Scale Dependence of Solar Heating Rates in Cloudy Skies—A 3-D Reconstruction of Heating Rates in a Regional-Scale Cloud Field from Satellite Data

A. M. Vogelmann, V. Ramanathan, and I. A. Podgorny
Scripps Institution of Oceanography
University of California
San Diego, California

Introduction

Climate models need to either explicitly resolve or parameterize the physical processes that govern our climate system. Towards this goal, the determination of the spatial scales upon which such physical processes operate will assist in the choice of horizontal and vertical grid resolutions used in climate models. For example, Boer and Ramanathan (1997) used satellite imagery and a Lagrangian tracking algorithm to establish the spatio-temporal statistics and scale-dependent properties of cloud systems, which they related to the scales that are explicitly resolved by general circulation models (GCMs) with varying horizontal resolutions.

We present three-dimensional (3-D) radiative transfer calculations of tropical cloud systems on scales of 25 km^2 to 160,000 km^2. The fundamental focus of this study is to examine the scale dependence of solar radiative heating rates in convective-cirrus systems. The distribution of the solar radiative heating rate is strongly affected by the presence of clouds, which may have a significant effect on atmospheric dynamics. This is particularly true of clouds in the upper troposphere which, owing to the absence of other significant atmospheric absorbers in that region, provide a significant source of heating and affect the upper tropospheric thermal structure (Ramaswamy and Ramanathan 1989). Our goal is to use our analyses to determine the spatial resolution needed in GCMs to treat the solar diabatic heating of these systems.

Approach

Radiative fluxes and heating rates are computed using a broadband, 3-D Monte Carlo model, where the 3-D cloud field inputs are reconstructed from satellite imagery. 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 water vapor, ozone, oxygen and carbon dioxide. Calculations of 3-D distributions of the atmospheric heating rates are computationally demanding and were run on a Cray T3E massively parallel processing computer. This approach enables the computation and pixel-by-pixel scale analysis of multiple cloud scenes spanning a variety of observed conditions.

The 3-D cloud fields used for model input are retrieved with a 4.8-km resolution over the Tropical Western Pacific (TWP) from Japanese geostationary satellite GMS-4 data using a visible and an infrared channel. Retrieved cloud properties include cloud top height, visible optical depth, and cloud thickness. The optical depth to geometrical depth conversion for the clouds is approximated using microphysical properties observed from aircraft during field experiments, and simulated by a numerical model. The heating rates are computed for a diverse number of 400 x 400 km cloud scenes that contain classic cloud types typically found in the TWP region, including tropical convective systems, altocumulus, mid-level stratus systems, and mixtures thereof. For each scene, over one billion photons are used in the Monte Carlo simulation, which were optimally distributed in spectral space.

Results

Figure 1 gives the cloud optical depths and 3-D heating rates for one of the scenes studied. It reveals interesting high-resolution structures, particularly the regions of intense, local heating values, or "hot spots." They tend to occur at the tops of clouds, where there is little above cloud attenuation; on the sun-side of cloud edges, for similar reasons; and where cloud extinction coefficients are greatest, e.g., the tops of mixed-phase clouds or where the water clouds reside. Figure 2 shows the cumulative frequency distribution of the pixel scale heating rates for this scene per height level. Note that, for the middle atmosphere, approximately 50% of the heating rate values come from pixels whose values are greater than about 6 K/day.

We use 6 K/day as a threshold for analyzing the heating rate field. The field for each atmospheric layer is screened for pixels with values greater than this threshold. Such pixels that are adjacent to one another (but separated from other such pixels by a gap) are grouped into single heating rate "features." The size of each feature and their contributions to the scene area and total heating rate then are determined. The results are given in Figure 3. The area contribution of features greater than 6 K/day account for a maximum of 7% of the area (Figure 3a), but the maximum contribution to the total heating rate is up to 38% of the scene heating (Figure 3b). The scale dependence of this heating (Figures 3c and 3d) indicates that most of the heating occurs in features that are at higher resolution than T213. Since T213 is the highest resolution typically used in GCMs, such features will not be explicitly resolved in the calculations. Further details and results are given in Vogelmann et al. (1999).

References

Boer, E. R., and V. Ramanathan, 1997: Lagrangian approach for deriving cloud characteristics from satellite observations and it implications to cloud parameterization. *J. Geophys. Res.*, **102**, 21,383-21,399.

Ramaswamy, V. and V. Ramanathan, 1989: Solar absorption by cirrus clouds and the maintenance of the Tropical upper troposphere thermal structure. *J. Atmos. Sci.*, **47**, 2293-2310.

Vogelmann, A. M., V. Ramanathan, and I. A. Podgorny, 1999: Scale dependence of solar heating rates in cloudy skies—Implications to climate modeling. In preparation.

