Analysis of Tropical Radiative Heating Profiles in the Multi-Scale Modeling Framework: A Comparison to Atmospheric Radiation Measurement Program Observations

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Introduction

Radiative heating associated with the distribution of water vapor and clouds in the atmosphere is an important driver of both local-scale and large-scale circulations in the tropics. One of the difficulties in producing accurate cloud and radiative heating rate profiles with a general circulation model (GCM) is the sub-grid scale nature of cloud processes and their interaction with radiation. The multi-scale modeling framework (MMF) is a new approach to climate modeling (Grabowski 2001; Khairoutdinov 2001) in which cloud processes are treated more explicitly by replacing the cloud and radiation parameterizations of a GCM with a 2D cloud system resolving model (CRM). Details of the MMF formulation are given by Khairoutdinov (2001). In this implementation of the MMF, the parent GCM is the National Center for Atmospheric Research Community Atmosphere Model (CAM), version 3 and the CRM is run with 64 columns with 4 km resolution.

In this analysis, we compare cloud and heating rate profiles from the CAM and MMF models with profiles calculated from the Atmospheric Radiation Measurement (ARM) Program radar observations at Manus from March-July, 2000. The CAM and MMF are run with observed sea surface temperatures. Profiles of atmospheric state parameters are derived from radiosonde measurements combined with surface observations of air temperature and column precipitable water vapor. Cloud properties for non-precipitating clouds are retrieved from the radar observations using simple, previously published algorithms and broadband heating rates are calculated using an updated version of the Fu-Liou correlated k-distribution model (Fu and Liou 1992). More details of the observations and heating rate calculations are given in Mather et al. (2006). Precipitating columns are removed from the ARM observations based on surface rain gauge values and radar reflectivity thresholds because the radar can saturate in precipitating conditions and cloud property retrieval algorithms are not valid during precipitation. Approximately 13% of the radar observations are removed due to precipitation.

Figure 1 shows the average water vapor mixing ratios over the study period from the CAM, MMF, and ARM observations. The magnitudes of the profiles are similar in the troposphere; however the CAM has several discontinuous dry regions near 1 km, 4 km, and 8 km. These discontinuities are believed to be related to the adiabatic adjustment process in the CAM convective parameterizations. The MMF shows much larger water vapor mixing ratios above 15 km, which may be associated with overactive convection in the MMF.

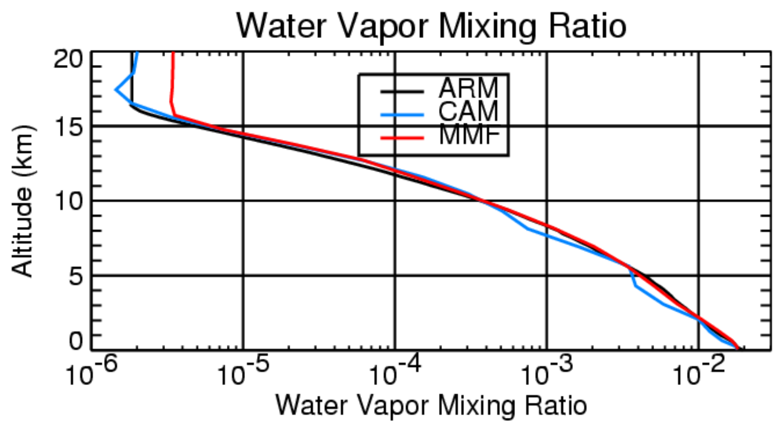

Figure 1. Average water vapor mixing ratio profiles over the study period.

The average clear sky heating rate profiles calculated from the observed and modeled cloud properties over the study period (Figure 2) have a similar structure with strong longwave cooling at the surface, longwave cooling throughout the troposphere with a peak in cooling near 8 km, and decreasing cooling above 8 km turning to heating above 15 km. The shortwave profiles show heating throughout the atmosphere due to absorption by water vapor (troposphere) and ozone (stratosphere). The CAM shows several discontinuities in the clear sky heating rates, including a local minimum in longwave cooling near 8 km, which are associated with the previously discussed discontinuities in the water vapor profiles.

