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Impacts of cloud overlap assumptions on radiative budgets and heating fields in convective regions

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ABSTRACT

Impacts of cloud overlap assumptions on radiative budgets and heating fields are explored with the aid of a cloud-resolving model (CRM), which provided cloud geometry as well as cloud micro and macro properties. Large-scale forcing data to drive the CRM are from TRMM Kwajalein Experiment and the Global Atmospheric Research Program's Atlantic Tropical Experiment field campaigns during which abundant convective systems were observed. The investigated overlap assumptions include those that were traditional and widely used in the past and the one that was recently addressed by Hogan and Illingworth (2000), in which the vertically projected cloud fraction is expressed by a linear combination of maximum and random overlap, with the weighting coefficient depending on the so-called decorrelation length L_{cf}. Results show that both shortwave and longwave cloud radiative forcings (SWCF/LWCF) are significantly underestimated under maximum (MO) and maximum-random (MRO) overlap assumptions, whereas remarkably overestimated under the random overlap (RO) assumption in comparison with that using CRM inherent cloud geometry. These biases can reach as high as 100 $\mathrm{Wm^{-2}}$ for SWCF and 60 $\mathrm{Wm^{-2}}$ for LWCF. By its very nature, the general overlap (GenO) assumption exhibits an encouraging performance on both SWCF and LWCF simulations, with the biases almost reduced by 3-fold compared with traditional overlap assumptions. The superiority of GenO assumption is also manifested in the simulation of shortwave and longwave radiative heating fields, which are either significantly overestimated or underestimated under traditional overlap assumptions. The study also pointed out the deficiency of constant assumption on L_{cf} in GenO assumption. Further examinations indicate that the CRM diagnostic L_{cf} varies among different cloud types and tends to be stratified in the vertical. The new parameterization that takes into account variation of L_{cf} in the vertical well reproduces such a relationship and leads to better simulations on radiative heating fields. It is therefore desirable to specify or parameterize L_{cf} in terms of cloud categories rather than constantly specified if to further improve the model performance.

1. Introduction

Clouds play an important role in modulating atmospheric circulations and climate change via regulating Earth's hydrological and energy cycles. Cloud parameterization in general circulation models (GCMs) still contributes to one of the largest uncertainties in climate modeling (Weare, 2001; Bony and Dufresne, 2005). Over the past decade, great efforts have been devoted to improving the representation of cloud microphysics and macrophysics in GCMs. These include sophisticated stratiform condensation schemes that explicitly treat cloud microphysical processes such as condensation (evaporation), deposition (sublimation), and coagulation (Morrision et al., 2005; Kuell and Bott, 2014), as well as advanced cloud cover schemes that are capable of representing subgrid-scale nature of cloud processes (Golaz et al., 2002). However, the challenge still exists even if cloud condensate and amount were perfectly simulated, because cloud morphology yet remains unresolved. For most GCMs, clouds are assumed to have plane-parallel geometry, so cloud morphology is particularly referred to the degree of vertical overlap. In reality, various kinds of overlap can occur. For example, two patches of cloud at different altitudes can be non-overlapped, maximally overlapped as in a convective tower or randomly overlapped as in flat cumulus and cirrus.

Cloud overlap has a great impact on both precipitation and radiation processes (Jakob and Klein, 1999, 2000). Different overlap assumptions can lead to large differences in radiative budgets (Barker et al., 1999, 2003). In the past, a few overlap assumptions have been proposed, including random (RO), maximum (MO), and their combination: maximum/random (MRO), which is assumed to be maximally overlapped between clouds in adjacent levels and randomly overlapped between groups of clouds separated by one or more clear layers. Recently, Hogan and Illingworth (2000) addressed a generalized form of cloud overlap (GenO) in which the vertically projected cloud fraction is expressed by a linear combination of maximum and random overlap. Distinguished from MRO that is abruptly switched between MO and RO, a weighting coefficient related with decorrelation length L_{cf} is introduced in GenO to smoothly incorporate the two. Barker (2008) applied

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Table 1
Experiment descriptions.

Experiment name	Description
RO	Radom overlap
MO	Maximum overlap
MRO	Maximum/Radom overlap
GenO	Generalized form of cloud overlap ($L_{cf} = 2$ km)

this method and found global median L_{cf} is ~2 km by using two months of cloud mask data from CloudSat and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite measurements. Furthermore, Zhang et al. (2013) extended Barker's work in Eastern Asia and found the average L_{cf} is ~2.5 km.

