture distributions, both positive and negative, was commonplace in the simulations. In addition, we have examined the effect of grid-scale trends on these probability density functions (PDFs), since real-world variability occurs on a range of scales. Our conclusion is that at least linear trends do not seem to have a significant enough effect to warrant their inclusion in GCMs, though we leave open the possibility that higher order trends could be examined in the future. So, overall, this research finds that the statistics of horizontal moisture variability on the sub-GCM scale can be well accounted for using a GEV distribution (either standard or reversed). To use a simple Gaussian distribution implies missing much of the skewed variability found in nature, often associated with atmospheric convection of various sorts. This work was reported at the *First Atmospheric Systems Research Science Team Meeting*, Bethesda, Maryland, March 15-19, 2010, as both a poster and invited oral presentation with the title

“Modeling the distribution of sub-grid moisture variability for cloud parameterizations in Large Scale Models” by P. Norris, L. Oreopoulos, and A. da Silva.

(2) *Constraint of horizontal PDFs using condensate data*: Condensation data provides information on the part of the total water distribution above saturation. We have devised a maximum likelihood method for fitting an analytical total water PDF with this “tail” data (if the cloud fraction is large enough), while at the same time preserving the clear (unsaturated) fraction. The method was presented as a poster “Using ARM data to model cloud overlap with copulas” by P. Norris and L. Oreopoulos at the *Nineteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Louisville, Kentucky, March 30 – April 4, 2009, and further elaborated on at the *AFWA Cloud Analysis Workshop*, National Center for Atmospheric Research, Boulder, Colorado, September 1-3, 2009: “Statistical cloud parameterizations and their constraint with satellite data: Plans for cloud data assimilation in the NASA Global Modeling and Assimilation Office’s GEOS-5 data assimilation system” by P. Norris, A. da Silva, and L. Oreopoulos. The method should form an important part of future cloud data assimilation efforts within the Global Modeling and Assimilation Office (GMAO), since the condensate portion of the total water distribution is most readily retrieved by satellite and ground based instruments. It was found that the new tail fitting method can retrieve reasonably accurate GEV parameters (within about 10-20%) for cloud fractions as low as 20% with 2500 samples (roughly equivalent to a sample every 1 km^2 for a 0.5° x 0.5° GCM gridbox).

(3) *Constraint of multi-layer cloud cases using copulas*: We have also begun to address the more difficult multi-layer cloud case using a maximum-likelihood “tail fitting” routine for the Gaussian copula associated with the correlation between two partially cloudy layers. This preliminary multi-layer work was presented at the 19^{th} ARM Science Team meeting. It is promising, but requires additional development prior to publication and implementation. The method

uses actual pairs of cloud water content measurements in sections of ARM microbase data in which both layers are cloudy, together with the fractions of data in which one or both of the layers is clear. One interesting finding in these preliminary results is the occurrence of minimally overlapped (anticorrelated) layers in the data. These can be handled by the copula approach, but not by other existing cloud overlap methods.

Vertical overlap and decorrelation of cloud fraction and condensate from MICROBASE

We conducted a cloud fraction overlap and condensate rank correlation analysis using 7 years of ARM Microbase data of very high temporal (10 sec) and spatial (45 m in the vertical) resolution. We have tested the appropriateness of fitting the overlap parameter determining the relative weighting of maximum and random cloud fraction overlap and the rank correlation with inverse exponential functions. With such fits, both cloud fraction and condensate overlap can be expressed in terms of decorrelation lenghts (vertical distances at which the parameter values falls to 1/e). We obtained the annual cycle of these decorrelation lengths for our 7-year time series. For the ARM SGP site both the cloud fraction overlap and condensate rank correlation decorrelation lenghts peak in July, indicating more vertical coherence of cloud structure (less randomness) due to the predominance of summertime convective activity. The decorrelation length maximum for cloud fraction overlap peaks at 3 km, with a seasonal range between 2 and 3 km throughout the year, while for condensate the peak value of decorrelation length is lower by about a factor of three, with a seasonal range between 0.8 and 1.1 km. The relationship between cloud fraction overlap parameter and rank correlation and dependencies on cloud vertical locations were also investigated.

Cloud size and reflectance distributions of shallow cumulus clouds from Landsat

To examine the direct and indirect aerosol forcing, one must distinguish between cloud-free and cloudy areas, which is not always trivial (as ARM observations show) for CLOWD-type clouds. The original PI co-authored the paper Koren et al. (2008), which uses Landsat data to examine the size distribution and optical properties of small, sparse cumulus and the associated optical properties of what is presumably cloud-free atmosphere within the cloud field. The study showed that the separation into clear and cloudy skies is, as expected, resolution dependent and misclassifications lead to large errors in the estimated aerosol direct radiative forcing. Essentially, the nature of the cloud size distribution of shallow cumulus is such that, at any resolution, a significant fraction of the clouds are missed, and their properties are attributed to apparently clear skies. It was also found that the largest contribution to the total cloud fraction and reflectance comes from the smallest clouds. Upon changing the resolution from 30 m to 1 km (Landsat to MODIS) the average 'non-cloudy' reflectance at 1.65 μm increased more than 25%, the cloud reflectance decreased by half, and cloud coverage doubled, resulting in a significant overestimate of aerosol forcing on the order of 1 Wm^{-2} per cloud field.

