

Constraining clouds in large-scale models with satellite observations

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1 Introduction and motivation

Clouds are a key piece of the global climate system, but accurate modeling of clouds in large-scale models is difficult, and cloud feedbacks in global climate models (GCMs) are recognized as a primary contributor to inter-model differences in responses to climate forcings (e.g., Cess et al., 1990; Bony and Dufresne, 2005; Williams and Webb, 2009; Medeiros et al., 2008).

Evaluating clouds in simulations of present day climate against observations provides a first-order test of their representation models. Satellite observations of clouds serve as a useful baseline for evaluation because they provide near global coverage and sample all meteorological regimes. But comparisons of this sort can be challenging because the quantities measurable from space are different from those that can be simulated by models. While models can diagnose cloud properties directly (e.g., cloud fraction, cloud height, cloud liquid and ice water content, particle size, etc.), satellite retrievals must infer these quantities from measured radiances using inversion techniques. Cloud properties retrieved by these techniques can often carry large uncertainties and inherent biases due to the challenges and limitations of the instruments and inversions (e.g., Marchand et al., 2010; Pincus et al., 2012).

Satellite instrument simulators such as those available in the Cloud Feedback Model Intercomparison Project (CFMIP; Bony et al., 2011) Observation Simulator Package (COSP; Bodas-Salcedo et al., 2011) have emerged as a means to account for the limitations of satellite retrievals, thereby enabling more consistent comparisons between satellite observations of clouds and model representations of clouds (e.g., Klein and Jakob, 1999; Bodas-Salcedo et al., 2011; Zhang et al., 2005; Marchand and Ackerman, 2010; Kay et al., 2012; Klein et al., 2013; Pincus et al., 2012). The purpose of the simulators is to produce synthetic observations for specific high-level satellite observation products given a model atmospheric state. To the extent that the simulators accurately account for the limitations and features of the specific satellite retrievals, the resulting diagnostics are taken to be directly comparable to the corresponding satellite data. But the performance of these simulators have seen little scrutiny (Mace et al., 2010), and any remaining uncertainties and ambiguities in comparisons involving observations from satellites with satellite-simulated model diagnostics potentially

undermines the robustness of the conclusions of such comparisons.

The goal of this research is to quantify uncertainties in comparisons between models and observations using instrument simulators and remove ambiguities in those comparisons that result from assumptions about the unresolved cloud and precipitation structure by providing an improved representation of that structure for use in both GCM radiation parameterizations and satellite instrument simulators. In doing so, the results of this research will lead to more robust model evaluation practices and greater confidence in diagnosed biases in model cloud statistics, and lead to future improvements in the way the small-scale cloud and precipitation properties are treated in global models.

2 Background

Simulating satellite-observable retrieval products from GCM output using COSP is a three-part process. First, the mis-match in resolved scales between the satellite pixel and model resolution is accounted for by downscaling the gridbox mean cloud properties (the subgrid generator). Second, the known limitations and features of the satellite retrieval products are emulated by applying algorithms that account for assumptions consistent with the individual satellite instruments and retrieval methodologies (the forward operators). Lastly, the subgrid-level simulator outputs are aggregated to produce statistical summaries consistent with the available satellite statistical summaries. There are two primary sources of uncertainty in this process: sensitivity of the simulated diagnostics to the statistical downscaling of the gridbox means, and inaccuracy or incompleteness in the simulator forward operators in accounting for limitations in the satellite retrievals.

The complexity of simulating the climate system and current computational resources limit GCM resolutions to tens or hundreds of kilometers, but clouds occur and vary on much smaller spatial scales. This means that traditional GCMs are unable to resolve individual clouds, and instead descriptions of clouds in GCMs are limited to large-scale statistical summaries of cloud properties (gridbox means). In order to account for the effect of overlapping multiple cloud layers on satellite retrievals, subcolumn profiles of individual cloud elements must be inferred from the gridbox means. This downscaling is done within COSP by generating an ensemble of subcolumns for each GCM gridbox that is consistent with the gridbox mean cloud properties. But the large-scale mean description of cloud properties alone is insufficient to uniquely specify how individual cloud elements should be distributed vertically and horizontally within the gridbox, and inferring subgrid structure depends on additional assumptions about how clouds in different layers should overlap and how cloud properties should be distributed within each gridbox.

