The Role of Atmospheric Radiation in the Generation and Maintenance of Circulations of Different Scales

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Introduction

It is well known that the radiation budget of the atmosphere is an important component of the earth's climate system. On shorter time scales, radiative transfer affects the evolution of atmospheric circulation, principally through interaction with cloud and storm systems, and destabilizes the atmosphere continuously. This destabilization is important for subsequent development of clouds and storm systems. The clouds and storm systems feed back to the radiation budget, as clouds significantly alter both shortwave and longwave radiative transfer. It is important to understand the role that radiative transfer plays in the evolution of these circulation systems to accurately quantify the radiation budget.

The results presented here are from modeling studies designed to isolate the effect of radiative transfer on the generation of circulation systems of different spatial and temporal scales. Two different numerical weather prediction models were used and will be described briefly in the next section. Following that, the radiative transfer model that was used with both circulation models will be described. Finally, results from the modeling studies will be presented, and conclusions and future research efforts will be discussed.

Model Descriptions

The numerical model used for the smaller scale simulations has been previously described elsewhere (Huang and Raman 1991). The model is a hydrostatic primitive equation model with TKE-ε closure. The model simulations are two-dimensional in a horizontal domain of 1200 km with grid spacing of 5 km. The vertical domain is 12 km on a stretched σz (sigma-z) coordinate, with increased resolution in the boundary layer. There are 33 grid points in the vertical. The grid is staggered in both the horizontal and vertical. An explicit upstream cubic spline scheme is used for advection, with a quasi-implicit vertical diffusion scheme (Paegle et al. 1976). Recent improvements to the model include the addition of a five-category explicit cloud physics scheme (Rutledge and Hobbs 1984), a surface energy balance scheme which includes soil moisture (Louis 1979), and a radiative transfer scheme (Harshvardhan et al. 1987).

The numerical model used in the larger scale simulations is also a hydrostatic primitive equation model, also described elsewhere (e.g., Holt et al. 1990). The model includes a modified Kuo parameterization for convective clouds and calculates large scale precipitation directly. The vertical coordinate is σp with 10 evenly spaced levels. The time differencing is split explicit. Lateral boundary conditions are obtained from larger scale models. Two separate case studies are described here: an extratropical and a tropical case study. The extratropical simulation is from January 24 through January 28, 1986, covering a domain from 40°W to 140°W and 10°N to 70°N on a 2° longitude by 1.5° latitude grid. Lateral boundary conditions are from National Meteorological Center analysis. The tropical case is from July 16 to July 25, 1988. The model domain is from O° to 180°E and 30°S to 60°N. The grid spacing is 1.5° by 1.5°. Boundary conditions are from European Center for Medium Range Weather Forecasting analysis.

The radiation transfer scheme is based on the scheme formulated by Harshvardhan et al. (1987). The scheme includes radiative transfer in both the shortwave (SW) and infrared (IR) parts of the electromagnetic spectrum. The SW scheme is a 2 stream, delta-Eddington approximation, with absorption by H_20 and 0_3. There is both absorption and reflection at the earth's surface. Clouds are assumed to have a constant optical depth. In the IR, there is line absorption by H_20, 0_3, and $C0_2$, as well as absorption in the H_20 continuum. Clouds are treated as black bodies.

Results

The explicit cloud physics model is initialized with horizontally homogeneous temperature and moisture profile with zero ambient wind. A circulation is developed by imposing a heating function in the middle of the domain for the first 40 minutes of the simulation. Clouds quickly develop after the artificially imposed heating ceases.

The model results shown in Figures 1 and 2 are from a 4-hour simulation. The circulation that develops is as expected, with convergence below cloud base and divergence above cloud top. The appearance of three "cells" of cloud ice and cloud water and the symmetry about the center suggest that gravity waves are starting to propagate away from the heat source. The latent heating in the hydrostatic model is insufficient to continue to organize the circulation.

The same fields are shown in Figures 3 and 4, but with radiative transfer included. The differences in the temperature and wind fields are evident. The atmosphere is cooler through the entire domain, especially in the lowest layers. This is due to the lack of longwave cooling above the first layer in case 1. The differences in the middle troposphere are less pronounced. The convergence below cloud base for case 2 is much weaker, with shorter wavelength gravity waves in the upper part of the domain. Much less water in both phases forms in case 2. It appears that the radiative forcing helps to maintain the organization of the cloud system, as there is less evidence of the gravity wave activity in the cloud fields. The greater amount of cloud water that forms in case 1 is in response to the greater destabilization of the entire atmosphere through stronger surface heating.

The regional scale model is used with real initial conditions to determine the effect of radiative transfer on larger scale circulation. In the extratropics, the model was initialized with data from Genesis of Atlantic Lows Experiment (GALE) intensive observing period (IOP)2. The results from a 108-hour (4.5-day) simulation are presented in Figures 5 and 6.

The fields shown are the isentropic potential vorticity (IPV) and the v component of the geostrophic wind (v_g). The verification for this case is a very strong north-south jet streak imbedded in a high amplitude mean flow. To isolate the effects of radiative transfer, the surface energy budget in the model was not included in the simulations. With this severe constraint, neither the simulations with or without atmospheric radiation transfer verify very well. However, radiative transfer maintains the circulation somewhat better, as is evident in both IPV and v_g.

The same regional scale model was used for a tropical simulation, initialized with data from July 1988. Zonal means for temperature, moisture and the u and v wind components for a 10-day simulation in the Indian monsoon region are shown in Figures 7 and 8. The model was also run in this case without the surface energy budget included.

