The Effects of Radiative Transfer on Low-Level Cyclogenesis

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Introduction

Many investigators have documented the role that thermodynamic forcing due to radiative flux divergence plays in the enhancement or generation of circulation. Most of these studies involve large-scale systems (e.g., Slingo et al. 1988), small-scale systems such as thunderstorms (Chen and Cotton 1988), and squall lines (Chin, submitted). The generation of circulation on large scales results from the creation of divergence in the upper troposphere and the maintenance of low-level potentially unstable air, and the maintenance of baroclinicity throughout the atmosphere. On smaller scales, radiative flux divergence acts similarly. In the thunderstorms and squall lines, the radiative forcing acts as a pump, increasing the divergence at the top of the storm systems and increasing the updraft velocity and the intensity of inflow at mid-levels in the storm systems (Tripoli and Cotton 1989; Chin[(a)]). Other researchers have examined the role of surface processes (Cione et al. 1991; Holt and Raman 1990) and low-level baroclinicity (Lin 1990) in east coast cyclogenesis.

In this paper, we examine the interactive role that radiative flux divergence, clouds, and surface processes play in low-level cyclogenesis and the creation or maintenance of the boundary layer baroclinicity.

Description of the Experiment

The North Carolina State University (NCSU) mesoscale model is initialized with a temperature and moisture profile from the Genesis of Atmosphere Lows Experiment (GALE) intensive observing period IOP-2, in which a coastal front formed following a cold air outbreak. Following the coastal front, intensive cyclogenesis over the Gulf Stream occurred.

The model is run in three dimensions with no external forcing imposed. The model domain is 41 X 41 grid points with a 10-km grid spacing. The land-sea interface is idealized to approximate the coast line of North Carolina. The maximum sea-surface temperature (SST) marks the core of the Gulf Stream and is at the middle of the domain at the southern border. A simple cosine function is fit to create the Gulf Stream curve to the north and east, a situation favorable for surface cyclogenesis (Cione et al. 1991).

Discussion of Results

The results of two model runs, one with radiative transfer (R) and one without (NR) are presented. The simulations lasted for 15 hours, beginning at 0600 local time in late January. More cloud water and rain water were produced in the model runs when radiative transfer was included. The differential surface heating at the Gulf Stream front created convergence which forced upward vertical motion, and, in both cases, clouds formed over the Gulf Stream. Radiative forcing results in greater cloud water amounts spread over a larger horizontal area. The greater amounts result from feedback to the circulation, as well as the role that radiative forcing plays in maintaining boundary layer clouds. Radiative cooling at cloud top and heating at cloud base maintain clouds at the top of the boundary layer, while the thermal forcing feeds back to the circulation, creating greater convergence, hence, more cloud water and, ultimately, rain water.

The temperature gradient is greater along the Gulf Stream front in case R, but the gradient is greater at the coastline

(a) Chin, H.-N.S. 1994. The Impact of Ice Phase and Radiation on a Midlatitude Squall Line System. Submitted to the *J. of Atmos. Sci.*

in case NR. The land surface temperature is a few degrees warmer in the case without radiative transfer, as there is no attenuation of the solar radiation reaching the surface. The temperatures in the clear air over the cool shelf water are cooler in case R. This region is frequently associated with difluence and sinking motion during cyclogenesis over the Gulf Stream (Reddy and Raman, in press). The sinking motion heats the lower atmosphere adiabatically. However, in case R, radiative cooling of the entire vertical column offsets the adiabatic warming. The radiative cooling is primarily responsible for the maintenance of the sharp temperature gradients at the Gulf Stream front. The differences in the temperature distribution have two effects. The sharper gradient at the Gulf Stream front in the radiative transfer case generates more circulation in that region, while the greater gradient over land in the case without radiative transfer generates a stronger sea-breeze convergence area in that region.