Subgrid cloud fields in COSP are stochastically generated consistent with the overlap assumptions used in the radiative transfer parameterization that describe how individual clouds are assumed to align vertically. These are usually simple rules, such as the popular maximum-random overlap assumption (Geleyn and Hollingsworth, 1979) in which clouds in adjacent layers are assumed to overlap maximally (perfect correlation)

and clouds in non-adjacent layers are assumed to overlap randomly (zero correlation). However, a number of studies have shown that this simple specification of overlap fails to capture the complexity of clouds in nature (e.g., Hogan and Illingworth, 2000; Mace and Benson-Troth, 2002; Pincus et al., 2005; Barker, 2008) and can lead to substantial biases in calculated radiative fluxes and heating rates (Barker et al., 1999; Oreopoulos et al., 2012). Because the satellite simulators attempt to account for the effects of multiple overlapping cloud layers on the retrievals (such as screening of low clouds by high clouds) it is likely that the simulators will likewise be sensitive to assumptions about cloud overlap. Cloud properties (liquid and ice water contents and effective radii) are often assumed to be homogeneous over the entire cloudy portion of model gridboxes, but studies have shown that this assumption is also inappropriate and leads to errors in radiative fluxes and heating rates (Barker et al., 1999; Oreopoulos et al., 2012). The sensitivity of simulated satellite-observable diagnostics to this unresolved variability has not been evaluated, but it is likely to be important as well especially for quantities with a non-linear dependence on cloud properties (e.g., radar reflectivity). Radar reflectivity is also highly sensitive to precipitation, and radar reflectivity simulated by COSP will likely to be sensitive to the treatment of precipitation overlap and variability as well (e.g., Di Michele et al., 2012). Sensitivity to these assumptions would imply that inaccurate assumptions about the unresolved scales in models could lead to inaccurate conclusions about the simulated cloud statistics even if a model is capable of accurately diagnosing the large-scale mean cloud properties, thus undermining conclusions reached in model-observation comparisons.

Inaccurately or incompletely accounting for the limitations of satellite retrievals is another potential source of ambiguity in model evaluations. Satellite simulators have been used extensively in global model evaluations (e.g., Kay et al., 2012; Klein et al., 2013), but often without a rigorous validation of the simulators themselves (Mace et al., 2010). A danger in using simulators to remove ambiguities in comparisons between models and observations lies in naively assuming that all ambiguities are removed in these comparisons, and that differences between observed and simulated cloud statistics therefore represent actual model biases and not just unaccounted for observational biases. An evaluation of the MISR and ISCCP simulators is proposed in the following section to quantify these uncertainties.

3 Proposed work

3.1 Evaluation of ISCCP and MISR simulators

The ISCCP and MISR simulators take profiles of a model atmospheric state and attempt to determine the cloud top height and column cloud optical depth that would be retrieved by the satellite. It is assumed that if the inputs are correct, then the cloud top height and optical depth calculated by the simulator will be representative of what the satellite would retrieve. But the performance of the simulators in accurately

accounting for the limitations of the satellite retrievals has not been extensively tested and documented.

Mace et al. (2010) performed a preliminary evaluation of the ISCCP simulator by using as input extinction and atmospheric profiles derived from ground-based data at the Atmospheric Radiation Measurement program (ARM) Southern Great Plains (SGP) site and comparing the simulated cloud top pressure and optical depth with collocated ISCCP retrievals. The results of their study suggest that the ISCCP simulator brings the diagnosed cloud top pressure from ARM measurements closer to those retrieved from ISCCP, indicating that the simulator reasonably accounted for features in the ISCCP retrieval of cloud top pressure. However, differences between the ISCCP-retrieved and ISCCP-simulated cloud top pressure remained unaccounted for, and the simulator fails to account for biases in ISCCP-retrieved cloud optical depths.

While the Mace et al. (2010) study provides a first-step toward identifying ambiguities in the simulator forward operators, the results are limited to a single geographic site (which severely limits the meteorology and cloud regimes sampled), and only evaluates the performance of the ISCCP simulator. Remaining differences between the simulated and retrieved ISCCP cloud top pressure also suggest that more work should be done to understand the uncertainties in these comparisons, and in simulated diagnostics from the MISR and MODIS simulators as well. A similar analysis technique will be employed here to evaluate the performance and sensitivity of the ISCCP and MISR simulator over a larger geographic region, and to evaluate multi-layer statistics such as those described in Marchand et al. (2010) and Marchand and Ackerman (2010).

