High Resolution Heating and Cooling Rates in 3-D Clouds

W. O'Hirok and C. Gautier
Institute for Computational Earth System Science
University of California, Santa Barbara
Santa Barbara, California

Introduction

It is well known that the assumption of horizontal cloud homogeneity in radiative transfer modeling can bias estimates of surface and top of atmosphere (TOA) fluxes and vertical heating and cooling rate profiles. Presently, methods are being developed to parameterize the effects of heterogeneous clouds in climate models while maintaining the convenience of the plane-parallel method. The general goal of these techniques is to derive profiles that correctly portray the mean radiative effect of clouds within a model grid cell. In this study, we examine how well the domain-averaged heating and cooling rate profile represents the actual spatial variability of those quantities. To accomplish this, we compute high spatially resolved heating and cooling rate profiles and compare these profiles to the domain mean profile.

Model Computations

A three-dimensional (3-D) radiative transfer model (O'Hirok and Gautier 1998) computes both shortwave (0.25 μm to 5.00 μm) and longwave (4.0 μm to 50.0 μm) radiative fluxes and associated heating and cooling rates. In the shortwave, the spectrum is composed of 550 gaseous bands, each represented by 8 or 16 *k*-terms. In the longwave, the spectral interval is 20 cm^{-1} and the gaseous optical properties are derived from LOWTRAN7. Computations in the longwave are performed using a backward propagation mode where photons are traced back to diffusely radiating infrared sources.

The input consists of a two-dimensional (2-D) slice of a convective cloud field (Figure 1). The cloud field is partitioned into 1000 horizontal columns (50 m) and 32 vertical layers (125 m). The vertically integrated mean optical thickness equals 61 with a maximum value of 156. The effective radius ranges from 4 to 22 with the largest droplets located near the cloud tops. The cloud field is embedded in a tropical atmosphere. The atmosphere is divided into 67 layers and extends from the ocean surface to the TOA referenced at 100 km. Maritime aerosols representing a visibility of 23 km are included in the lower part of the atmosphere. Shortwave fluxes were computed for solar zenith angles of 0°, 41°, 60°, and 75°. The temperature of the ocean is equated to the adjoining atmospheric layer.

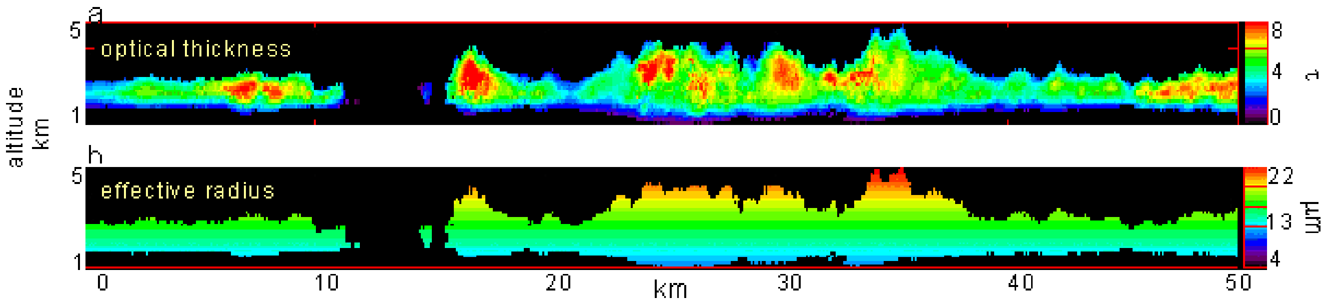

Figure 1. (a) Optical thickness and (b) cloud droplet effective radius for model cloud input.

Results

Figure 2 displays the downwelling and upwelling broadband solar irradiance and heating. For overhead sun, photon leakage from the higher portions of the cloud top combined with internal multiple scattering at cloud top troughs produce fluxes greater than the TOA input (Figure 2a). For oblique solar zenith angles, the highest downwelling fluxes occur where the surface of the cloud is perpendicular to the solar beam. For upwelling fluxes, horizontal photon transport causes the field to diffuse. In some localized areas, the broadband albedo appears greater than unity due to multiple scattering at cloud edges and 3-D effects (Figure 2b).

