Radiative Heating in Global Climate Models

F. Baer, N. Arsky, and K. Rocque
University of Maryland College Park
College Park, Maryland

Climate Prediction and Radiative Heating

Climate model dynamics are driven by external and internal forcing. The primary forces affecting the thermal field are long wave radiative (LWR) heating, short wave radiative (SWR) heating, and convection (cumulus, etc.). These forcing effects are cycled through the thermal field to the motion field by nonlinear transfer. The model dependent variables, in particular temperature (T), moisture (Q), and especially clouds, evolve in time in a Global Climate Model (GCM) and thereby determine the subsequent forcing. If the dependent variables are not accurately calculated in space and time, the predicted forcing functions will be adversely affected. As integration time proceeds, such inaccuracies will lead to systematic errors in the prediction of climate.

Since it is neither possible nor advisable to study the effects of all these forcing functions simultaneously, we focus here on LWR heating and attempt to assess how sensitive this force is to its required input variables. This forcing is determined in GCMs by a LWR heating algorithm. Such algorithms compute heating rate (HR) profiles from the profiles of T, Q, clouds, and minor constituents. The HRs depend on the vertical structure of the input variables in addition to the physics built into the algorithm.

Sensitivity of LWR Algorithms to Input Variables

We tested the sensitivity of various algorithms taken from GCMs. The following seven algorithms were chosen: Canadian Climate Center (J.-P. Blanchet), ECMWF (J.-J. Morcrette), NCAR (J. Kiehl), Colorado State University (D. Randall), University of Maryland (R. Ellingson), Recherche en Prevision Numerique (L. Garand), and the National Meteorological Center (K. Campana). These models represent a cross section of GCMs which include LWR heating algorithms. For reference we selected the line-by-line model of Clough (1992) which is highly accurate under clear sky conditions. The algorithms were tested on a variety of data profiles to cover different geographic regions and seasons. The standard McClatchey et al. (1971) and a selection of Phillips et al. (1988) soundings were used for clear sky conditions. For tests under cloudy sky conditions, we used soundings taken from the Atmospheric Radiation Measurermnt (ARM) Cloud and Radiation Testbed (CART) Great Plains site in Oklahoma.

Figure 1 shows heating rates generated by all seven LWR algorithms for the mid-latitude summer (MLS) and mid-latitude winter (MLW) McClatchey et al. data sets under clear sky conditions and compared to the line-by-line (CLO) calculation. Both the results for 30 and 18 vertical levels are presented. Note that even for this statistically averaged data, the models tend to vary by as much as one- half degree K per day, independent of the number of levels chosen. It is noteworthy that the model HRs cluster about the reference CLO results.

The Phillips et al. data allow us to look more closely at individual soundings and their impact on the HRs. Using individual sounding Phillips et al. data as input to the algorithms for 100 soundings in each season and regional grouping, the mean HRs generated by each model were averaged and standard deviations on each level were calculated. Results show that on average the models do not conform well to the reference (CLO) in the tropics, but do better in MLW. The effect of variability amongst the individual Phillips et al. soundings within a data set on HRs was also tested and showed that the standard deviations of HRs derived from the soundings for each of the algorithms considered were substantial and also differed amongst the models.

The variability amongst the algorithms is implicit in the construction of the LWR model physics and is related to the input parameters as described above. The sensitivity to moisture is highlighted by comparing HRs from the algorithms using McClatchey et al. MLS and MLW data with and without moisture. Although almost all the cooling disappears in the troposphere without moisture, the variability amongst the models remains.