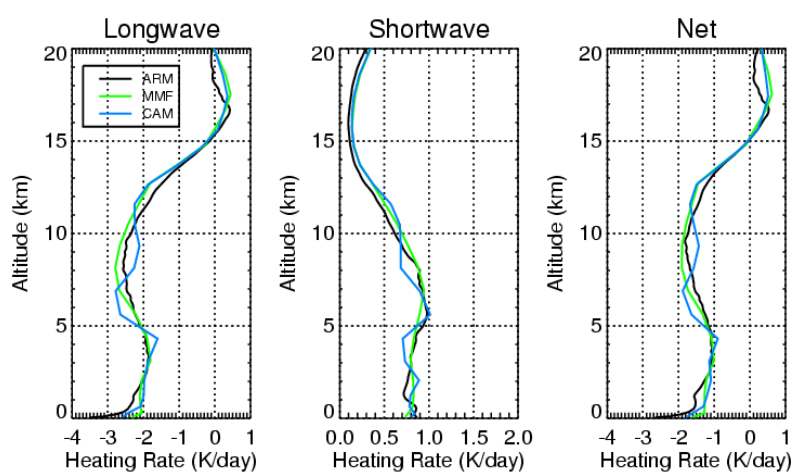

Figure 2. Average clear sky a) longwave, b) shortwave, and c) net hearing rate profiles.

The vertical distributions of cloud frequency (from ARM and MMF) and mean grid box cloud fraction (from CAM) are shown in Figure 3. For the MMF simulation (for which precipitation statistics were kept), we classify non precipitating columns based on surface rain rate and rain water mixing ratio values. Approximately 30% of the MMF columns were classified as precipitating by these criteria, compared to 13% of the observations, indicating overactive convection in the MMF model. Precipitation statistics were not kept in the CAM simulations so precipitating periods can not be classified. However, previous studies (Zhang and Mu 2005) indicate that the CAM 3.0 tends to overestimate the frequency of light precipitation in the tropics. Figure 3 shows that the CAM and MMF have significantly larger ice cloud amounts than the observations. Additionally the model ice cloud distributions peak higher than the observed ice cloud peak and have ice cloud at much higher altitudes. The ARM radar is known to miss high, thin cirrus above 15 km (Comstock et al. 2002) so it is unclear how much of the model high cloud is realistic.

