Boundary-Layer Cloud Properties and Surface Flux Distributions over the ARM SGP CART Site

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Introduction

Boundary-layer clouds are closely coupled to land surfaces through heat and moisture transport at the surface and through radiative impact of clouds on surface energy and water balances. Several studies have been carried out to investigate the impact of land surface heterogeneities on boundary-layer properties including boundary-layer clouds, and they show that clouds frequently form near the boundary between two different landuse types as a result of organized secondary circulations (Segal et al. 1988; Chen and Avissar 1994; Seth and Giorgi 1996). One common feature shared by most of these studies is the use of idealized surface boundary conditions, which usually exaggerate the contrasts in surface heating and, therefore, overpredict the strength of coherent circulations induced by surface heterogeneities. To overcome this weakness, data from the dense surface observation network at the SGP CART site are used, in combination with the Simple Biosphere Model (Sib2), to produce a realistic surface boundary condition for a mesoscale model that is used to study how boundary layer clouds respond to changes in surface boundary conditions.

A case was selected from the Surface Energy Exchange Intensive Observation Period (IOP) in the summer of 1995 that had relatively settled weather and large contrasts in surface fluxes. The sky was clear in the morning, and in the afternoon, some fair weather cumulus appeared over the southern portion of the Cloud and Radiation Testbed (CART) site. Surface winds on this day were between 3-6 m s^{-1} from the south across the site.

Model and Simulations

The model used for this study is the Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992). RAMS is a terrain-following, three-dimensional, non-hydrostatic model, with explicit cloud microphysics and a radiation scheme which accounts for the radiative effects of liquid water and ice. The modeling domain consists of 4 nested grids with horizontal resolutions of 100, 25, 6.25, and 2.083 km, respectively. The outermost grid covers the entire Great Plains, the Rockies, and the Gulf of Mexico. Grid 2 covers the Southern Plains. Grid 3 is a 360 km x 300 km rectangular box that encompasses the entire ARM Southern Great Plains (SGP) CART site, and finally, grid 4, the innermost grid, is a 200-km square covering the Oklahoma part of the CART site where clouds formed in the afternoon of the case study day. The simulations were initialized at sunrise using meteorological fields obtained from objective analysis of data from various sources, including the National Weather Center mandatory pressure level analysis, the standard rawinsonde soundings, and the spatial soundings released by ARM. The model's lateral and top boundaries were forced towards the objective analysis fields through the use of Davis Nudging. At the lower boundary, the two inner grids were forced by the prescribed spatial and temporal distribution of sensible and latent heat fluxes. For the two outer grids, which extend far beyond the CART site to areas where the surface flux data are unavailable, the lower boundary flux conditions were provided by a multi-layer soil model along with a surface energy budget equation.

A detailed description of the spatial distributions of surface sensible and latent heat fluxes and their diurnal variations for the entire CART site was obtained from the Simple Biosphere Model (Sib2), using CART vegetation and soil characteristics as well as meteorological data from the surface network. A full description on how the flux values are derived and checked against the Energy Balance Bowen Ratio (EBBR) data is provided in Shaw et al. (1997). An example of the spatial distributions of the sensible heat fluxes for the model's innermost grid is shown in Figure 1 for the case study day at 1400 local solar time (LST). It shows a large variation in sensible heat flux with values ranging from less than 50 W m^{-2} to about 500 W m^{-2} across the site. These flux differences arise primarily from variations in local vegetation and secondarily from gradients in precipitation. Similar flux maps are generated every half hour, and the model uses linear interpolation to get the values for the time steps in between the half hours.

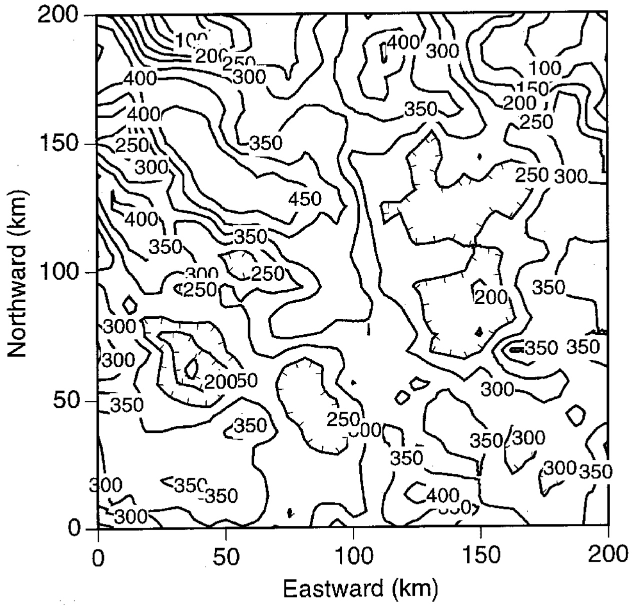

Figure 1. Surface sensible heat flux distribution for the innermost model grid at 1400 LST on the case study day. The contour interval is 50 w m^{-2}.