Figure 2c shows the heating rates from the absorption of shortwave radiation by gases and cloud droplets. Gases are the dominant absorbers, but the high peaks at the cloud edges mask the overall gaseous absorption in the image. Shadowing by clouds reduces gaseous absorption in the lower part of the atmosphere. Multiple scattering at cloud edges enhances photon pathlengths causing increased absorption by gases. The maximum absorption by droplets occurs where the solar beam is perpendicular to the cloud edge. Thus, while the TOA solar irradiance input for the solar zenith angle of 75° ($\mu = 0.26$) is one quarter that of overhead sun, the maximum absorption at 75° is only reduced by about one third. For non-overhead sun, large horizontal gradients in heating rates are observed with differences of more than 1° K^{-1} occurring over distances of a few hundred meters.

Figure 3 displays upwelling and downwelling longwave irradiance and longwave cooling and heating rates by gases and cloud droplets. Calculation of longwave fluxes assumes a constant temperature within an atmospheric layer. However, as observed from the previous plot, such an assumption may not be true considering the large variation in heating rates occurring within single layers. The effect of the clear patch in the cloud field can be seen with reduced downwelling infrared radiation near the surface caused by a cooler sky brightness temperature. Rapid cooling is observed at the top of the clouds, while heating at the cloud base is caused by the absorption of infrared radiation emitted primarily from the ocean surface.

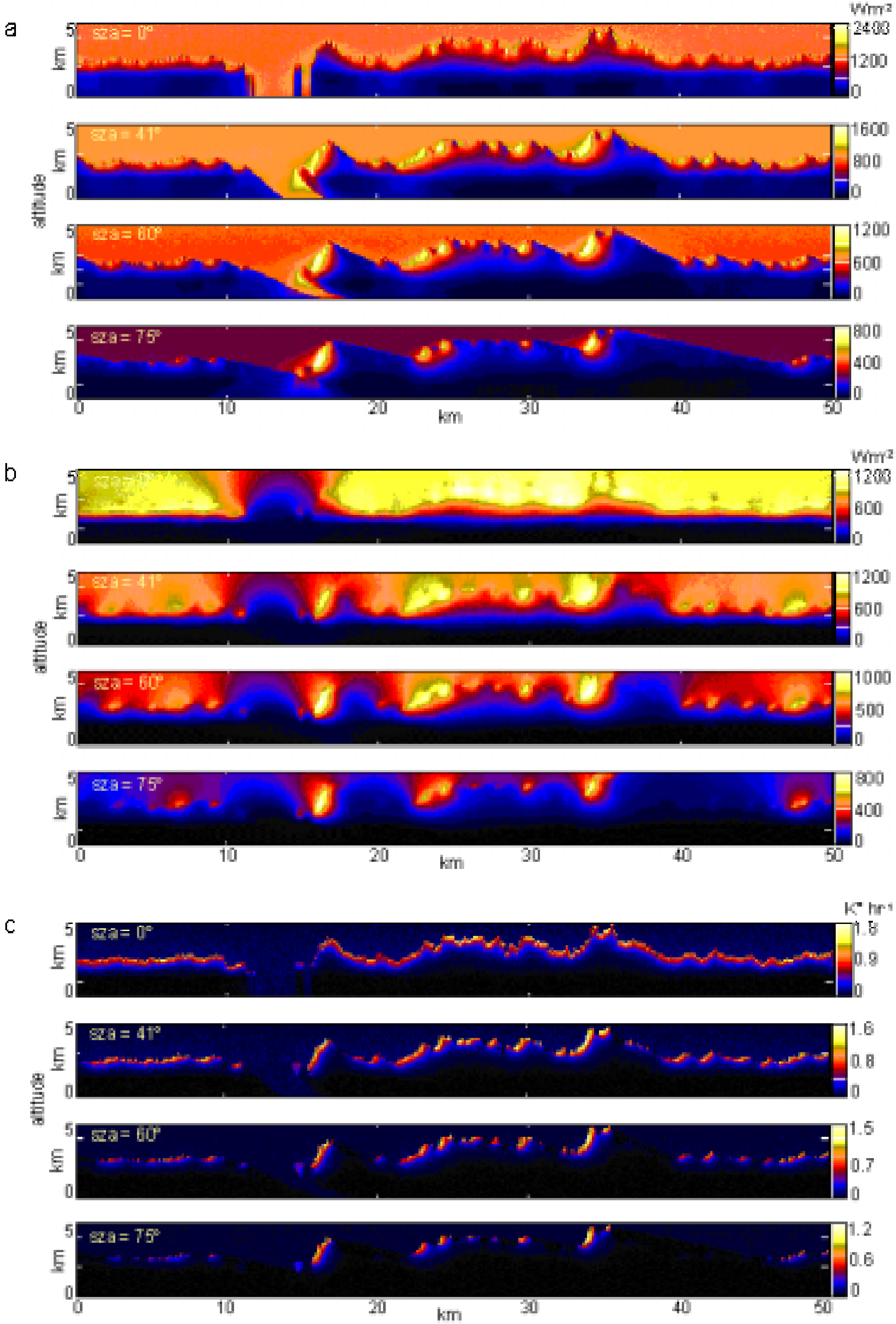

Figure 2. (a) Upwelling and (b) downwelling solar irradiance, and (c) heating rates for solar zenith angles of 0°, 41°, 60°, and 75°.