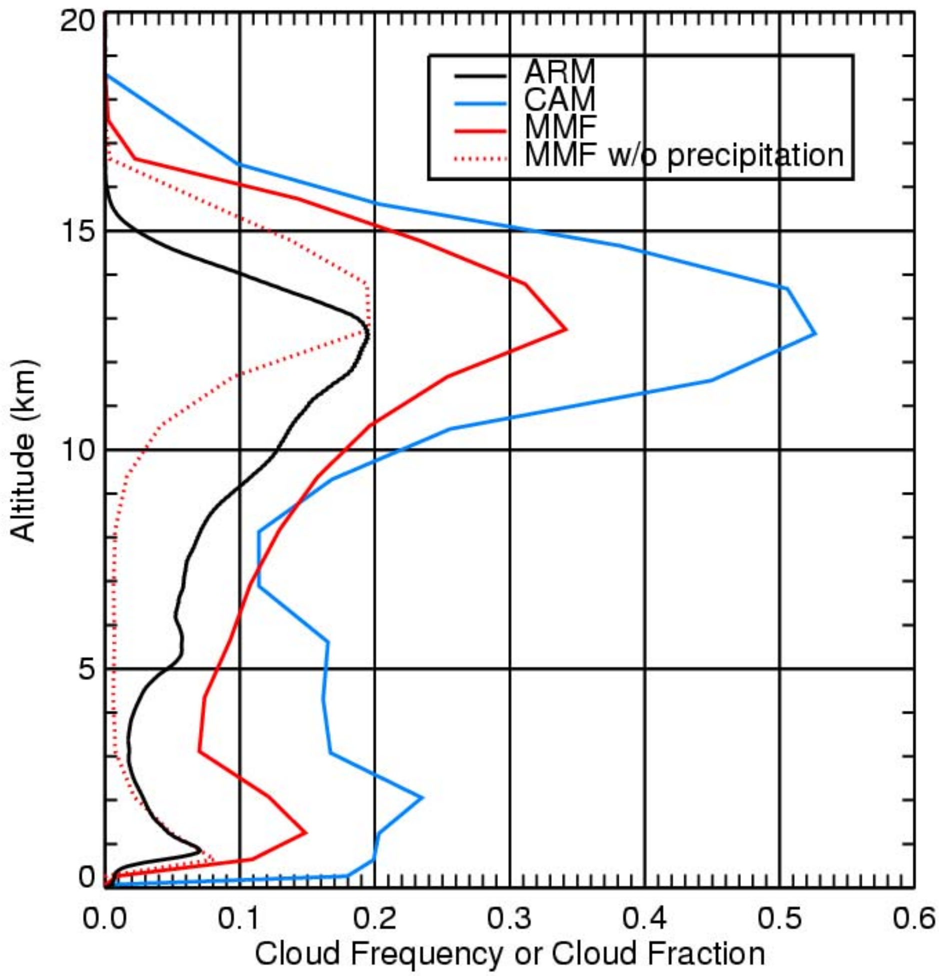

Figure 3. Average cloud frequency profiles from the ARM observations and the models. Also shown is the average cloud frequency from the MMF when precipitating columns are removed (red dashed line).

Figure 4 shows frequency distributions of condensed water content retrieved from the ARM observations, and from the MMF and CAM models. The observations and models show a similar range of condensed water content (CWC) in boundary layer clouds, although the models have larger median values. The CAM ice cloud feature shows a discontinuity near 11 km and a very narrow range of CWC above this height. This discontinuity is due to the difference of treatment of cloud condensate in the convective and stratiform parameterizations; cloud above 11 km is primarily stratiform. Although the median CWC in the ice cloud layer is similar in all profiles, the MMF and ARM retrievals have a much wider range of CWC, with maximum CWC an order of magnitude larger than seen in the CAM. The region of very low CWC in the MMF distributions from 4-12 km is associated with the current treatment of sedimentation in the model and has only a small impact on the calculated heating rate profiles.

