Radiation Impacts on Global Climate Models

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Climate Prediction and Radiative Heating

Climate models are driven by forcing, and these forces are seen primarily by the thermal field in general circulation models (GCMs). The major forces that affect the thermal field are longwave radiative (LWR) heating, shortwave radiative (SWR) heating, and convection (cumulus, etc.). These forcing effects are cycled through the thermal field to the motion field by nonlinear transfer. The dependent variables—in particular, temperature (T), moisture (Q) and especially *clouds*—evolve in time in a model and determine the subsequent forcing. If the dependent variables are not accurately calculated in space and time, the forcing functions will be adversely affected. As integration time proceeds, such inaccuracies will lead to systematic errors in the prediction of climate.

It is thus imperative to determine how sensitive these forces are to the input variables. In our presentation we will focus on LWR heating. This forcing is determined by a LWR heating algorithm that computes heating rate (HR) profiles from the profiles of T, Q, clouds, and minor constituents. The HRs therefore depend on the vertical structure of the input variables plus the physics built into the algorithm.

We tested the sensitivity of various algorithms taken from global climate models. The following seven algorithms were chosen:

- Canadian Climate Center (J. P. Blanchet)
- European Centre for Medium-Range Weather Forecasts (ECMWF) (J.-J. Morcrette)
- National Center for Atmospheric Research (NCAR) (J. Kiehl)
- Colorado State University (D. Randall)
- University of Maryland (R. Ellingson)
- Recherche en Prevision Numerique (L. Garand)
- National Meteorological Center (NMC) (K. Campana).

These models represent a cross section of GCMs which include LWR heating algorithms. The algorithms were tested on a variety of data profiles to cover different geographic regions and seasons. The standard McClatchey (1971) data and a selection of Phillips (1988) soundings were used.

In Figure 1, the *heating rates* generated by all seven LWR algorithms for various data sets under clear sky conditions are compared with a line-by-line model (Clough) for reference. We note that even for such statistically averaged data, the models can vary by more than one-half degree per day. If one looks at variations within the Phillips data itself, one finds that the standard deviation from the mean can be even larger.

The algorithms are sensitive to a number of issues, and we have tested some. In particular, the *number and placement* of vertical levels for LWR calculations are of great concern. A test in which the heating rates calculated at 18 NMC levels are compared to 30 levels was made and demonstrated significant differences, a variability whose impact on climate prediction could be substantial and must be assessed in more detail.

Sensitivity of the LWR algorithms to model parameters must also be assessed. The sensitivity to *moisture* was examined by comparing HRs for four algorithms using McClatchey mid-latitude summer (MLS) and mid-latitude winter (MLW) data with comparable calculations from which all moisture was removed. As a consequence, almost all the cooling in the troposphere disappeared without moisture.

The impact of *clouds* is probably the single most significant factor in these algorithms. Six of the models were intercompared for various cloud conditions which were inserted into the algorithms together with the other variables as specified. When thin clouds (one level only) were