An evaluation of the simulators over a broader geographic region and a greater diversity of cloud regimes is proposed. Extending the analysis technique used by Mace et al. (2010) is dependent on being able to obtain the needed inputs with high confidence, which include profiles of extinction, temperature, relative humidity, and visible and infrared radiances. Satellite measurements are an attractive option for the source of these inputs because they provide data with large spatial coverage, enabling an evaluation across a large diversity of cloud regimes in different geographic regions. The CloudSat cloud profiling radar (Stephens et al., 2002) and the CALIPSO lidar (Winker et al., 2007) have proven to be capable of accurately retrieving profiles of hydrometeor layers Mace et al. (2009), and Mace and Wrenn (2013) describe a method for deriving extinction profiles from a combination of observations from CloudSat, CALIPSO, and MODIS. Temperature and relative humidity profiles are taken from ECMWF reanalysis mapped to the CloudSat orbit and height bins. Mace and Wrenn (2013) use these as inputs to the ISCCP simulator in order to characterize the different types of hydrometeor profiles that can be categorized into the different ISCCP CTP-OD histogram bins. But these profiles also allow evaluation of the ISCCP simulator against ISCCP observations, and the analysis can be naturally extended to include the MISR simulator and observations.

While deriving the inputs to the simulators from other satellite data enables an evaluation over a larger geographic range, it also introduces other challenges:

1. Because the satellites from which the inputs are derived and the satellites for which simulated-

observations are to be evaluated are in different orbits, it is impossible to compare the simulated observations directly for each individual profile. Instead, only aggregated statistics (over a given region and time period) will be comparable.

2. Uncertainties are introduced into the analysis by using satellite-retrieved cloud properties. CloudSat and CALIPSO are able to characterize the structure of hydrometeor layers accurately, but microphysical retrievals from radar reflectivity measurements can carry large uncertainties due to the presence of precipitation.
3. The Mace and Wrenn (2013) retrieval uses MODIS column optical depths to constrain the extinction profiles. But the MODIS optical depth retrieval is known to be biased due to the limitations of 1D radiative transfer and the sampling restrictions of the MODIS retrieval (Pincus et al., 2012). Because MISR uses a similar optical depth retrieval that is also limited by 1D radiative transfer (Marchand et al., 2010), the optical depth will likely be similarly biased, and any significant differences will likely be due to the sampling issues with the MODIS clear-sky retrieval. This limits the evaluation to the simulation of cloud top height.

After deriving the extinction profiles, the analysis technique is straightforward. The derived profiles will be used as inputs to the MISR and ISCCP simulators along with thermodynamic profiles from ECMWF reanalysis mapped to the CloudSat orbit. Cloud top height output from the simulators will be aggregated for selected regions and time periods and compared to similarly aggregated MISR and ISCCP observations. The differences will be compared against the sampling uncertainties and the uncertainties arising from the two different retrieval techniques to determine where differences are significant. In order to further evaluate the uncertainties in the simulators, the thresholds used within the MISR simulator that determine where MISR is able to see through thin cloud layers will be adjusted within reasonable values and the differences in the outputs compared against the sampling uncertainties as well to determine the sensitivity to these choices.

3.2 Sensitivity of satellite-observable cloud diagnostics to unresolved cloud and precipitation structure

The sensitivity of COSP-simulated diagnostics to assumptions about unresolved cloud and precipitation structure can be evaluated by using fields with fully resolved cloud and precipitation structure as inputs to the simulators themselves, and then modifying the inputs to mimic the assumptions about overlap and variability used in GCMs. Outputs from the modified fields can then be compared to the outputs from the unmodified fields to quantify the sensitivity of the outputs to the assumptions mimicked by the modifications.

Options for the source of resolved cloud and precipitation properties is somewhat limited. Previous studies have used cloud resolving model (CRM) simulations in a similar manner to evaluate the sensitivity of radiative fluxes (Barker et al., 1999; Wu and Liang, 2005), but this limits the analysis to the specific conditions represented by the case studies. A more comprehensive sampling of different meteorological regimes is obtained for this study by using output from the Multi-scale Modeling Framework (MMF; Randall et al., 2003). The MMF replaces the cloud parameterizations in a traditional GCM with a 2D cloud resolving model in each gridbox. This provides global fields with resolved subgrid structure that can be passed directly to the individual instrument simulators within COSP. While these fields may not be perfectly accurate depictions of hydrometeor fields in nature, as long as the variability in these fields is reasonable they are sufficient for the purpose of evaluating the sensitivity of the diagnostics to the variability (perform comparison of overlap statistics and condensate PDFs compared to those derived from CloudSat to show that this is true?).

