Scale Dependence of Solar Radiative Heating Rates in Tropical-Convective Cloud Systems with Implications to General Circulation Models

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Introduction

Climate models must explicitly resolve or else parameterize the physical processes that govern the climate system. Towards this goal, we should guide our model development by an understanding of the spatial scales upon which these physical processes operate. This scale-dependent information enables distinguishing those processes that are resolvable by the horizontal resolution of the climate model's grid (i.e., grid-resolvable) versus those that are smaller than the model grid (i.e., subgrid scale) and therefore must be parameterized. (For reference, a typical general circulation model [GCM] grid size is about 310 km x 310 km.) Such information may also be useful for designing related observational programs.

We examine three-dimensional (3-D) solar radiative heating rates within tropical convective-cirrus systems to identify the scales that contribute significantly to the spatial average over a climate model's grid cell (i.e., its grid-mean), and determine their relationship to the cloud field properties (e.g., cloud-top height variation). These results are used to understand the spatial resolution and subgrid-scale cloud property information needed in climate models to accurately simulate the grid-mean solar heating of these systems. We will also determine the biases in GCM heating rates which ignore the cloud subgrid-scale variability.

Approach

We investigate these effects by retrieving the regional-scale, 3-D cloud field structure from satellite imagery, and computing the radiative fluxes of the cloud field using a broadband Monte Carlo model. Several cloud fields ($[400\ \text{km}]^2$) are retrieved with a 5-km resolution over the Tropical Western Pacific using Japanese geostationary satellite GMS-4 visible and infrared data. The optical depth to geometrical depth conversion for the clouds is approximated using microphysical properties simulated by a numerical model and observed from aircraft during field experiments. Cloud heating rates for regional-scale, 3-D cloud fields are computed at the pixel scale by a Monte Carlo model. The model has 25 band-intervals covering the solar spectrum from 0.25 μm to 5.0 μm. It treats 3-D distributions of cloud water/ice and water vapor, and uses correlated-*k* distributions to incorporate gaseous absorption by H_2O, O_3, O_2, and CO_2. Because calculations of 3-D distributions of the atmospheric heating rates are computationally demanding, they were run on a Cray T3E massively parallel processing computer. This enabled the use of over a billion photons per scene, which were optimally distributed in spectral space.

Results

Results of our study are as follows:

- We have identified two key subgrid-scale features within these systems that largely govern the grid-mean heating rates: the variability in the cloud-top height, and the structure of the cloud edge.

- These features give rise to hot spots—regions of intense local heating that occupy a small area but dominate the grid-mean value. For example, for the fields we considered, 5% to 25% of the grid area can contribute 30% to 60% of the total heating rate, respectively.

- Explicitly resolving the hot spots requires a model grid of about $(20\ \text{km})^2$ to $(30\ \text{km})^2$, which is smaller than that currently used in GCMs for weather forecasting and about a factor of 20 smaller than that used for climate studies.

- Unless a grid of $\sim(20\ \text{km})^2$ is used, GCM-style heating rate calculations that employ a standard cloud overlap type treatment can significantly overestimate the solar heating aloft and underestimate it below. This might enhance the vertical velocity within the cloud layer and suppress it at cloud base.

- Thus, over the long-term, biases in the GCM treatments of the vertical heating rate might have consequences to cloud evolution and feedback, particularly for clouds in weak local dynamical regimes.

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Reference

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