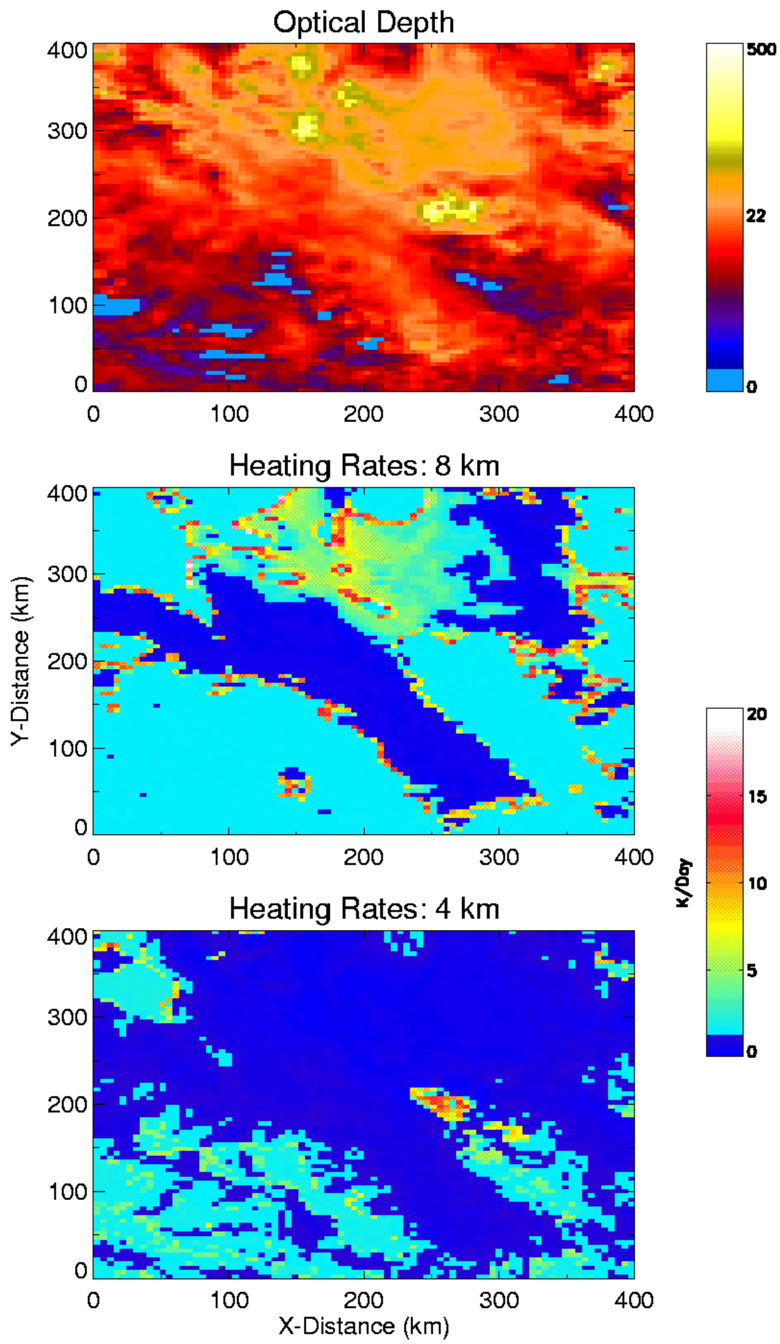

Figure 1. Top panel: Cloud optical depths for a scene containing cirrus and mid-level stratus. The middle and low panels give the pixel-resolved solar radiative heating rates computed by the Monte Carlo model for two horizontal cross sections for the altitudes given. A solar zenith angle of 60° was used for the calculations.

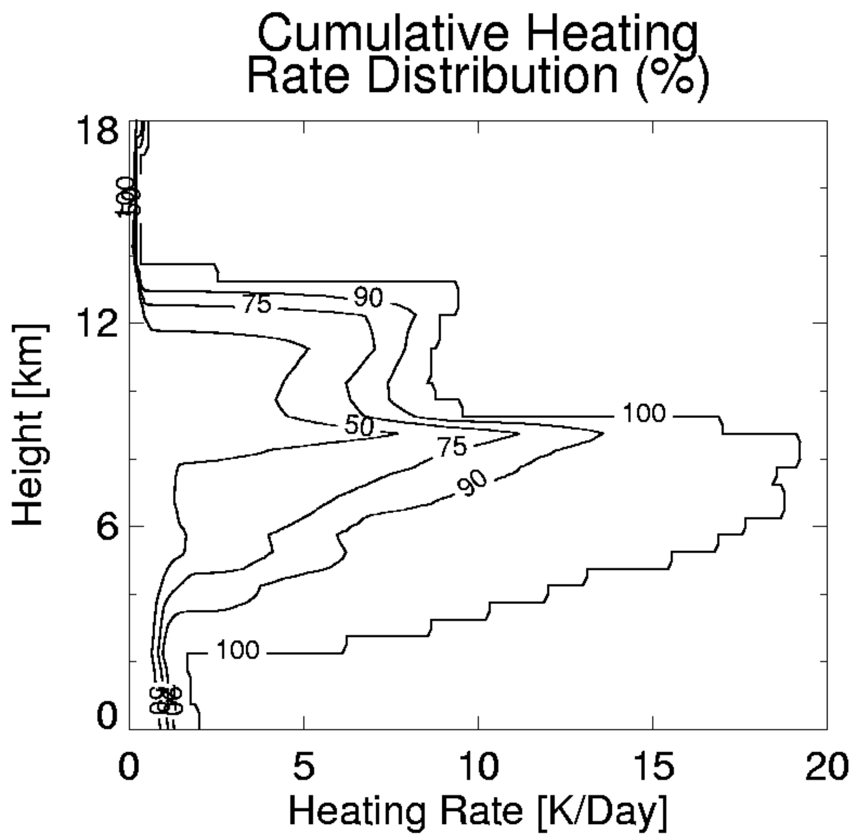

Figure 2. Cumulative heating rate frequency distribution per height level. The scene is the same given in Figure 1.