The x-axis of the figures is latitude from 30°S to 60°N. The effect of radiative transfer is evident in the wind fields. The upper branch of the Hadley cell is more intense in both hemispheres with radiation, while the equatorial easterly jet is stronger in the case without radiation. This indicates that meridional transport is more effectively maintained by the cloud/radiation interaction. The effect on the precipitation is shown in Figure 9.

Means for a box bounded by 45°E to 105°E and 5°N to 30°N are plotted. The precipitation is segregated into grid scale and convective components and also segregated into precipitation over land and over water. Evaporation from sea surface is included. All fields are significantly increased when radiative transfer is included.

Summary and Future Research

Model results have been presented showing the effects of radiative transfer on mesoscale to regional scale circulations. Radiative transfer appears to be part of the organization mechanism for mesoscale circulation, most likely through interaction with the ice layer. The intensity and activity of a model atmosphere at longer time scales also depends on the radiative transfer.

Results from the mesoscale model will be compared to simple analytic models. More simulations without the surface energy budget will isolate the effect of atmospheric radiative transfer. The effect of explicit cloud physics on the radiation budget will be compared with parameterized clouds. The work on the role of radiative transfer on tropical monsoon and on east coast cyclogenesis will be continued

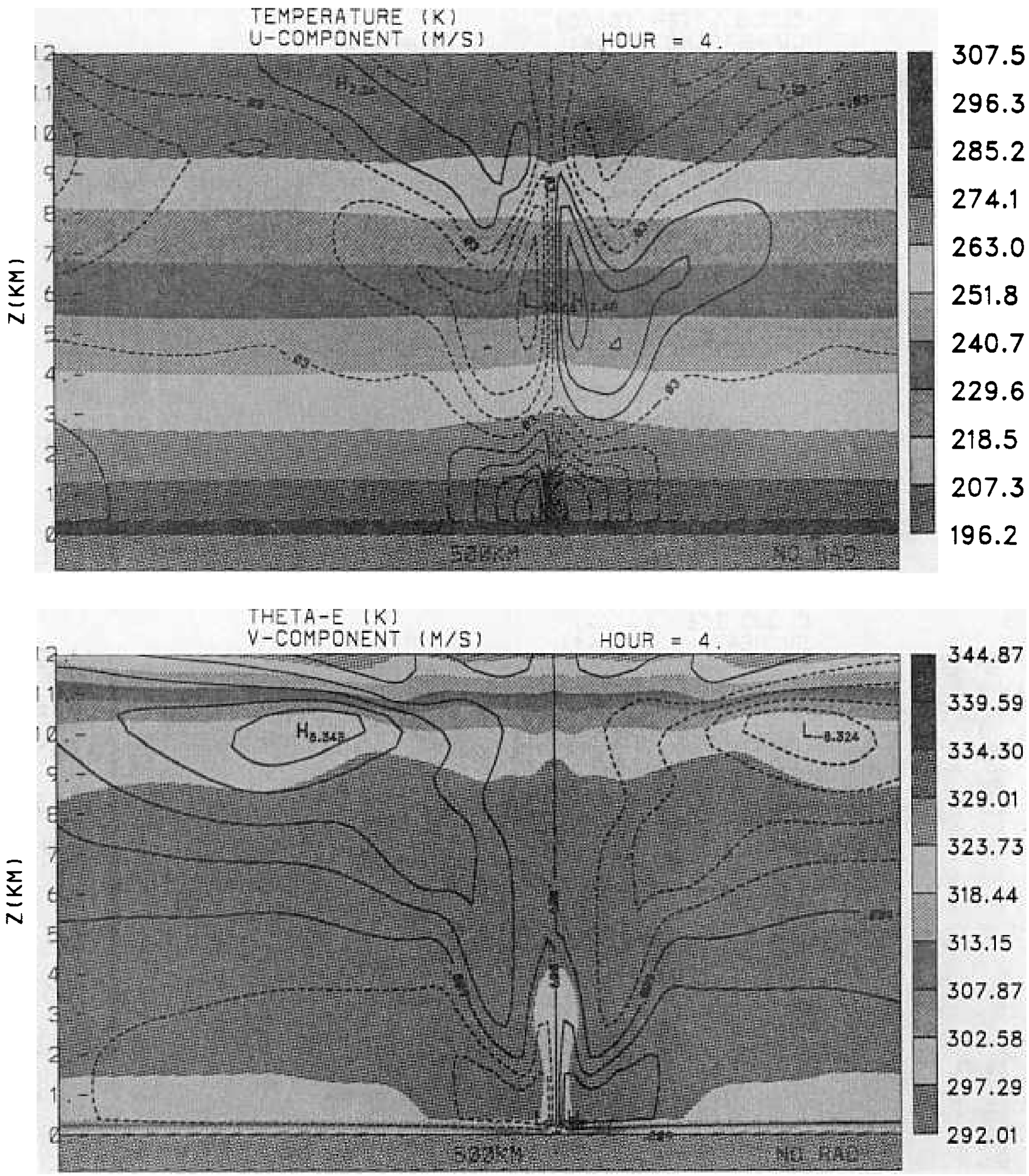

Figure 1. The upper panel is the u component of the wind superimposed on the temperature, and the lower panel is the v component of the wind with the equivalent potential temperature. 500 km from the middle of a 1200-km domain are presented. The results are from the explicit cloud physics model 4 hours into the simulation. This is for the case without radiation.