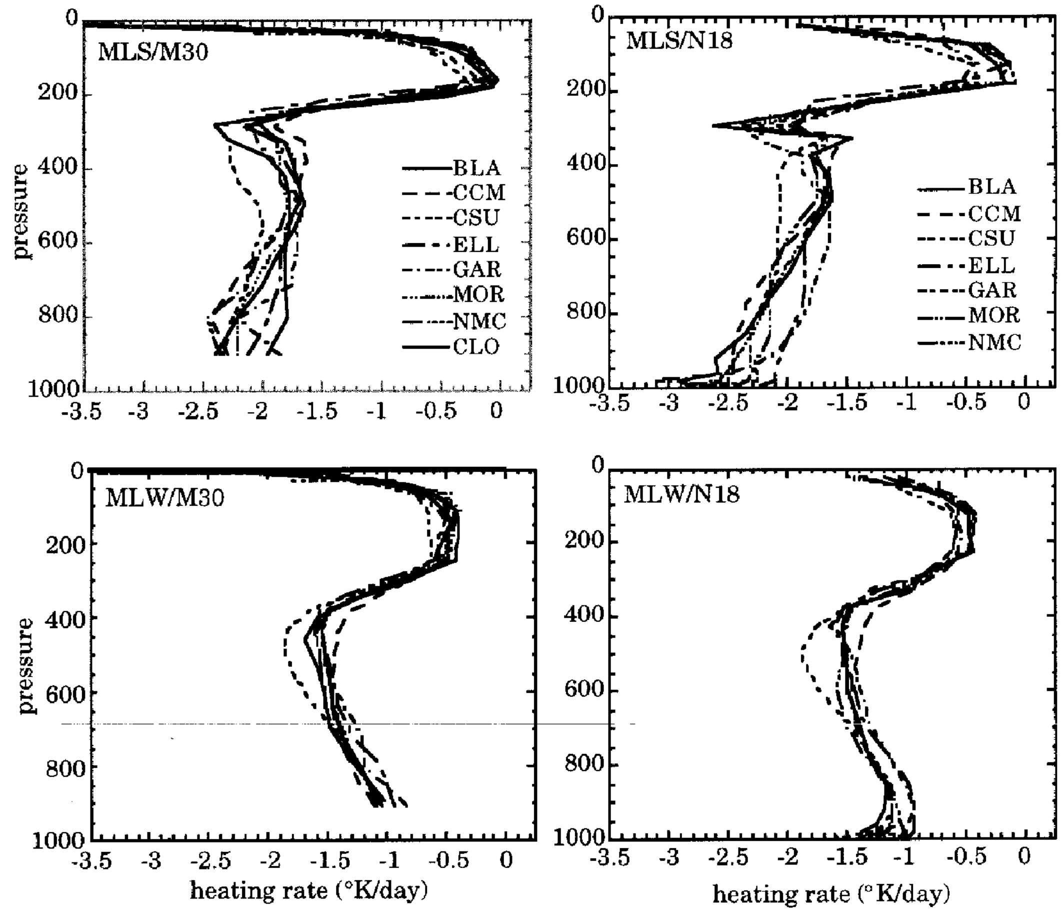

Figure 1. Heating rates generated by the seven tested algorithms and the reference algorithm (CLO) for the McClatchey data sets representing mid-latitude summer and mid-latitude winter.

Inclusion of clouds exacerbates this variability. Since clouds are difficult to measure let alone predict in a GCM, the LWRM response to clouds was first tested by inserting them artificially at given levels and with fixed intensity. We studied the response to single level clouds (thin clouds) by inserted them one at a time at the lowest eleven model levels of the 30-level distribution. The resulting HR profiles show extreme sensitivity to clouds and overwhelm the effects of temperature and moisture in the vicinity of the cloud.

The algorithms were subsequently tested under real cloud conditions. We chose to perform this test with data taken from the May 1994 ARM archives at the Oklahoma site. Figure 2 shows the heating rates produced for two cloudy soundings as representative of a number of soundings tested. To demonstrate the effect of clouds on the HRs, we show the HRs which are produced by the algorithms for the same cloud structure but with the sounding data (T and Q) taken from the McClatchey et al. MLS data set (Figure 2, panel d). The cloud structure of the data samples presented are included in the figure.