Radiative forcing of tropospheric ozone from satellite observations

Estimates of the radiative forcing due to anthropogenically-produced tropospheric O_3 are derived primarily from models. The original PI participated in a study where tropospheric ozone and cloud data from several instruments in the A-train constellation of satellites are used in conjunction with information from the GEOS-5 Data Assimilation System to accurately estimate the instantaneous radiative forcing from tropospheric O_3 for January and July 2005. The work improves upon previous estimates of tropospheric ozone mixing ratios from a residual approach using the NASA Earth Observing System (EOS) Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) by incorporating cloud pressure information from OMI. Since we cannot distinguish between natural and anthropogenic sources with the satellite data, our estimates reflect the total forcing due to tropospheric O_3. We focused specifically on the magnitude and spatial structure of the cloud effect on both the shortwave and longwave radiative forcing. The estimates produced by this work (~1.3 Wm^{-2} net radiative forcing, reduced by ~16% by clouds compared to clear-sky conditions — individual shortwave and longwave cloud effects are larger at +87% and -24% respectively) can be used to validate present day $O_3$3 radiative forcing produced by models and quoted in IPCC assessments.

Radiative forcing of nitrogen dioxide from satellite observations

NO_2, a mostly anthropogenic gas, absorbs solar radiation at ultraviolet and visible wavelengths. We parameterized NO_2 absorption for fast radiative transfer calculations and along with cloud, surface, and NO_2 information from different sensors in the NASA A-train constellation of satellites as well as NO_2 profiles from the Global Modeling Initiative (GMI), we computed the global distribution of net atmospheric heating (NAH) due to tropospheric NO_2 for January and July 2005. While the globally-averaged NAH values due to tropospheric NO_2 are very low, 0.05 W/m2, the local instantaneous NAH can be as high as 2–4 W/m2 in heavily polluted areas. Clouds reduce the globally-averaged NAH values by 5–6% only, but because most of NO_2 is contained in the boundary layer in polluted regions, the cloud shielding effect can significantly reduce the net atmospheric heating due to tropospheric NO_2 up to 50%. We found that diurnal variations in NO_2 emissions and chemistry have only a small impact on daily-averaged NAH. Examination of the sensitivity of NO_2 absorption to various geophysical conditions such as vertical distributions of cloud optical depth and NO_2 revealed that the maximum effect of NO_2 on downwelling radiance occurs when the NO_2 is located in the middle part of the cloud where the optical extinction peaks.

Products developed under the award and technology transfer activities

Websites

http://circ.gsfc.nasa.gov

Journal Articles

Joiner, J., M. R. Schoeberl, A. P. Vasilkov, L. Oreopoulos, S. Platnick, N. J. Livesey, and P. F. Levelt, 2009: Accurate satellite-derived estimates of the tropospheric ozone impact on the global radiation budget. *Atmos. Chem. Phys.*, 9, 4447-4465.

Koren, I., L. Oreopoulos, G. Feingold, L. A. Remer, and O. Altaratz, 2008: How small is a small cloud? *Atmos. Chem. Phys.*, **8**, 3855-3864.

Norris, P. M., L. Oreopoulos, A. Y. Hou, W-K Tao, X. Zeng, 2008: Representation of 3D heterogeneous cloud fields using copulas: Theory for water clouds. *Q. J. R. Meteorol. Soc.,* **134**: 1843-1864. doi:10.1002/qj.321.

Oreopoulos, L., and S. Platnick, 2008: The radiative susceptibility of cloudy atmospheres to droplet number perturbations: 2. Global analysis from MODIS. *J. Geophys. Res.*, **113**, D14S21, doi:10.1029/2007JD009655.

Oreopoulos, L., S. Platnick, G. Hong, P. Yang, and R. F. Cahalan, 2009: The shortwave radiative forcing bias of liquid and ice clouds from MODIS observations. *Atmos. Chem. Phys.* 9, 5865-5875.

Oreopoulos, L., and E. Mlawer, 2009: CIRC to Provide Key Intercomparisons of GCM Radiative Transfer Codes Prior to Next IPCC Assessment. GEWEX Feb 09 Newsletter, 8.

Oreopoulos, L., and E. Mlawer, 2010: The Continual Intercomparison of Radiation Codes (CIRC): Assessing anew the quality of GCM radiation algorithms. *Bull. Am. Met. Soc.*, March 2010, 305-310.

Platnick, S., and L. Oreopoulos, 2008: The radiative susceptibility of cloudy atmospheres to droplet number perturbations: 1. Theoretical analysis and examples from MODIS. *J. Geophys. Res.*, **113**, D14S20, doi:10.1029/2007JD009654.