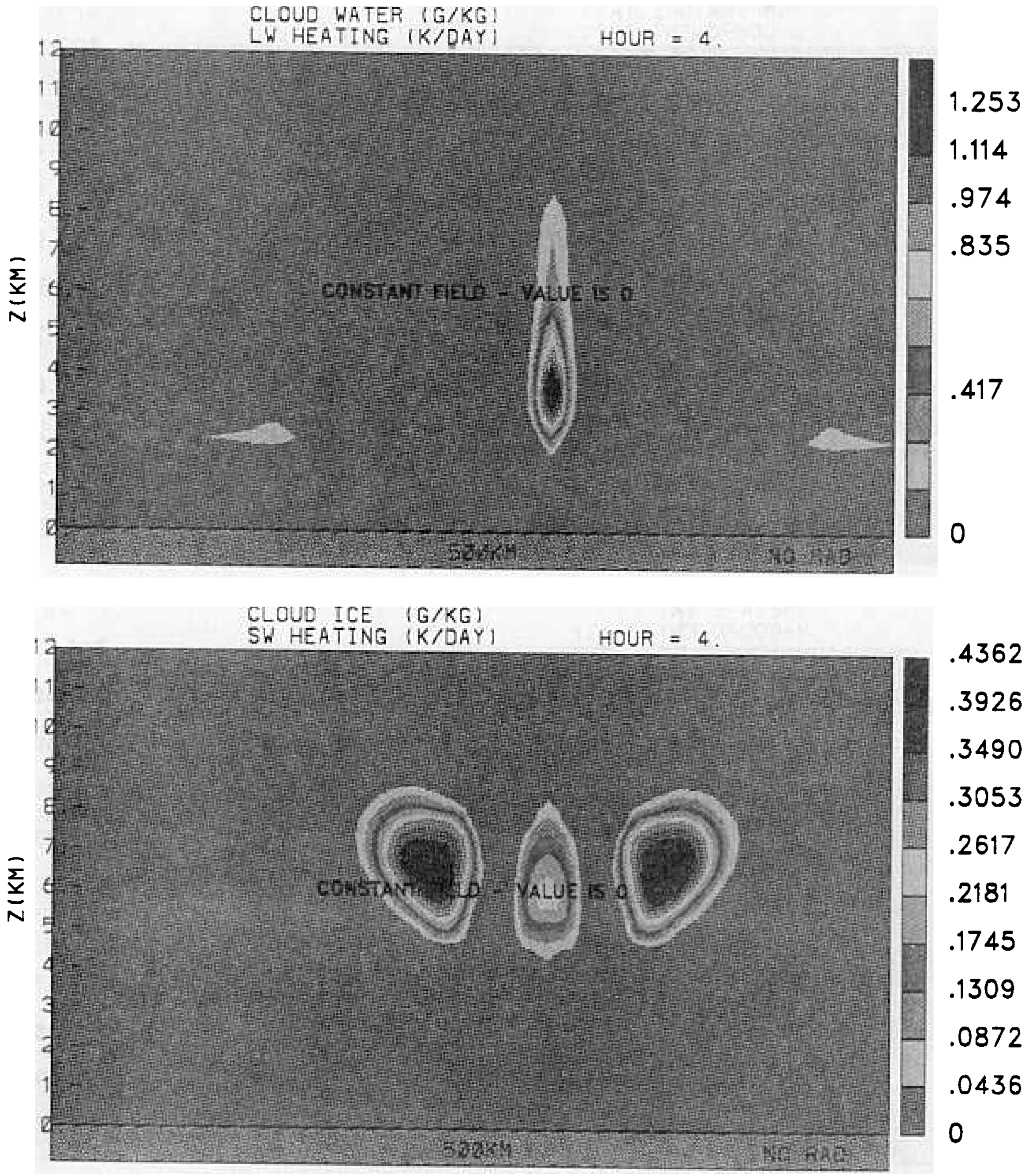

Figure 2. The upper panel is cloud water superimposed on the longwave heating, and the lower panel is cloud ice with shortwave heating. 500 km from the middle of a 1200-km domain are presented. This is for the case without radiation.