The horizontal velocity components for case R are shown in Figures 1 and 2. The surface forcing of low-level circulation

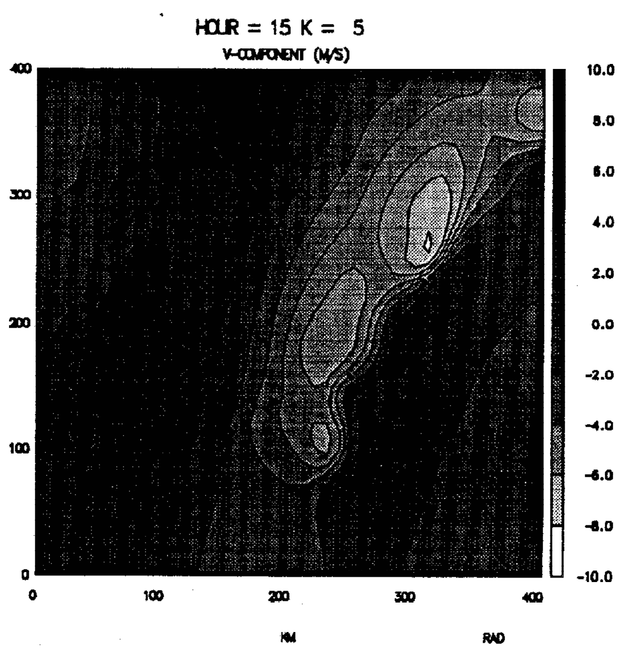

Figure 2. The horizontal distribution of the v component of the wind in m/s for the same level and time as in Figure 1.

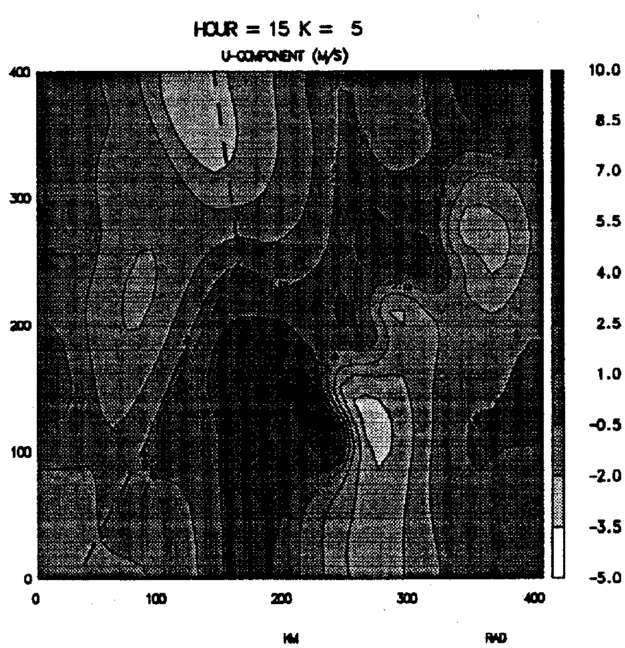

Figure 1. The horizontal distribution of the u component of the wind in m/s at level 5 (approximately 700 m) after 15 hours simulation for the case with radiative transfer.

creates the circulation forming at 250 km E and 100 km N. (All references to distance refer to distance from the western or southern border.) There is another convergence area just to the north of the first one and another one still farther north at about 300 km N and 330 km E. Convergence occurs at the same places in NR, but the intensity of the convergence and the induced circulation are less. The gradients of both velocity components are much greater when radiative transfer is included and stronger circulation develops. In both cases, the largest velocity gradients correspond to regions where the temperature gradients are large. Since the temperature gradients are greater when radiative transfer is included, the induced circulation is more intense.

The vorticity generation at this level results from increased baroclinicity. How is the greater baroclinicity generated? Radiative heating below clouds enhances the heating of the lower atmosphere. At the same time, cooling of the atmosphere in the cloud-free region creates cooler temperatures, further enhancing the temperature gradient.