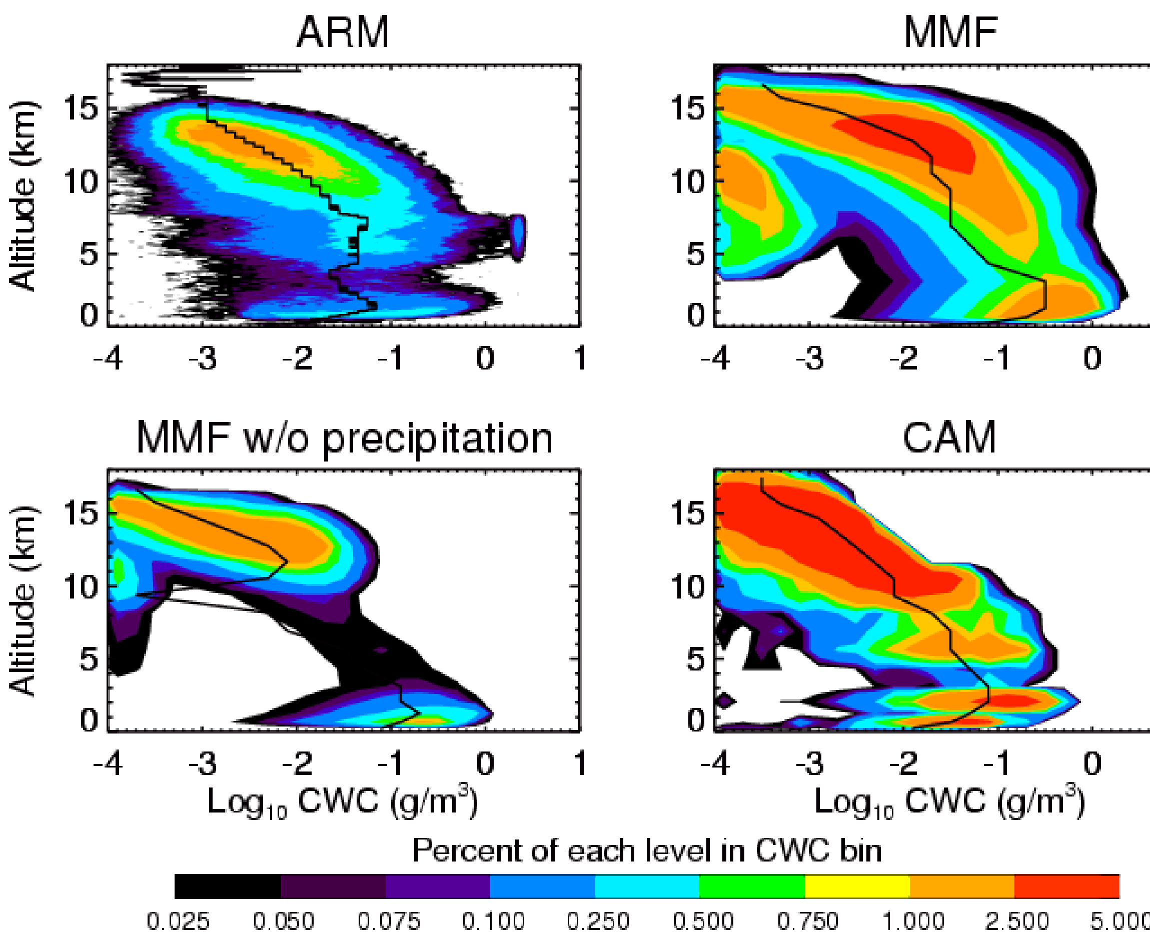

Figure 4. Frequency distributions of CWC at Manus from a) ARM retrievals, b) MMF model, c) MMF model with precipitating columns removed, and d) CAM model.

Specification of the correct vertical distribution of cloud properties is important to climate simulation because of the role of clouds in redistributing energy vertically within the atmospheric column. The differences between the all-sky heating rate profiles and the clear-sky heating rate profiles are examined to isolate the effects of clouds on the heating rate profiles (Figure 5). There are large differences in the effects of clouds on the vertical distribution of heating rates in the models and observations. In the longwave (LW), all profiles show a peak in warming due to clouds below the boundary layer cloud base and then an additional peak in the upper troposphere. In the ARM profiles, the peak of LW warming is at 9 km, near the base of the observed ice cloud feature and there is little warming above 12 km. The MMF peak LW heating due to clouds is at 12 km, which corresponds to the peak in ice cloud frequency in the MMF. Additionally, the MMF profile shows average LW cooling from 14-16 km, near the top of the MMF ice cloud layer. The CAM heating rate profiles show widespread LW heating due to clouds from 9-18 km, with peak magnitude from 9-13 km. The CAM profile shows no average cooling at the top of the ice cloud layer.