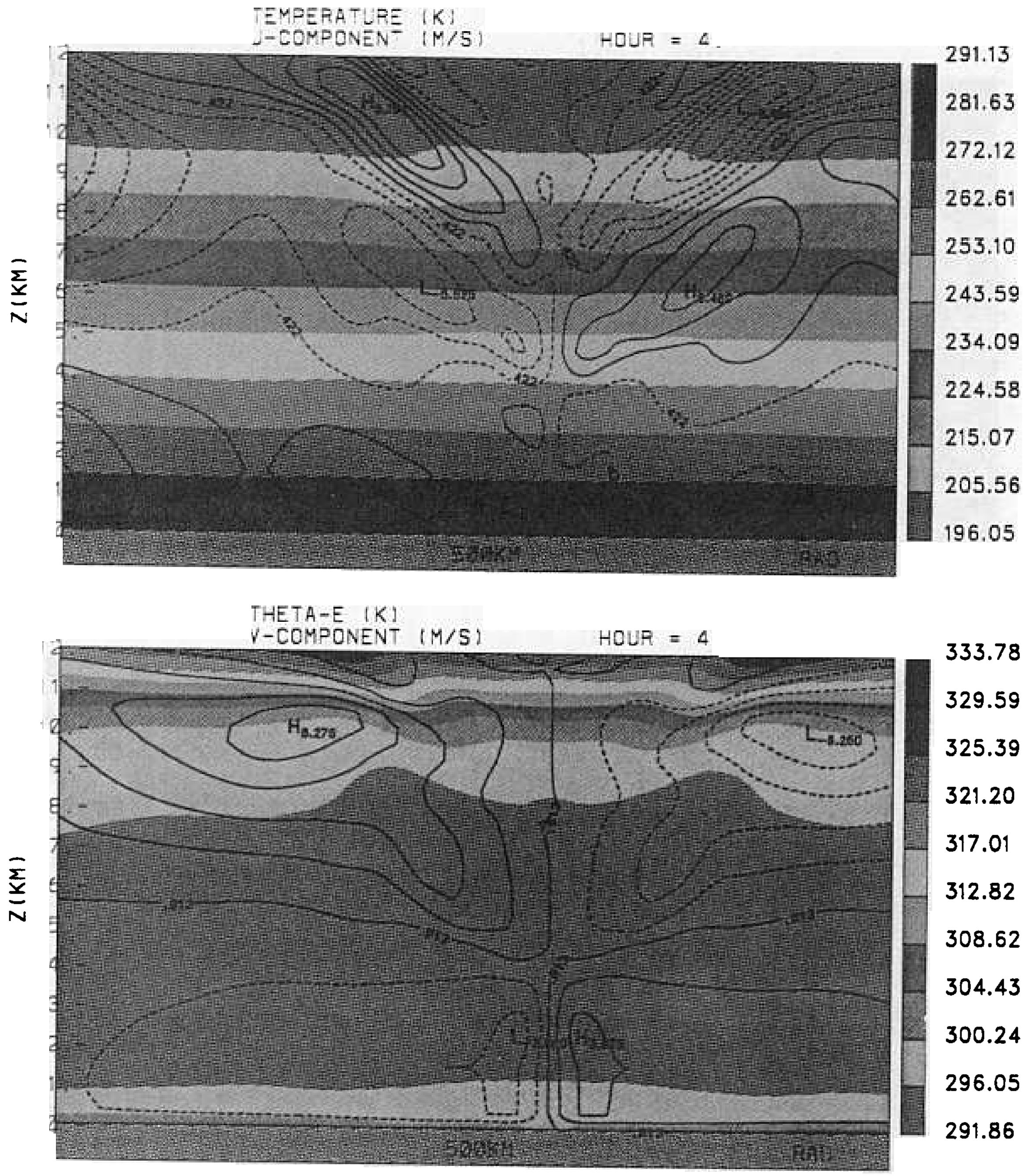

Figure 3. The upper panel is the u component of the wind superimposed on the temperature, and the lower panel is the v component of the wind with the equivalent potential temperature. 500 km from the middle of a 1200-km domain are presented. This is for the case with radiation.