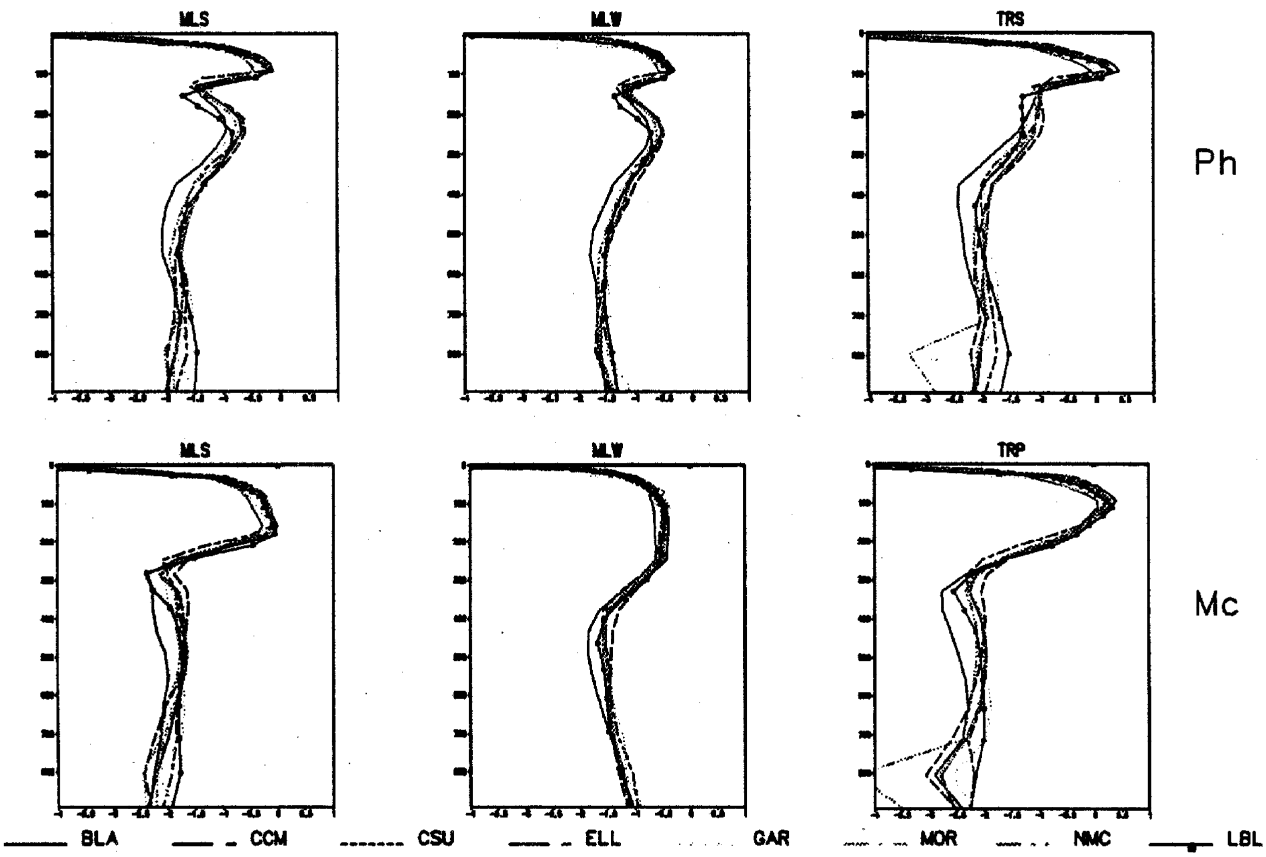

Figure 1. Profiles of heating rates (HRs) in Deg. K/day from seven algorithms and the Clough line-by-line model for various data samples

introduced into the lower or middle troposphere, most of the models gave comparable HRs independent of cloud amount. When clouds were thickened to at least two levels, the HRs produced by the various algorithms differed significantly, especially in the region of the clouds. When multilayer clouds were introduced into the algorithms the differences in their output became very pronounced, and the HRs were extremely different for a very thick cloud. Unfortunately, there are as yet no measurements to give a reference for these calculations, but clearly one is needed.

How General Circulation Models Are Affected by the Heating Rates Generated from Longwave Radiation Algorithms

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

Space Scale Dependence

Since climate prediction must provide realistic regional information, accuracy of the forcing functions must occur on all scales resolved by a model. To sample the scale effect, HR fields are to be presented as amplitudes in resolvable horizontal scales and on model levels in the vertical. Since most models are spectral, an appropriate horizontal scale representation is the planetary wave integrated over all latitudes. Such a representation was used in the analyses presented.

Data To Be Analyzed

Three-dimensional HR fields taken from GCM archives are presented to demonstrate model sensitivity to LWR input. Model outputs of LWR HR fields at each archived time were averaged over 60-day wintertime periods to generate comprehensive statistics. Models available for this presentation include

- NCAR CCM1: R15, T42; 12 levels; climatology
- NCAR CCM2: R15, T42; T106; 18 levels; climatology
- NCAR CCM2: T42; 18 levels; Atmospheric Model Intercomparison Project (AMIP).

HRs are strongly dependent on *model truncation*. HR amplitudes in the 15 longest planetary waves as a function of pressure for a 60-day average winter period of the NCAR CCM2 climatology run were analyzed allowing only the model truncation to vary. The three truncations for R15, T42, and T106 were considered. The analysis clearly shows that the cooling distribution is radically different for all scales from one truncation run to another. This difference should have a pronounced impact on the climate which will evolve.

The HR's dependence on *model changes*, including changes to the incorporated LWR algorithm, was tested by sampling the differences in the 60-day average wintertime HRs taken from CCM1 and CCM2 runs. The same time interval was chosen for each model, and both began with identical initial conditions. The most noteworthy observations from this analysis were the high concentration of cooling in the longest scales and nearer the surface for the CCM2 run; this result must also have a strong impact on the developing model climate.

Finally, *surface forcing* in the form of sea-surface temperature (SST) could have a significant effect on the evolution of the T, Q and cloud fields in a model and the resulting HRs generated by the LWR algorithm. To test this effect, two wintertime periods (J-F, 87 and J-F, 83) were selected from the CCM2 AMIP run and processed and analyzed in the same way as the CCM2 wintertime climatology described above. Figure 2 shows the J-F, 87 results. Note that the AMIP run has observed SST, and the climatology run has a 20-year climatological SST. The differences in HR statistics for the two AMIP samples are not significant, nor do they differ substantially from the run with climatological SST. This result suggests some model insensitivity to SST.

Reference to Observations

In general, there are no observed measurements of LWR heating in the atmosphere. Thus we cannot compare model results to observations. However, one could take the observed AMIP data, which have been archived, and calculate instantaneous HR fields using the LWR algorithm from the model. Unfortunately, cloud information is not available, and as seen earlier in this study, clouds are essential to the algorithm.