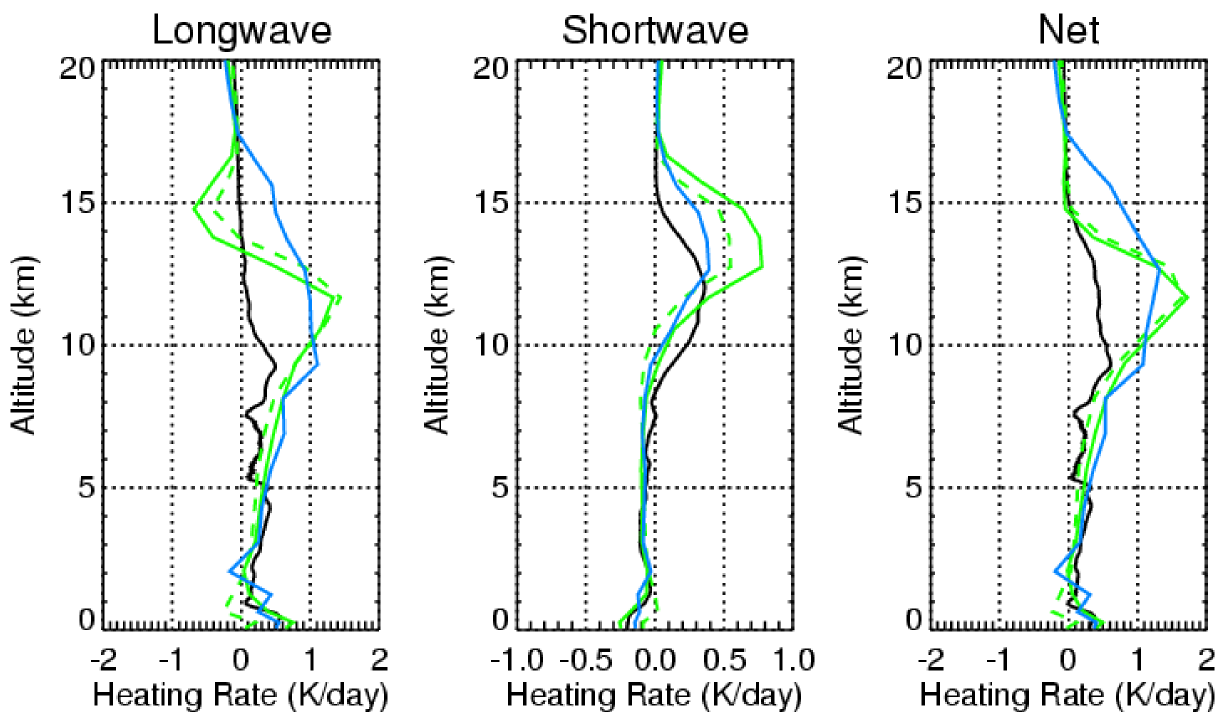

Figure 5. Average calculated all-sky minus clear-sky heating rate profiles, which illustrate the average impact of clouds on the a) longwave, b) shortwave, and c) net heating rates for ARM calculations (black line), CAM (blue line), MMF (solid green line), and MMF with precipitating columns removed (dashed green line).

All of the profiles show shortwave (SW) cooling due to clouds throughout the lower troposphere, with peak cooling occurring below the base of the low cloud layer. This cooling is due to the reflection of SW radiation from clouds which then reduces the amount of radiation available for absorption by water vapor lower in the atmosphere. The ARM profiles show SW heating due to clouds between 8-15 km with a peak at 12 km. The SW cloud effect profiles in the CAM and MMF models have similar shapes, with heating from 9-16 km and peak heating at 13-14 km. The height of the peak SW heating corresponds to the peak in ice cloud frequency, while the LW heating peaks lower in the cloud layer.