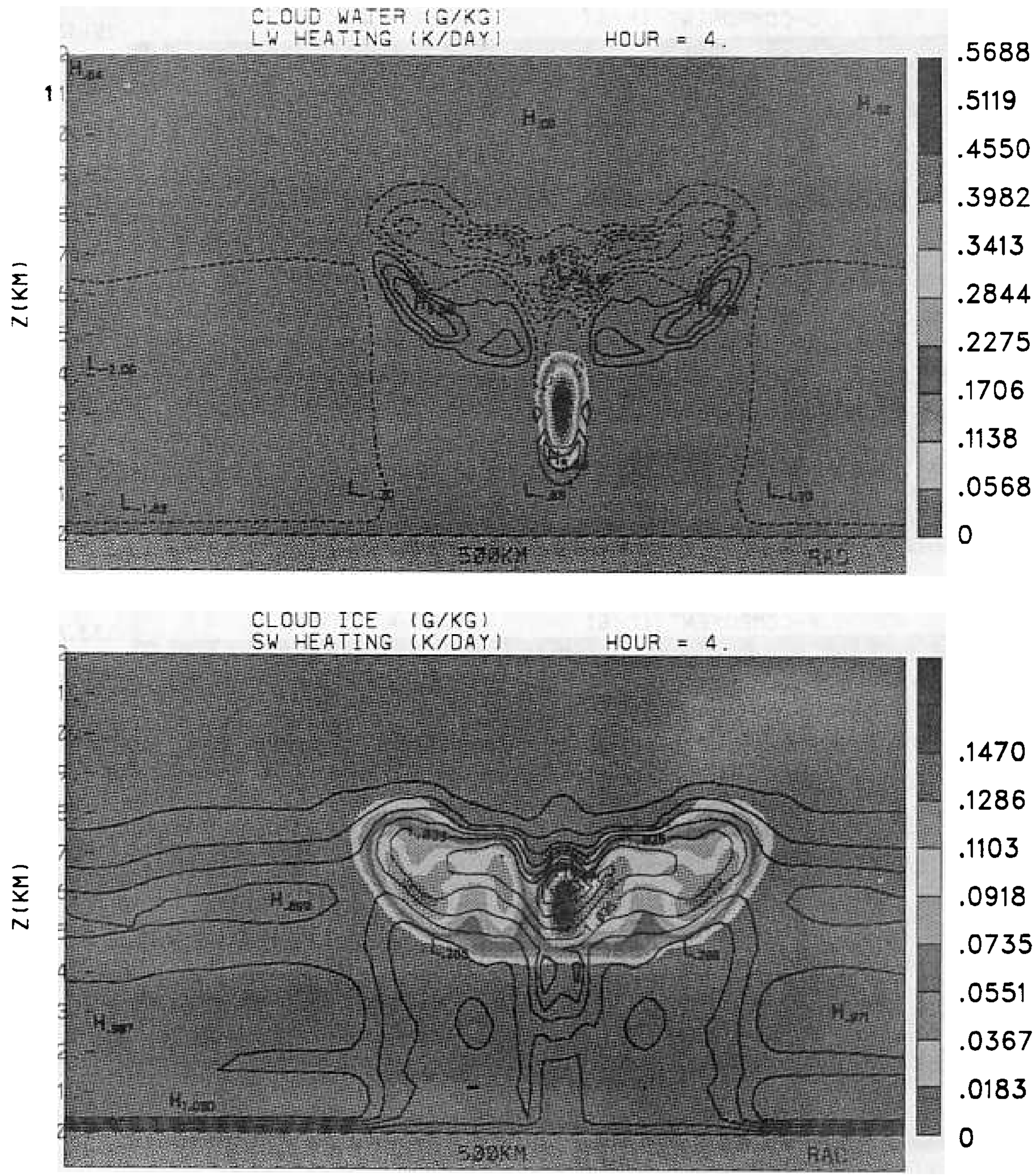

Figure 4. The upper panel is cloud water superimposed on the longwave heating and the lower panel is cloud ice with shortwave heating. 500 km from the middle of a 1200-km domain are presented. This is for the case with radiation.

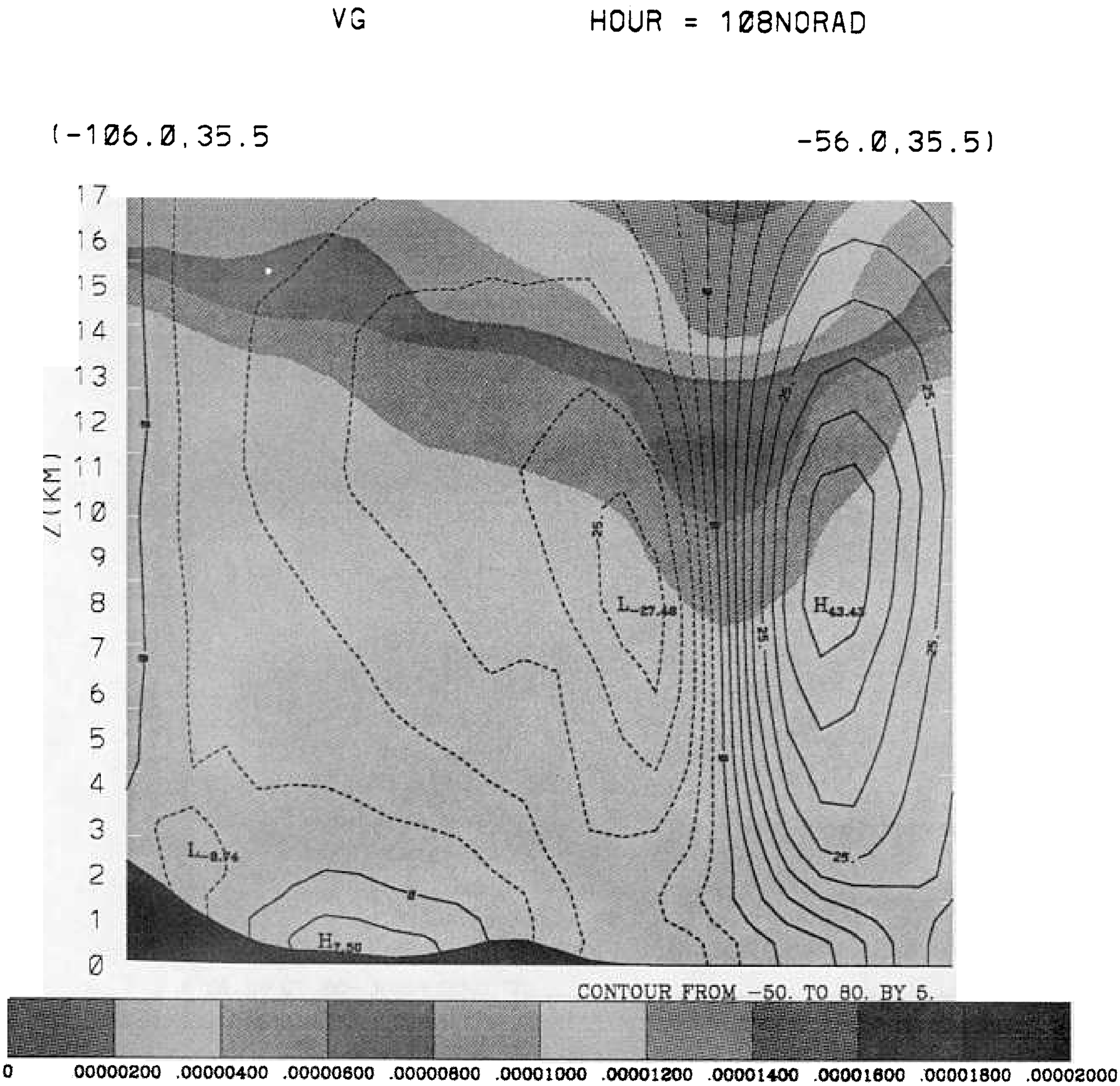

Figure 5. The meridional component of the geostrophic wind is superimposed on the isentropic potential vorticity for 108 hours into a forecast with the regional scale model. This is for the case without radiation.