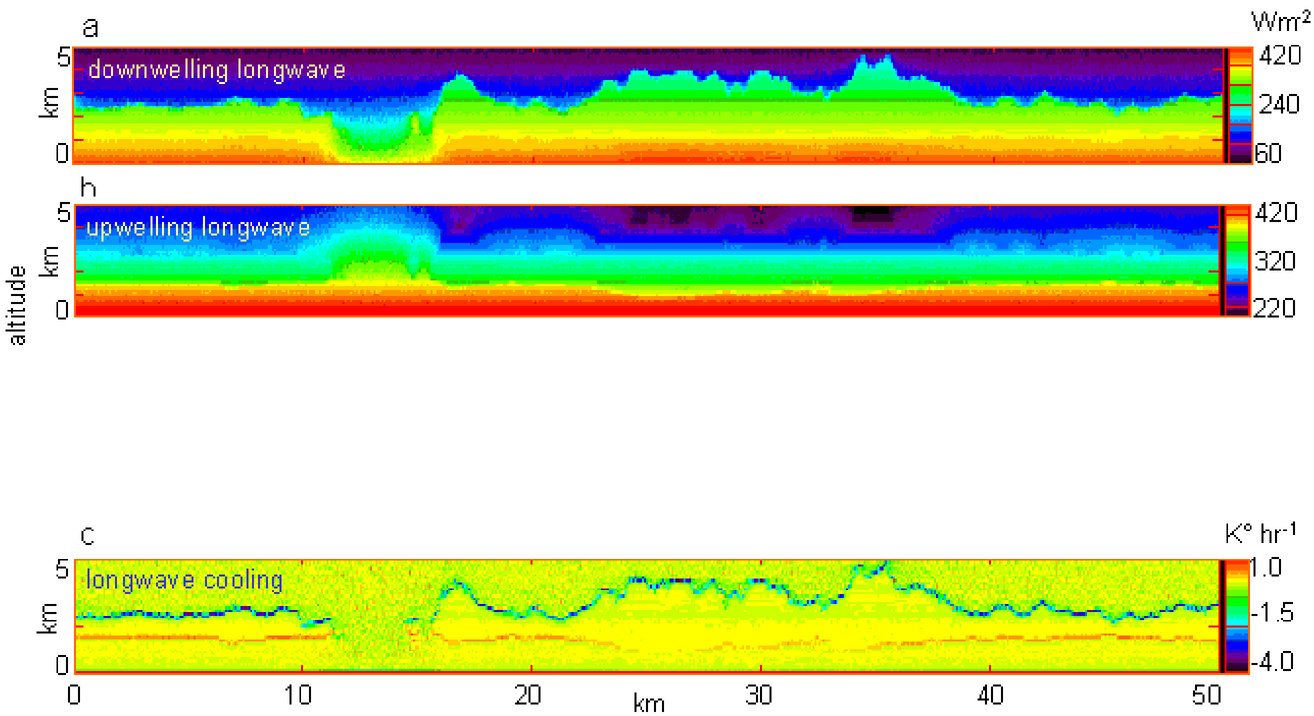

Figure 3. (a) Upwelling and (b) downwelling longwave fluxes, and (c) cooling rates.

Discussion

To examine the variability of the heating and cooling rate profiles, five sampled profiles are plotted in Figure 4b. The locations of the profiles are represented by the color bars in Figure 4a. The thick red line represents the domain average profile. As shown, both the sampled heating and cooling rate profiles are poorly characterized by the domain average profile. At no location does the mean profile match that of an individual column. The maximum average heating rate is less than 0.5° K hr^{-1} while individual columns have heating rates approaching 1.5° K. Generally, these peaks correspond to the individual column's cloud top altitude. However, 3-D effects can also be important. For example, as the sun approaches the horizon, the columns represented by the two shades of green show heating rates that actually increase as the domain average peak decreases. In conclusion, for the cloud field depicted, the use of domain averages or even highly resolved independent column approximations of the radiative fluxes cannot characterize the actual heating rate of a cloud field. The extent to which the error associated with using a mean profile is propagated into modeling of cloud dynamics needs further examination.