Our observations considering a number of cloudy soundings are the following. For clear skies, the profiles depend exclusively on the soundings which differ from Oklahoma (clear) to MLS/MC, and the algorithms differ from one another as seen previously. For only thin low clouds (one level) the cloud effect is clearly seen locally and the algorithms' output begins to differ from one another. Concurrently, the sounding data tend to become less important. As the clouds become thicker and/or move higher in the troposphere, the effects just noted become amplified (Figure 2) to the extent that each algorithm gives a unique profile different from all others.

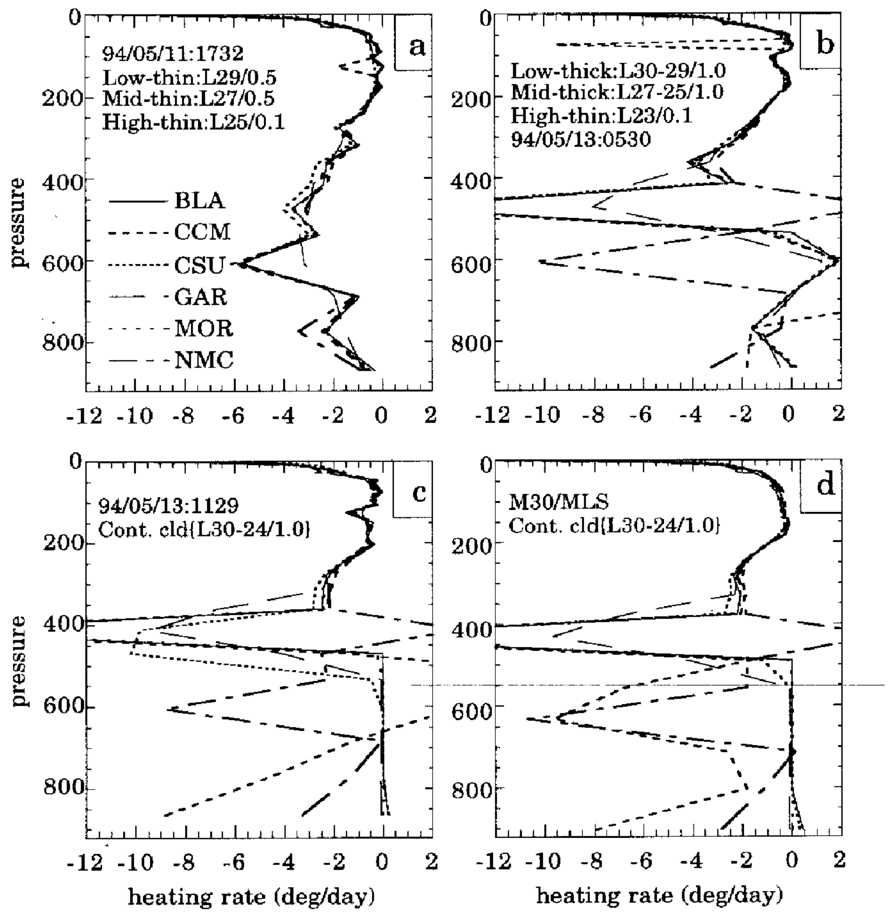

Figure 2. Heating rate profiles generated by six algorithms from observed data including clouds. Note cloud level/density (lxx/xx.x).

The Affect on GCMs by HRs Generated from LWR Algorithms

LWR algorithms calculate vertical profiles of HRs at each horizontal point in a GCM, and these are calculated periodically in time. Thus they produce three dimensional fields. These HR fields represent the appropriate LWR forcing which directly determines the temperature tendencies. The temperature field predicted from these tendencies modifies the wind field tendencies by nonlinear interaction in space. The predicted wind field then modifies the temperature tendencies by nonlinear advection. Thus the impact of the HRs is spread in time and space to all the variables (T, Q, clouds). These modified variables are then used to recalculate new HRs.