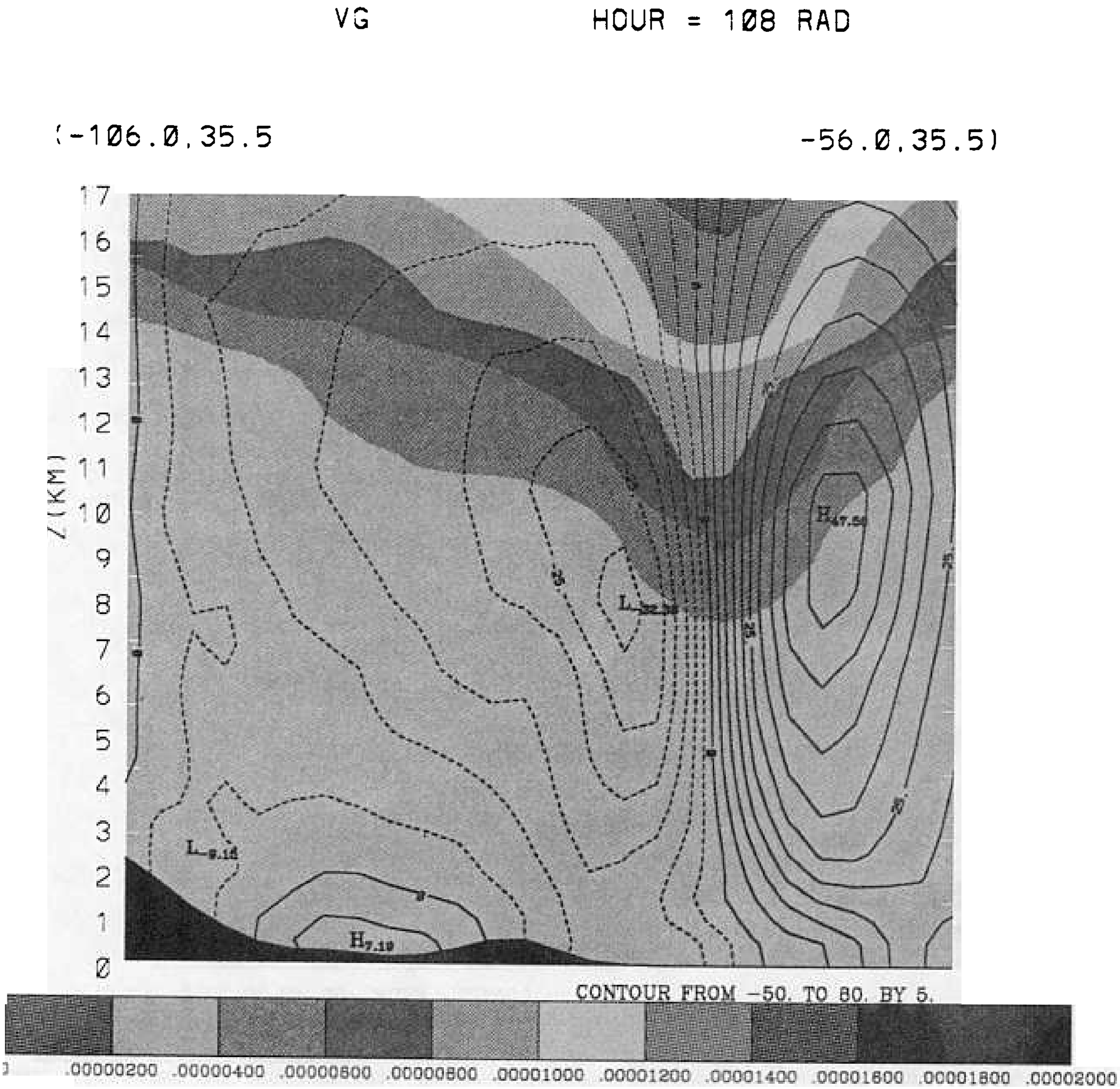

Figure 6. The meridional component of the geostrophic wind is superimposed on the isentropic potential vorticity for 108 hours into a forecast with the regional scale model. This is for the case with radiation.