Corresponding Author

William O'Hirok, bill@icess.ucsb.edu, (805) 893-7355

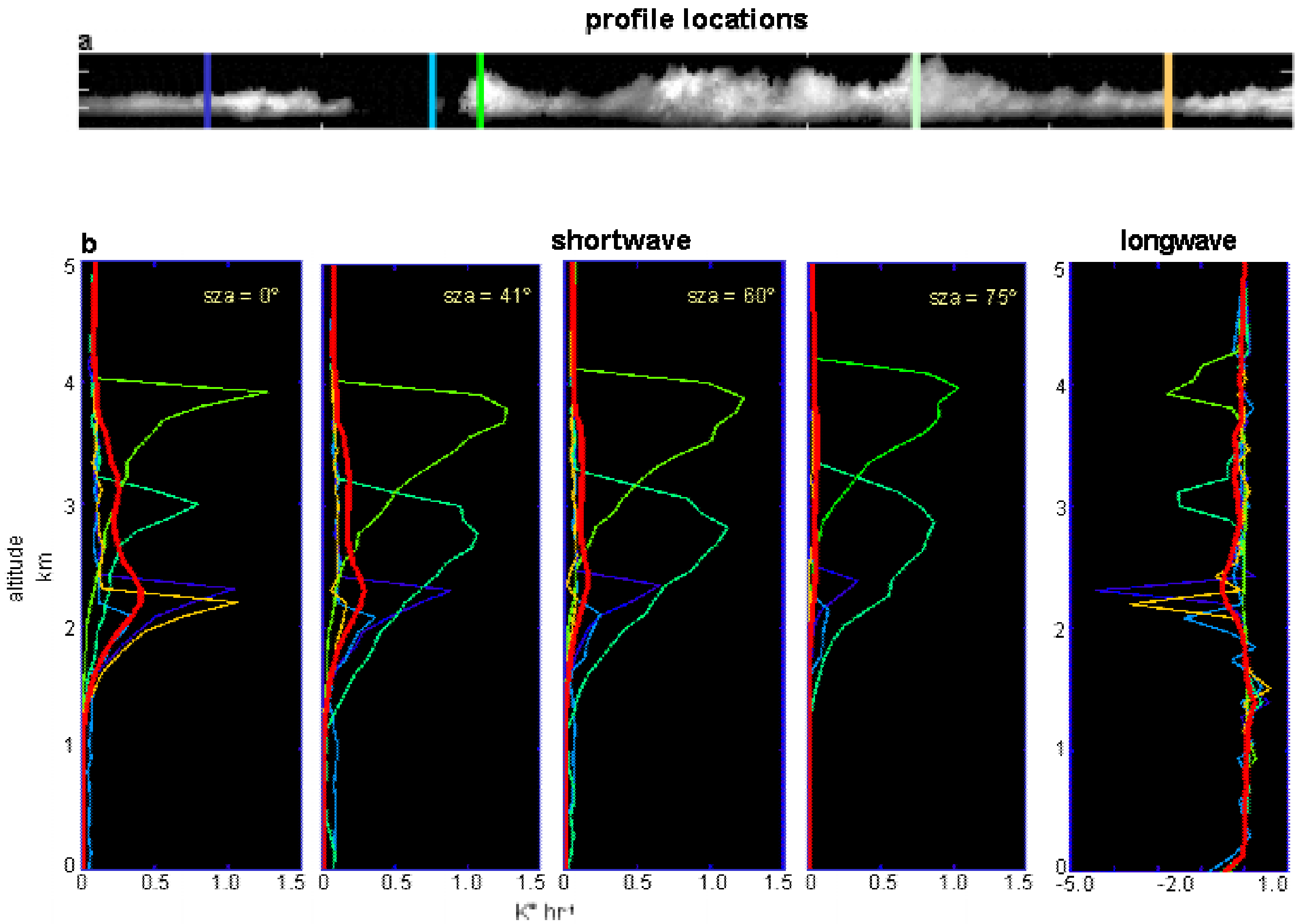

Figure 4. (a) Location of profile samples. Color bars match selected profiles. (b) Heating and cooling rate profiles for sampled locations.

Reference

O'Hirok, W., and C. Gautier, 1998: A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci.*, **55**, 2162-2179.