A difficulty in comparing climate models to observations is that the model might not get the day-to-day weather correct because of errors in the dynamics, thus instantaneous differences in the observations and model output will be very large. A way around this is by examining the differences in the models and observations as a function of meteorological regime or cloud type (Jakob et al. 2005). As a simple regime analysis, we classify each observation or model time-step by the value of the calculated outgoing longwave radiation (OLR), which is a function of both cloud top height and optical thickness. For each OLR class, we examine the difference between the average all-sky heating rate profile in the class and the average clear-sky heating rate profile (Figure 6). For the lowest OLR range (black line), all profiles show warming in the base of the cloud layer and cooling above, with the ARM and MMF profiles having peak cooling much higher in altitude than the CAM profile. For the ARM heating rates, the second-lowest OLR profile (blue line) also shows cooling above cloud, although the peak cooling is lower in altitude. 1.3% of the ARM profiles are in the lowest OLR class, compared to 14.3% of MMF profiles and only 0.2% of CAM profiles (Table 1). Additionally, 10.3% of the ARM profiles are in the second-lowest OLR class, which also shows cooling above cloud. The ARM and MMF profiles show a much wider variety of possible heating rate profiles, while the CAM only has a very small percentage of cloud profiles that show cooling above cloud. This is related to the wide range of CWC seen in the ARM/MMF cloud profiles compared to the very narrow range seen in the CAM. In order to accurately predict cloud feedbacks to a changing climate, a climate model needs to be able to produce the entire range of cloud behaviors. The primary difference in the ARM and MMF average heating rates appears to be due to the different frequencies of various cloud types, with the MMF over-predicting the frequency of convection and deep clouds, however the CAM has much different clouds than the ARM or MMF and has trouble producing any clouds thick enough to cause cooling above the cloud layer.

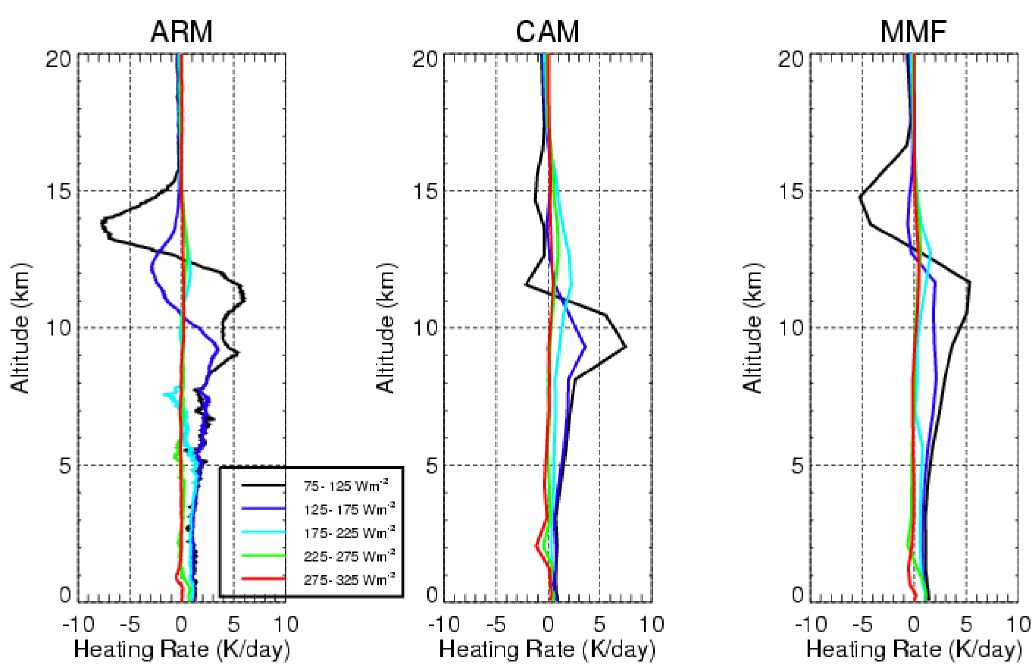

Figure 6. Average heating rate profiles for given ranges of OLR.

Table 1. Percent of observations or model time-steps in each OLR range.

	75-125 W/m^2	**125-175 W/m^2**	**175-225 W/m^2**	**225-275 W/m^2**	**275-325 W/m^2**
ARM	1.3	10.3	15.0	31.3	42.1
MMF	14.3	10.6	8.7	22.5	43.8
CAM	0.2	21.4	24.9	30.3	23.3

Acknowledgements

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