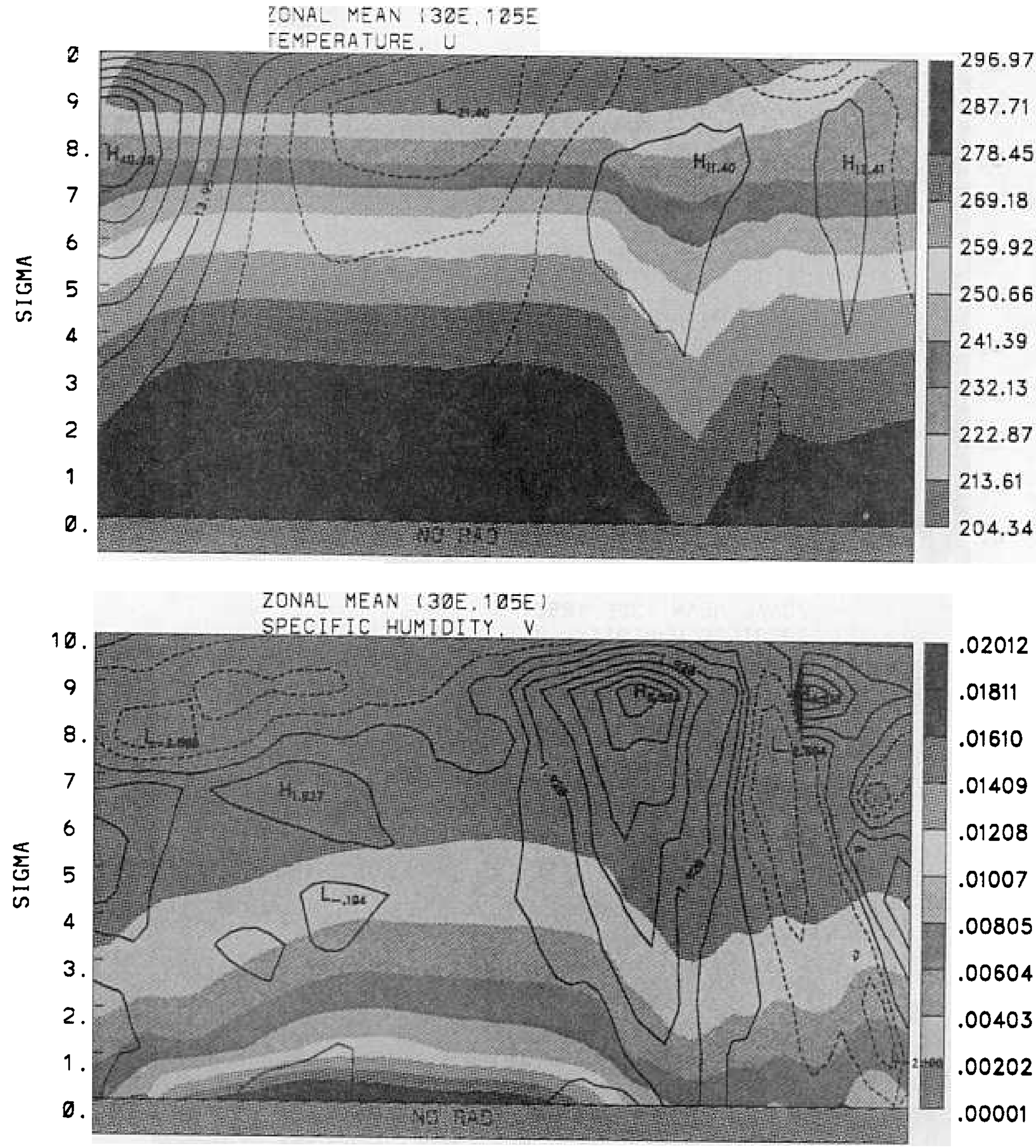

Figure 7. The upper panel is the zonal mean temperature with the zonal mean u component superimposed for a 10-day simulation with the regional scale model. The domain extends from 30°S to 60°N. This is for the case without radiation. The lower panel is the zonal mean specific humidity with the zonal mean v-component superimposed.