There are four main questions to be answered regarding sensitivity to subgrid cloud and precipitation structure:

1. Occurrence overlap: how important is the vertical correlation in cloud and precipitation occurrence?
2. Heterogeneity: how important is local variability in cloud and precipitation condensate amount?
3. Condensate overlap: for heterogeneous condensate, how important is vertical correlation in condensate amount?
4. Phase overlap: how important is correlation between hydrometeors of different species (cloud and precipitation)?

To begin to answer these questions and to motivate the work to improve the representation of overlap and heterogeneity, the following set of modified MMF fields are passed as input to the simulators directly:

- CRM: The original CRM fields within each gridbox of the MMF are used as inputs to the individual instrument simulators in COSP. This provides a baseline for comparison.
- CRM-AVG: hydrometeor mixing ratios are replaced with in-cloud averages, but the locations of hydrometeors (both cloud and precipitation) are retained from the full CRM fields. This set of modified fields mimics the layer homogeneous assumption, while retaining exact overlap. Any differences between this case and the full CRM case represent errors arising solely due to the assumption of homogeneous cloud and precipitation properties.
- CRM-RES: hydrometeor mixing ratios are resampled from the full distribution of mixing ratios from the CRM fields at each level, while again retaining the locations of hydrometeors from the full CRM fields. This modification tests the importance of condensate and phase overlap, since any vertical correlation in the original CRM condensate amount is destroyed by the resampling.

The above described simulations have been performed with a month of MMF output from the Super-Parameterized Community Atmosphere Model (SP-CAM). Preliminary results suggest that the simulated diagnostics are sensitive to condensate heterogeneity and condensate and phase overlap, as expected. While these simple tests are useful, they do not completely answer the questions posed above, and do not separate the sensitivity of the diagnostics to the different assumptions. That is, difference between the CRM-RES simulation and the CRM simulation arise due to both condensate and phase overlap errors. These simple simulations also do not test the sensitivity of the diagnostics to occurrence overlap. These questions will be revisited in the context of improvements in the treatment of subgrid cloud and precipitation structure in the following section.

3.3 Improving the representation of unresolved cloud and precipitation structure in large-scale models

The sensitivity of simulated satellite diagnostics identified in the previous section and the sensitivity of radiative fluxes and heating rates discussed in the background both motivate efforts to improve the representation of unresolved cloud and precipitation structure for use in radiative transfer parameterizations and in calculating satellite-observable diagnostics. This is the focus of this section, and the primary contribution of this research.

The development of the Monte Carlo Independent Column approximation (McICA; Pincus et al., 2003) has opened the door for more complete treatments of the subgrid variability of cloud overlap and condensate amount by providing a computationally feasible means of computing radiative fluxes on stochastically generated subcolumns that sample different cloud states. Räisänen et al. (2004) outline a subcolumn sampling strategy compatible with McICA that includes the ability to treat cloud occurrence and condensate overlap in a more flexible manner than has traditionally been used in GCMs. The Räisänen et al. (2004) generator allows for “generalized overlap”, in which cloud overlap is assumed to be a linear combination of maximum and random overlap following Hogan and Illingworth (2000). Generalized overlap is defined as follows: let $C_{\max} = \max(c_i, c_j)$ be the vertically projected cloud cover assuming maximal overlap due to two overlapped layers i, j with partial cloud fractions c_i, c_j , and let $C_{\text{ran}} = c_i + c_j - c_i c_j$ be the vertically projected cloud cover assuming random overlap due to two overlapped layers. Then the true vertically projected cloud cover C is approximated by the generalized overlap C_{gen} , where

$$C_{\text{gen}} = \alpha C_{\max} + (1 - \alpha) C_{\text{ran}}$$

where α is the overlap parameter that determines the weighting between maximal and random overlap. Hogan and Illingworth (2000) suggest that α can be approximated as a decaying exponential function of the

separation distance Δz between two layers, such that

$$\alpha(\Delta z) = \exp\left(-\frac{\Delta z}{z_0}\right)$$

where z_0 is the “e-folding” or “decorrelation” length and describes the rate at which overlap changes from maximum to random.