While the GenO method is conceptually advanced, it is desirable to objectively evaluate its performance and compare it with traditional overlap assumptions, which are still employed in a majority of GCMs. Although cloud overlap impacts on radiative budgets and climate have been studied in many previous studies using either regional or global models (e.g. Liang and Wang, 1997; Zhang and Jing, 2010; Willen et al., 2005), few focused on idealized cases using CRM inherent cloud geometry as a reference. Wu and Liang (2005) used month-long cloud-resolving model simulations to investigate the impacts of cloud optical property and geometry on the simulation of radiation. This study, however, addresses a more limited issue: Given a particular plane-parallel homogenous cloud field, how radiative characteristics behave under different cloud overlap assumptions and how much are their biases against the realistic cloud geometry? Because cloud-resolving models are fine enough that the atmosphere can be considered as a binary mixture of completely clear and cloud-filled elements, and bear at least some resemblance to reality (Raisanen et al., 2004), the CRM explicit simulation can be deemed as a good surrogate for realistic cloud geometry. Two field experimental campaigns with abundant cloud systems are selected: the Tropical Rainfall Measuring Mission (TRMM) Kwajalein Experiment (KWAJEX) and the Global Atmospheric Research Program's Atlantic Tropical Experiment (GATE).

The paper is structured as follows: Section 2 introduces models and experiments. Section 3 compares the radiative budgets and heating fields under various overlap assumptions. Also explored in this section are the reasons for different responses to various overlap assumptions. Section 4 describes the limitation of vertically constant L_{cf} in GenO assumption and its further improvement. The last section gives the conclusion and discussion.

2. Model and experiments

2.1. Cloud-resolving model

The cloud-resolving model used in this study is a three-dimensional model named SAM developed by Marat Khairoutdinov of Stony Brook University (Khairoutdinov and Kogan, 1999). Modeled flow is anelastic. The prognostic thermodynamical variables include liquid/ice moist static energy and total nonprecipitating/precipitating water. This model has been widely used in cumulus convection and cloud studies (e.g., Fan et al., 2009; Wang and Zhang, 2014; Wang et al., 2015). For more detailed information about SAM, refer to Khairoutdinov and Randall (2003).

For each field campaign, the model configuration is set as follows: 64 vertical levels with a stretched coordinate that increases smoothly from 75 m at the surface to a nearly uniform spacing of 400 m through the troposphere and a larger spacing of 1 km in the Newtonian damping region. A horizontal grid of 64 × 64 points is used with a resolution of 4 km.

2.2. Radiative transfer model

The radiative transfer model used is the single column version of RRTMG (rapid radiative transfer method for GCMs), which uses an efficient and accurate correlated-k method for calculating radiative fluxes and heating rates (Clough et al., 2005). For longwave, the number of quadrature points (g points) is added up to a total of 140 for 16 spectral bands. In the shortwave, the total number of g points is 112 for 14 spectral bands. To ease the complexity of radiation transfer in cloudy skies, the independent column approximation (ICA) method is introduced, which is a statistical technique for representing subgrid-scale cloud variability including overlap. This brings an advantage that clouds can be assumed to be filling a grid box fully in both the vertical and horizontal; otherwise, the weighting has to be made between contributions from cloudy and clear parts above and below the layer with the cloud cover. Accompanied with ICA is a stochastic cloud generator (SCG) that is used to produce subcolumns within large-scale model cells (Raisanen et al., 2004). For an arbitrarily specified cloud profile, the randomly binary cloud fraction samples can be readily obtained given a certain overlap assumption. Accordingly, cloud optical properties can be obtained following the arrangement of the corresponding binary cloud fraction samples.

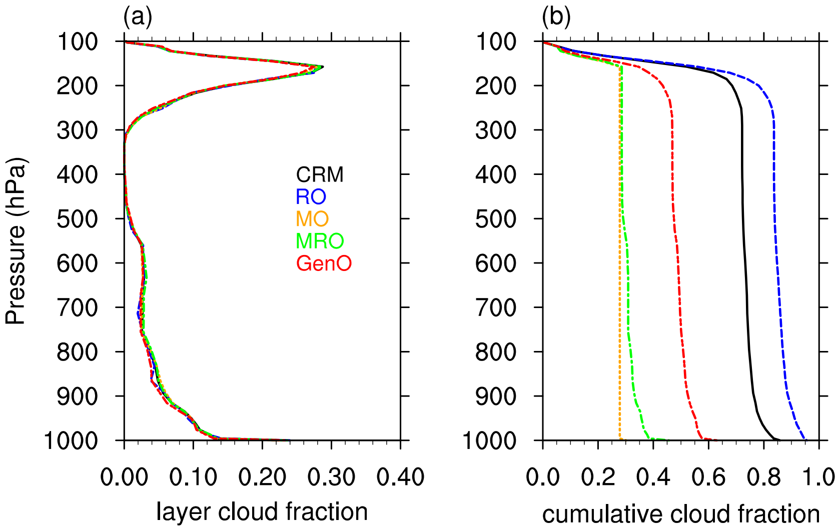

Fig. 1. Simulated layer cloud fraction (a) and downward cumulative cloud fraction (b) under different cloud overlap assumptions for one snapshot of KWAJEX Case (units: 100%).