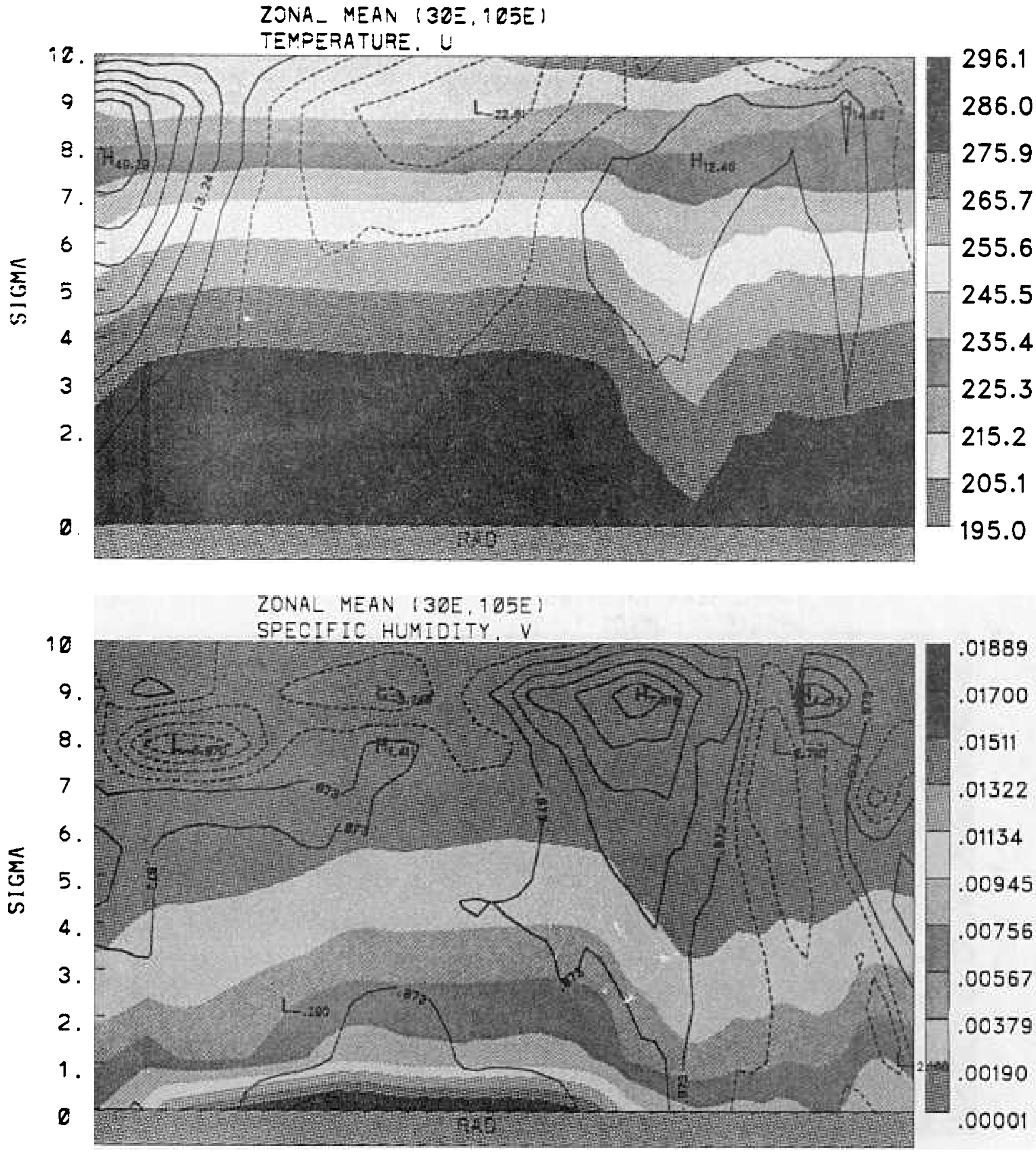

Figure 8. The upper panel is the zonal mean temperature with the zonal mean u component superimposed for a 10-day simulation with the regional scale model. The domain extends from 30°S to 60°N. This is for the case with radiation. The lower panel is the zonal mean specific humidity with the zonal mean v-component superimposed.

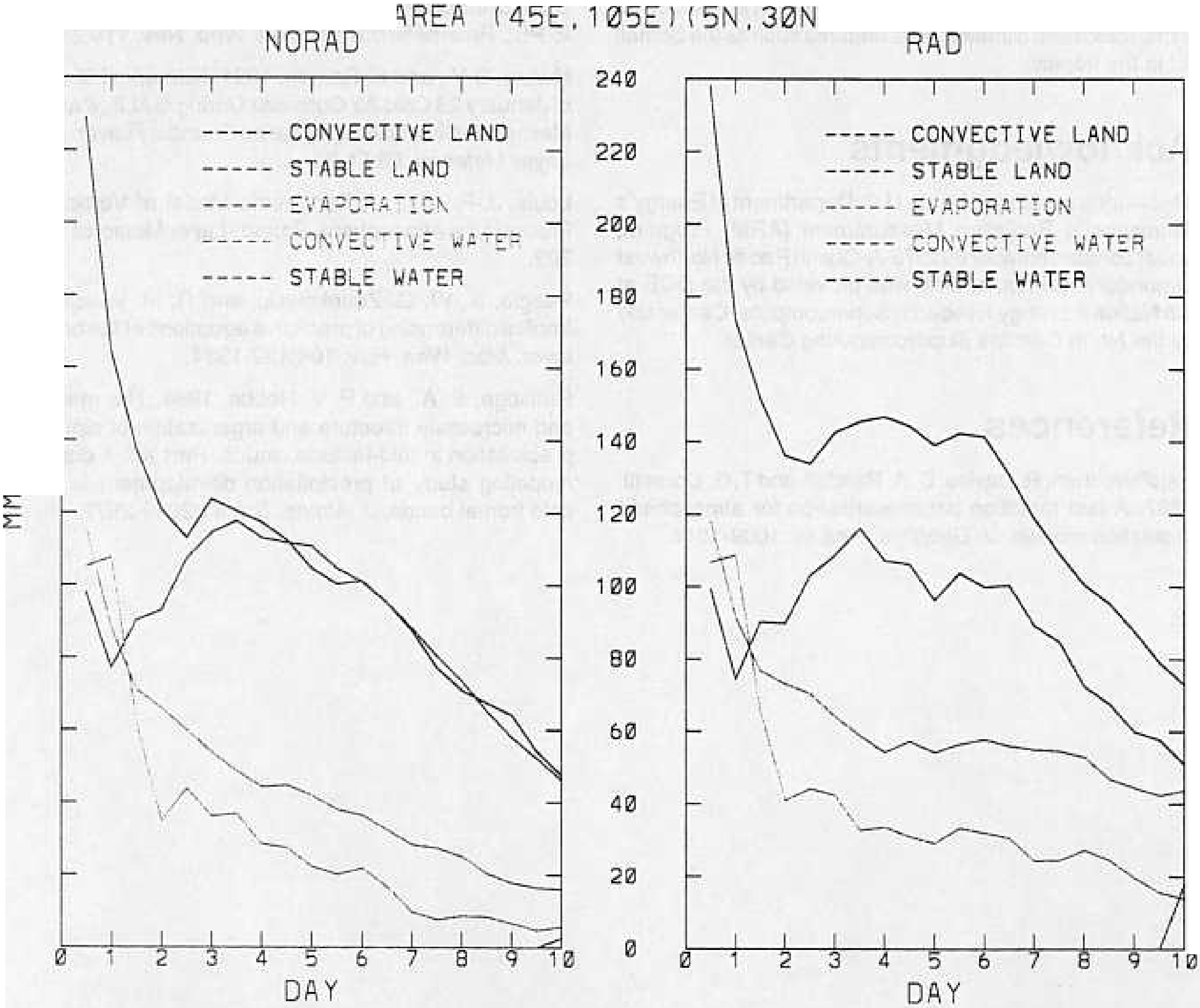

Figure 9. Mean water budget terms for the 10-day simulation for a subdomain of the simulation. The subdomain is centered over the Indian subcontinent and extends from 5°N to 30°N and from 45°E to 105°E. The labeling scheme is convective land represents convective precipitation from the model over land, convective water represents convective precipitation over water. The same scheme is used for stable precipitation. Evaporation from the sea surface is also displayed.

and expanded, especially to look at the feedback to specific features. This includes looking at jet streaks in the extratropics and climatological features such as the Somali jet in the tropics.

Acknowledgments

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