As an alternative, we have chosen to use the model to generate clouds from the observed data and, using that information, to generate HRs in the model itself. Specifically, we introduce observed data into the CCM2 as initial conditions for each day of the AMIP period (J-F, 87) and run the model for 36 hours. We use the HR fields the model develops at this time and define them as "observations" (our approximation) to compare with the model output of the AMIP run. Although this is not unique, it gives us an estimate of how the model itself is responding to its internal forcing.

When compared with the corresponding HRs taken from the AMIP run for the same time period (J-F, 87), the average HRs from these "observations" show that the HRs differ significantly on all scales and at all levels.

These differences are apparent in Figure 2. The T and Q fields from the "observations" and the comparable fields from the AMIP run, the fields used by the LWR algorithm to generate the HRs, do not show the large differences seen in the HRs. The implications of this observation must be that the cloud parameterization plays a crucial role in the calculation of HRs. Moreover, with such pronounced differences in forcing, the ultimate climate predicted by the model must be substantially affected.

Finally, we considered the *relative effects of longwave versus shortwave* radiative heating. To demonstrate this association, we present the ratio of the average amplitude of the heating for a 60-day wintertime period from the CCM1 climatology runs with truncations R15 and T42. The presentation shows that the SW/LW ratio, again with planetary scale versus pressure, indicates the LWR cooling/heating dominates everywhere and is a much more important forcing function in the free atmosphere.

Conclusions

- LWR algorithms vary considerably given clear sky input data.
- The variability becomes pronounced when clouds are added.
- The algorithms play a vital role in GCMs.
- GCMs redistribute the HRs produced by their LWR algorithm.
- The LWR heating in the GCM depends on
  - model truncation
  - model construction (including the LWR algorithm)
  - surface heating effects
  - most notably clouds and their parameterization.
- For the free atmosphere, LWR heating is more significant than SWR heating in GCMs.

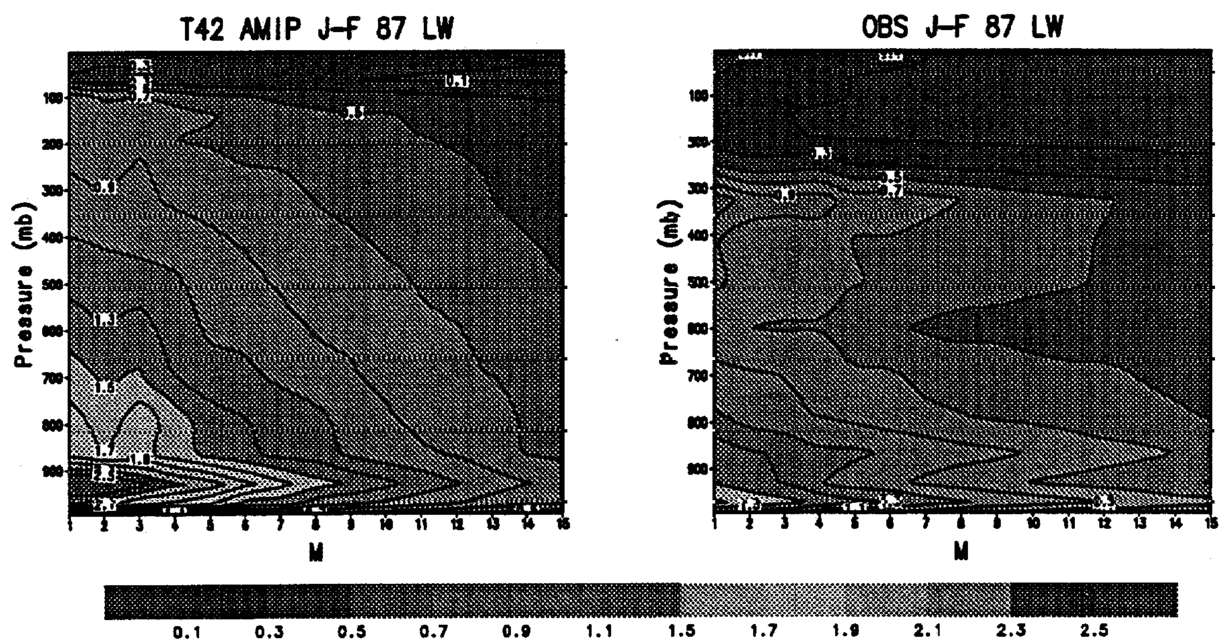

Figure 2. Two wintertime months' statistics of HRs shown for the long planetary waves and pressure, taken from an AMIP winter archive of the NCAR/CCM2 and our best estimate from observations (see text).

- Atmospheric Radiation Measurement/Cloud and Radiation Testbed (ARM/CART) data applications
  - Intensive Operation Period (IOP) data are being analyzed to assess subgrid distributions of HRs and their variability on short time scales (a few hours).

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