Two types of model runs were performed, the control simulation and the sensitivity simulations. The control simulation used spatially varying surface flux distribution which was assumed to closely resemble the real world surface boundary condition at this site. The sensitivity simulations used the same model parameters and the same atmospheric conditions, but different surface boundary conditions. The first sensitivity simulation, which was designed to see whether cloud properties are sensitive to the spatial variation of surface fluxes, used horizontally averaged surface sensible and latent heat fluxes that are applied uniformly at each grid point in the two inner model grids. Notice that no time averaging was done so that the average flux values still change diurnally. Since the model parameters and atmospheric conditions are kept identical to the control run, the differences between this and the control run can be attributed solely to the effect of surface flux heterogeneities. The rest of the sensitivity simulations also assumed uniform flux distribution across the CART site, but the values of the fluxes were modified. In these simulations, we assumed that the net radiative fluxes did not change, but an error was introduced in the partitioning of the energy into sensible and latent heat fluxes. To do so, we increased the averaged sensible heat flux by some percentage, and subtracted the corresponding flux amount from the averaged latent heat flux value, and vice versa. The percentages were 20%, 40%, and 60%, respectively, in the simulations. These sensitivity runs should help us determine how accurately one has to specify the average value of surface sensible and latent heat fluxes for a GCM grid cell or for a single column model in order to properly simulate boundary-layer cloud properties.

The model simulated vertical profiles of potential temperature, mixing ratio, wind speed, and direction were compared to the rawinsonde soundings launched at the CART central facility and showed very good agreement.

Results and Discussions

All the model results presented in this section are from the innermost model grid.

The control simulation and the sensitivity simulations all show clear skies in the morning. Some clouds started to appear at 1400 LST, but were only limited to a very small area in the southeast corner of the CART site. By 1600 LST, more clouds have appeared over the southern portion of the domain. The clouds appear to be shallow boundary-layer clouds that form near the top of the boundary layer.

Figure 2 shows a comparison of distributions of vertically integrated cloud liquid water content from the control simulation with variable surface fluxes and from the sensitivity simulation with averaged surface fluxes. It shows that variable surface flux conditions produced a more skewed distribution and somewhat higher cloud liquid water content. With uniform flux boundary condition, the distribution is rather narrow, with less than 2% of cloudy pixels having integrated cloud liquid water content greater than 0.03 mm.

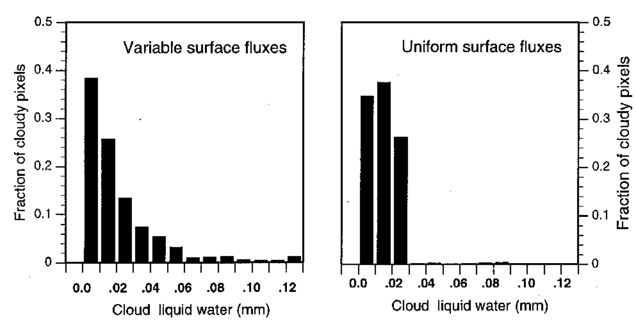

Figure 2. Distribution of vertically integrated cloud liquid water content from the variable flux simulation and the uniform flux simulation.

A comparison of cloud geometric properties between variable and uniform flux boundary conditions is shown in Figure 3. Clouds, in general, appear to be slightly higher and deeper when fluxes are allowed to vary across the site. With variable

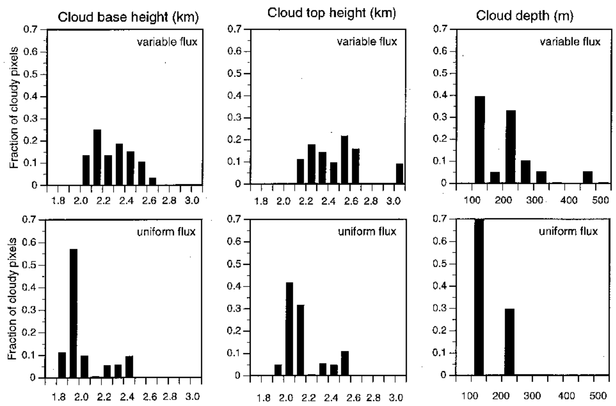

Figure 3. Distribution of cloud geometric properties from the variable flux simulation and the uniform flux simulation.