Three-dimensional HR fields from GCMs were used to demonstrate heating rate sensitivity to GCM characteristics. Model output of LWR HR fields at each archived time were averaged over 60-day wintertime (Jan-Feb) periods for comprehensive statistics. Models available for this analysis included

- NCAR CCM1: R15, T42; 12 levels; climatology
- NCAR CCM2: R15, T42, T106; 18 levels; climatology
- NCAR CCM2: T42; 18 levels; AMIP.

Previous observations from this study noted the following:

- *Truncation* plays an important role. Considering both the CCM1 and the CCM2, the cooling distribution is radically different for all space scales from one truncation run to another, other factors remaining identical.

- HRs are dependent on *model changes*, including changes to the incorporated LWR algorithm. Comparing output from the CCM1 and CCM2 runs with the same time interval chosen for each model and beginning with identical initial conditions, the HR output is substantially different.

- *Surface forcing* in the form of sea-surface temperature (SST) does not show a significant impact on the evolution of the T, Q, and cloud fields in a model and the resulting HRs generated by the LWR algorithm. Two wintertime periods (Jan-Feb 1987 and Jan-Feb 1983) from the CCM2 AMIP archive and the CCM2 wintertime climatology were compared. Note that the AMIP run has observed SST and the climatology run has climatological SST. The differences in HR statistics of the two AMIP samples were not significant, nor did they differ substantially from the run with climatological SST.

Reference to Observations

In general, there are no observed measurements of LWR heating in the atmosphere. Thus comparisons of model results to observations cannot be made. However, one could take the observed data during the AMIP period which have been archived and calculate instantaneous HR fields using the LWR algorithm in the GCM. Unfortunately observational cloud information is not available and, as seen earlier in this study, clouds are essential to the algorithm. As an alternative, we used the GCM to generate clouds from the observed data and used those clouds to generate HRs in the model. Specifically, we introduced observed data into the CCM2 as initial conditions for each day of the AMIP period (Jan-Feb 1987) and ran the model for 36 hours. We used the HR fields which the model developed at this time and defined them as “observations” (our approximation) to compare with the output of various AMIP model runs.

GCM Intercomparisons

To compare the predictions of various GCMs, we collected data fields from three individual models: the NCAR CCM2 model, the Colorado State University (CSU) Model, and the NASA/GSFC GEOS model, as well as the observations noted above. The data were taken from the AMIP runs of each model and averaged for the period of Jan-Feb 1987.

Global maps were available at three levels (850 mb, 500 mb, 250 mb) for the field variables long wave HRs, cloud fraction, temperature, and moisture. To give a flavor of the differences, we present on Figure 3 the heating rate patterns of the models at 250 mb and the clouds at 500 mb. Differences amongst the GCMs in all variables considered were pronounced. The CCM2 appears a bit closer to observations, probably because the same LWRM algorithm is used. The temperature and moisture fields are least different amongst the GCMs, but also do not compare well. The differences in the cloud fields amongst the GCMs are probably the primary factor leading to the large differences in HRs. Note that no detailed cloud maps were available for the GEOS-1. These results confirm our previous observations about clouds. However we did not know to what extent the GCMs would differ from one another.

Conclusions

LWR algorithms from various GCMs vary significantly from one another for the same clear sky input data. This variability becomes pronounced when clouds are included. We demonstrate this effect by intercomparing the various models' output using observed data including clouds from ARM/CART data taken in Oklahoma.

The LWRM algorithms play a vital role in GCMs insofar as they redistribute the HRs produced by their LWRM algorithm. Our analyses indicate that the LWR heating in the GCM depends

- significantly on model truncation

- significantly on model construction (including the LWR algorithm)

- less on surface heating effects

- most notably on clouds and their parameterization.

Intercomparison of AMIP statistics from several GCMs indicates substantial differences in model HR output under identical input conditions. We thus conclude that GCMs at the very least need better cloud parameterization and probably better LWRM algorithms.