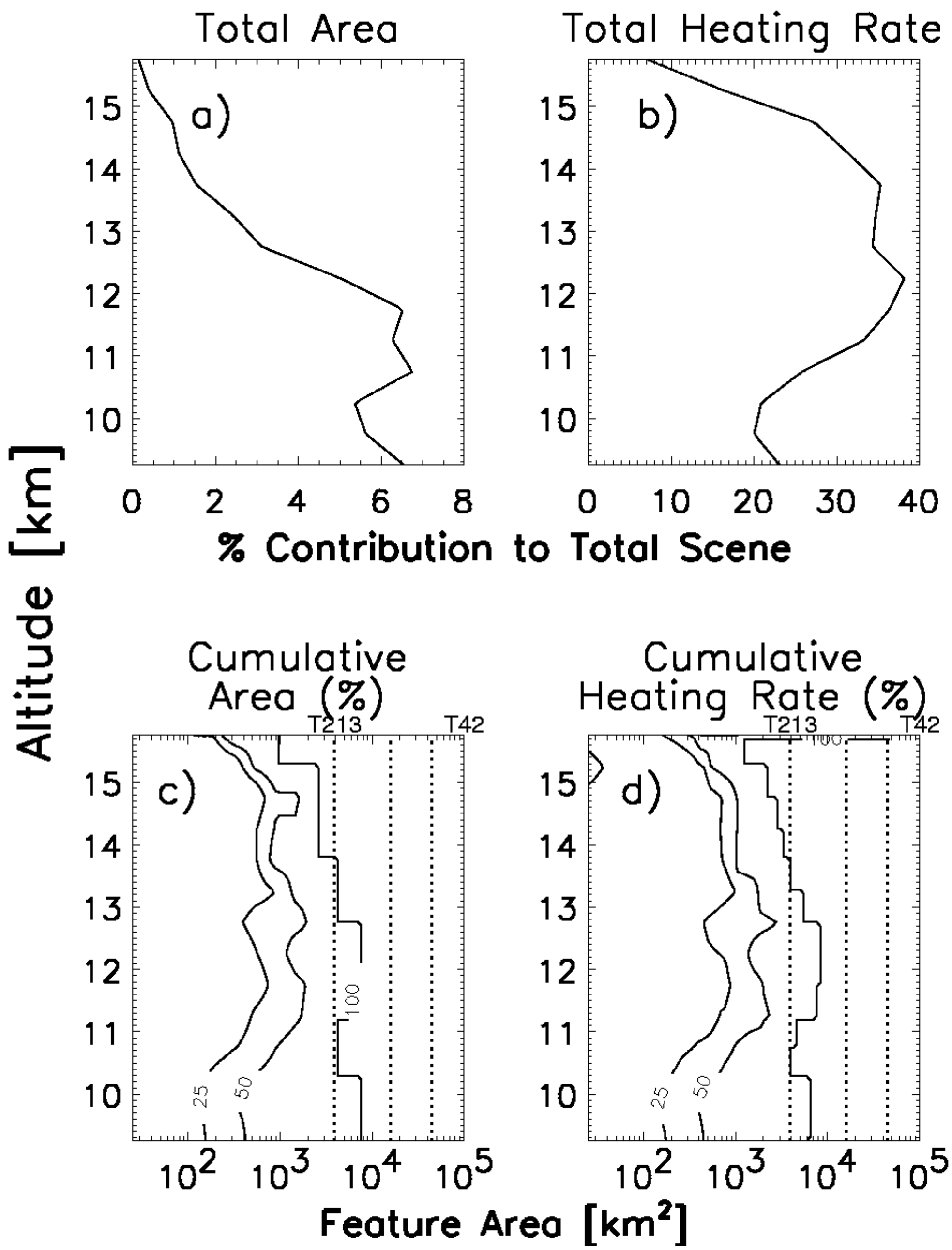

Figure 3. Size-dependence of heating rate features > 6 K/day for the scene in Figure 2. a) Total contribution of features > 6 K/day to the scene area. b) As for a), but for the contribution to the total heating rate. Note that the total heating rate contribution is about double that for the area contribution. c) Cumulative area contribution of heating rate features > 6 K/day (normalized by the maximum layer value from a). d) As for c), but for heating rates normalized by the maximum layer value from b). The equivalent GCM grid sizes T213 and T42 are given by dotted lines with the lines between them being T106 and T63.