flux conditions, more than 20% of the cloud depths exceeded 250 m and about 6 % exceeded 450 m, while no clouds exceeded 250 m in depths for uniform flux conditions. With uniform fluxes, 70% of cloud depths are between 100 to 150 m, while only 40% of the cloud depths fall in this range with variable flux conditions.

The simulated cloud properties not only appear to be sensitive to the subgrid-scale variation of surface fluxes, but are also sensitive to the partitioning between the sensible and latent heat fluxes when uniform flux values are applied at the low boundary. Figures 4 and 5 show distribution of integrated cloud liquid water and cloud geometric properties for a 40% change in sensible and latent heat fluxes, respectively. Increase in latent heat fluxes appear to produce somewhat broader distribution than increase in sensible heat fluxes.

The control simulation does not show any evidence of organized secondary circulation induced by gradients in surface fluxes. The cloud physical properties are modified by the spatial variations of surface fluxes not through organized subgrid scale secondary circulations, but through local modifications of boundary-layer growth and static stability.

Summary and Conclusions

We have used a mesoscale model with explicit cloud microphysics and fine resolution to investigate the effects of surface boundary conditions on physical properties of fair weather clouds over the SGP CART site. The temporal and spatial distributions of surface sensible and latent heat fluxe across the site were derived from Sib2 based on a knowledge of the vegetation and soil characteristics as well as high density surface meteorological measurements. These flux distributions were then used as the lower boundary condition to a model that was used to simulate boundary-layer clouds for a case in July of 1995. Sensitivity simulations were also carried out with horizontally uniform surface boundary conditions. These sensitivity simulations used domain averaged surface sensible and latent heat flux values, as well as modified values of these averages. The model results show that a failure to resolve subgrid scale surface flux variations appears to have some impact on model simulated cloud physical properties. Simulated clouds with resolved surface flux variation show higher liquid water content, higher cloud base, and larger cloud depth than simulations with uniform flux distribution. The distributions of cloud properties also change as the partitioning of surface fluxes changes.

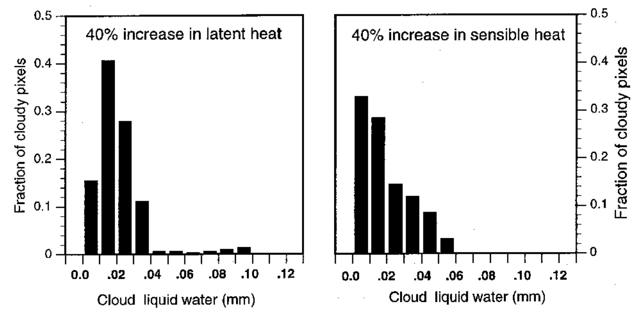

Figure 4. Distribution of integrated cloud liquid water for a 40% change in uniform sensible and latent heat flux distributions.

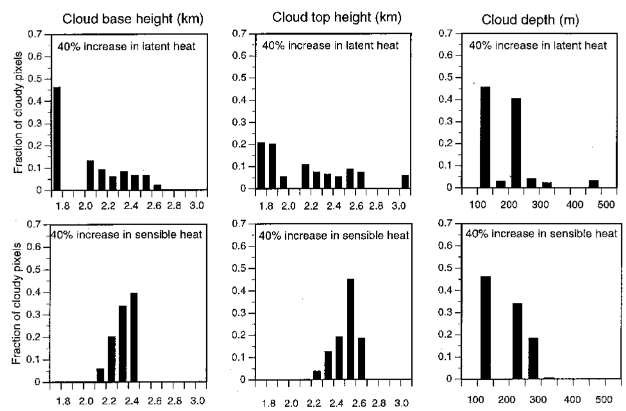

Figure 5. Distribution of cloud geometric properties for a 40% change in uniform sensible and latent heat flux distribution.

The results presented here are only for fair weather boundary-layer clouds and for one specific case. This work is currently being extended to more cases with fair weather clouds as well as to cases with deeper convective clouds.

Acknowledgment

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