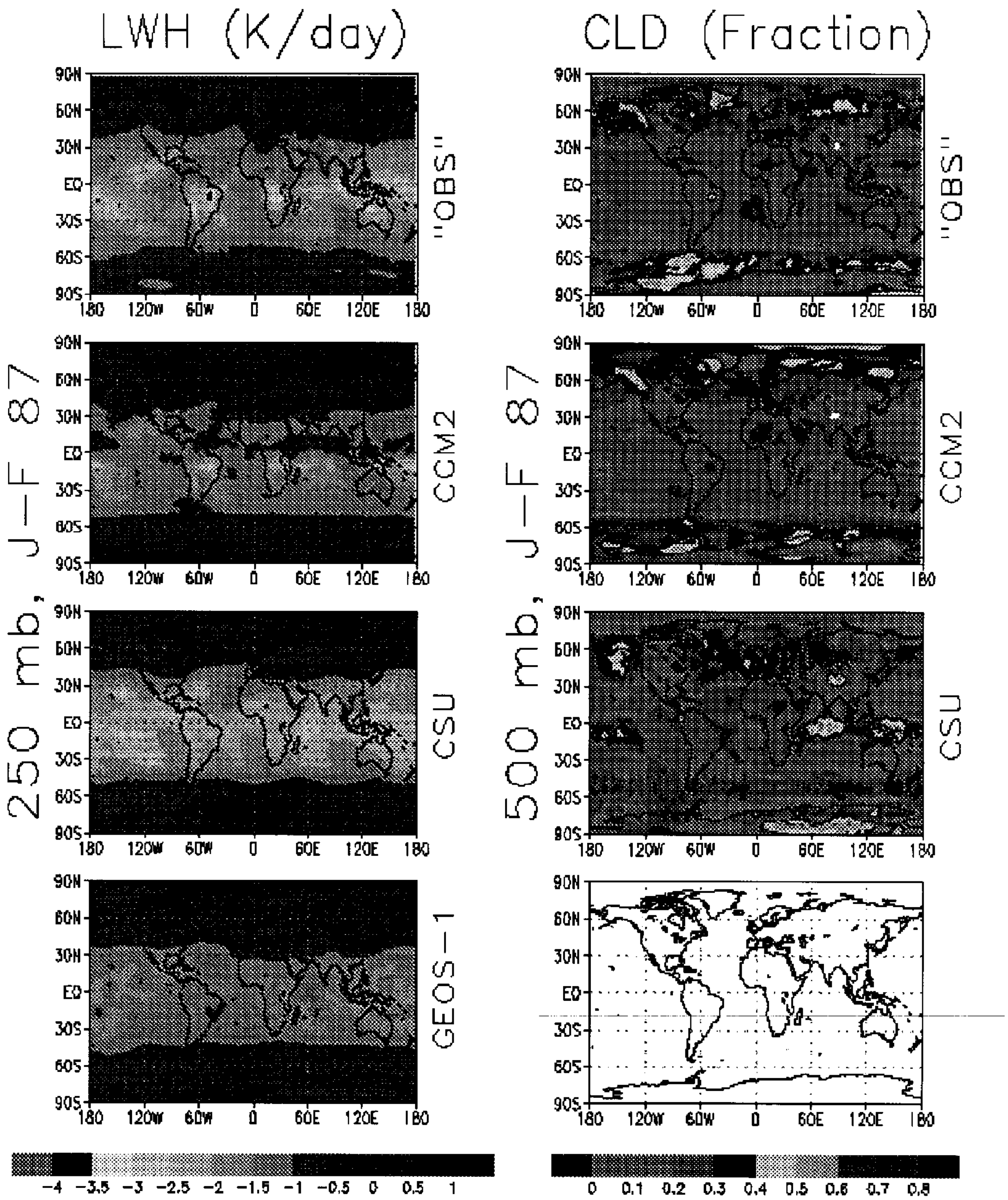

Figure 3. Maps of averaged HRs and clouds for the CCM2, CSU, and GEOS models and corresponding 'obs.' See text for details.

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