For heterogeneous hydrometeor fields, it has been suggested that the condensate overlap can be formulated in terms of a rank correlation r between layers that specifies the degree to which the distribution of condensate amounts in the two layers are lined up (e.g., Räisänen et al., 2004; Pincus et al., 2005). Assuming a similar exponential dependence for r as for the cloud occurrence overlap α ,

$$r(\Delta z) = \exp\left(-\frac{\Delta z}{z_{0,q}}\right)$$

where $z_{0,q}$ is the rank correlation for condensate between two layers separated by a distance Δz .

This is a good start to the problem of improving the representation of unresolved cloud structure, but a number of challenges remain to implementing this in GCMs and in improving the subgrid treatment in COSP.

1. The decorrelation lengths need to be specified. Some models have already implemented this framework using a constant decorrelation length for occurrence overlap (e.g., Donner et al., 2011), but observed decorrelation lengths have been shown to vary geographically and seasonally (Hogan and Illingworth, 2000; Mace and Benson-Troth, 2002; Barker, 2008). A more appropriate specification than constant values would be to parameterize decorrelation lengths in terms of the large-scale GCM fields, but this will require more work than has been done.
2. In order to generate subcolumns with heterogeneous condensate, PDFs of condensate amount need to be specified. The trend toward statistical cloud schemes in GCMs (e.g, Tompkins, 2002; Golaz et al., 2002) will hopefully provide these PDFs at some point. But this still leaves the problem of determining precipitation condensate, which is relevant to the simulated radar reflectivity.
3. Precipitation overlap has not been considered, as this is typically not included in GCM radiative transfer parameterizations. Precipitation fraction, overlap, and variability are important for simulated radar reflectivity and this subgrid framework will need to be modified to include these effects.
4. How to overlap condensate of different phases needs to be specified (cloud and precipitation). Di Michele et al. (2012) implement a simple method in which precipitation overlaps maximally with cloud. This is a good starting point for improving upon this problem.

Given this framework and the above remaining challenges, the following work is proposed to improve the representation of cloud and precipitation structure in GCMs and COSP diagnostics:

- Study hydrometeor structure in MMF output and in CloudSat data to determine relationships between decorrelation lengths and geophysical fields in GCMs.
- Implement the Räisänen et al. (2004) subcolumn generator into the COSP code to replace SCOPS, with modifications to include precipitation. Generalized overlap for cloud and precipitation occurrence and condensate with decorrelation lengths parameterized from above study using MMF output and CloudSat data.
- Determine appropriate condensate PDFs to use in the absence of PDFs from statistical cloud schemes (Oreopoulos et al. (2012) suggest beta distribution or other skewed distributions). Study MMF output and CloudSat data to determine this.
- Use the MMF to test the sensitivity of COSP diagnostics to specification and parameterization of decorrelation length scales.

The result of this work will be a parameterization of subgrid cloud and precipitation suitable for inclusion in traditional GCMs. Implementing this into a GCM is beyond the scope of this work but is a natural extension and next step.

4 Expected outcomes

- Quantitative evaluation of the performance of the MISR and ISCCP simulators in accounting for the limitations of the satellite retrievals.
- Characterization of cloud and precipitation overlap statistics and condensate variability, and parameterization of these statistics suitable for implementation in a GCM
- Implementation of (Räisänen et al., 2004) subgrid generator into COSP code with extensions for improved treatment of precipitation.
- Quantitative evaluation of the sensitivity of MISR, ISCCP, MODIS, CloudSat, CALIPSO simulator diagnostics to assumptions about unresolved cloud and precipitation structure and to improvements in that structure.

5 Timeline

- Autumn 2014: complete evaluation of MISR and ISCCP uncertainties.

- Winter and Spring 2015: study MMF output and CloudSat data to characterize cloud and precipitation overlap parameters and condensate variability. Use MMF to parameterize these in terms of large-scale variables available in GCMs
- Summer 2015: Implement my improved subgrid cloud and precipitation generator into COSP code and test sensitivity of diagnostics to subgrid structure using MMF output; write and defend dissertation.

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