Vasilkov, A. P., J. Joiner, L. Oreopoulos, J. F. Gleason, P. Veefkind, E. Bucsela, E. A. Celarier, R. J. D. Spurr, and S. Platnick, 2009: Impact of tropospheric nitrogen dioxide on the regional radiation budget. *Atmos. Chem. Phys.* 9, 6389-6400.

Conference Posters, Oral Presentations and Extended Abstracts

Bhattacharjee, P., L. Oreopoulos, Y. Sud, J. Wang, R. Yang: Inclusion of Ammonium Sulfate Aerosols in McRAS-AC: an SCM Evaluation. Poster at the *First Atmospheric Systems Research Science Team Meeting*, Bethesda, Maryland, March 15-19, 2010.

Norris, P. and L. Oreopoulos: Using ARM data to model cloud overlap with copulas. Poster at the *Nineteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* Louisville, Kentucky, March 30 – April 4, 2009.

Norris, P., A. da Silva, and L. Oreopoulos: Statistical cloud parameterizations and their constraint with satellite data: Plans for cloud data assimilation in the NASA Global Modeling and Assimilation Office’s GEOS-5 data assimilation system. Oral presentation at the *AFWA Cloud Analysis Workshop*, National Center for Atmospheric Research, Boulder, Colorado, September 1-3, 2009.

Norris, P. M., L. Oreopoulos, and A. M. da Silva: Modeling the distribution of sub-grid moisture variability for cloud parameterizations in Large Scale Models. Invited oral presentation and Poster at the *First Atmospheric Systems Research Science Team Meeting*, Bethesda, Maryland, March 15-19, 2010.

Oreopoulos, L., 2007: Characterization of cloud heterogeneity and susceptibility from MODIS measurements, invited talk at the Physics dept. of Univ. of Athens, Greece, November 2007.

Oreopoulos, L., 2007: How MODIS observations can be used to quantify cloud heterogeneity and susceptibiltiy, invited talk at the National Observatory of Athens, Greece, November 2007.

Oreopoulos, L., 2007: Status of CIRC, oral presentation at the annual GEWEX Radiation Panel Meeting, Buzios, Brazil, October 2007.

Oreopoulos, L., 2007: An update on CIRC, oral presentation at the Joint ARM Aerosol and Radiative Processes working group meeting, Madison, WI, September 2007.

Oreopoulos L., et al., 2007: The Continuous Intercomparison of Radiation Codes (CIRC): Phase I cases, poster presented at 17th ARM Science Team Meeting, Monterey. CA, March 2007.

Oreopoulos L., et al., 2008: Evaluating BBHRP radiative flux closure under cloudy conditions with a “shadow” dataset, poster presented at the 18th ARM Science Team Meeting, Norfolk, VA, March 2008.

Oreopoulos, L. et al., 2008: CIRC: status and update, oral presentation at the annual GEWEX Radiation Panel Meeting, Jeju, S. Korea, October 2008.

Oreopoulos, L., et al., 2008, Indirect aerosol forcing and cloud susceptibility, oral presentation at the Joint ARM Cloud Properties and Aerosol working group meeting, Lansdowne, VA, November, 2008.

Oreopoulos, L., et al., 2008, CIRC: status and update, oral presentation at the Joint ARM Radiative Processes and Cloud Modeling working group meeting, Princeton, NJ, November, 2008.

Oreopoulos, L., et al., 2008, Clouds and copulas: a new approach to cloud overlap, oral presentation at the Joint ARM Radiative Processes and Cloud Modeling working group meeting, Princeton, NJ, November, 2008.

Oreopoulos, L., E. Mlawer, J. Delamere, and T. Shippert, 2009: The Continual Intercomparison of Radiation Codes (CIRC): A New Standard for Evaluating GCM Radiation Codes. *Current Problems in Atmospheric Radiation (IRS 2008 Proceedings)*, 73-76.

Oreopoulos, L., S. E. Platnick, G. Hong, P. Yang, and R. F. Cahalan, 2009: The Shortwave Radiative Forcing Bias of Homogeneous Liquid and Ice Clouds Observed by MODIS. *Current Problems in Atmospheric Radiation (IRS 2008 Proceedings)*, **9**, 5865-5875.

Oreopoulos, L., et al., 2009: Results from Phase I of the Continual Intercomparison of Radiation Codes (CIRC). Poster presented at the 19th ARM STM, Louisville, KY, March 2009.

Oreopoulos, L. and E. Mlawer, 2009: CIRC: status and update, oral presentation at the annual GEWEX Radiation Panel Meeting, Rostock, Germany, October 2009.

Oreopoulos, L., and P. Norris: The Skill of Cloud Fraction and Condensate Decorrelation Lengths to Reproduce Cloud Field Statistics According to a High Resolution MICROBASE Data Set Poster at the *First Atmospheric Systems Research Science Team Meeting*, Bethesda, Maryland, March 15-19, 2010.

Shippert, T. et al. incl. L. Oreopoulos: Radiatively Important Parameters Best Estimate (RIPBE) Value-added Product (VAP). Poster at the *First Atmospheric Systems Research Science Team Meeting*, Bethesda, Maryland, March 15-19, 2010.