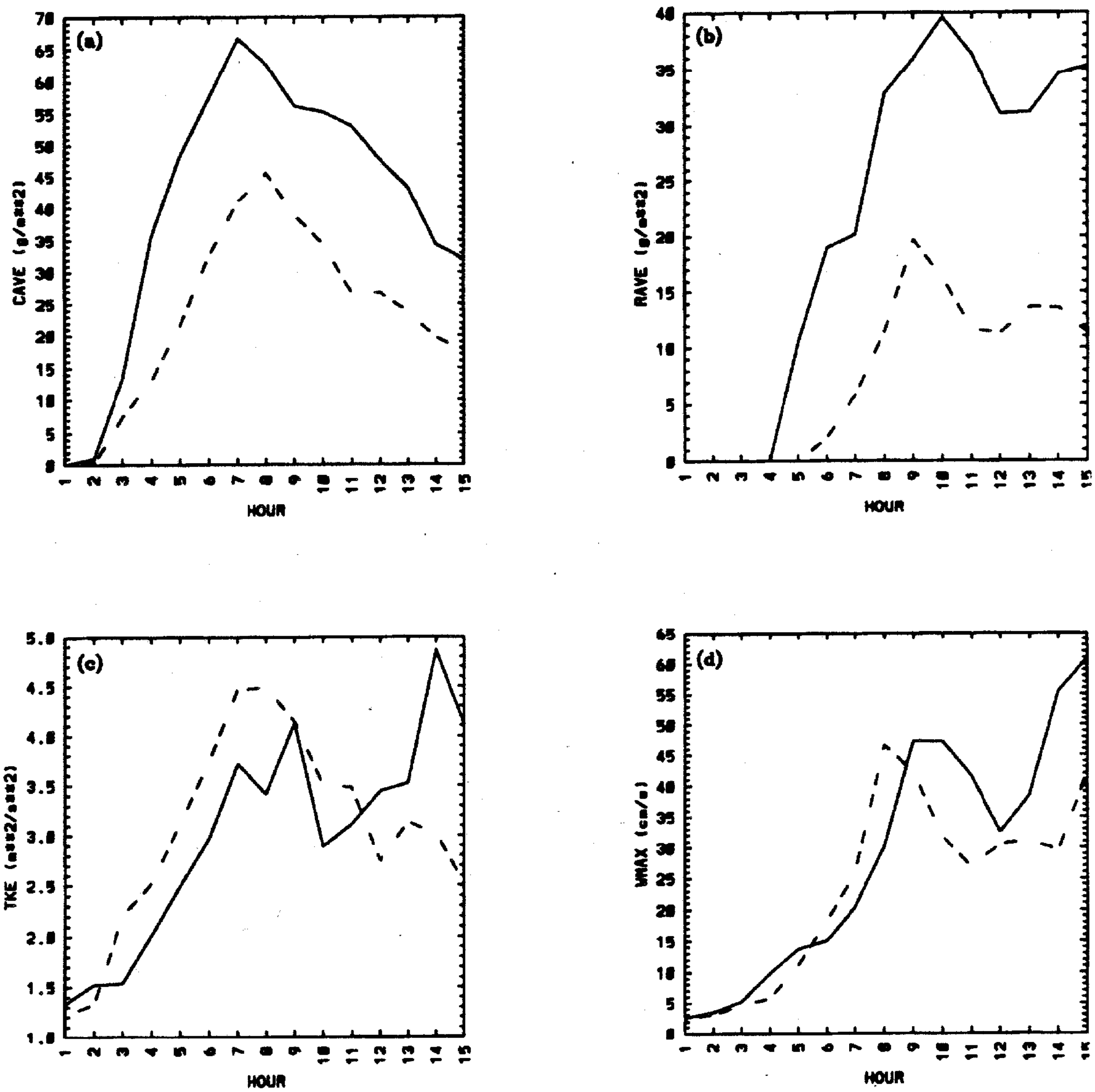

Figure 3. Summary information from both simulations. The solid lines represent the simulation with radiative transfer, the dashed line represents the case without radiative transfer. The abscissa is time. The domain averaged cloud water (g/m**2) is in (a), the domain averaged rain water (g/m**2) is in (b), the domain maximum value of TKE (m**2/s**2) is in (c), and the domain maximum positive vertical velocity (cm/s) is in (d).

The radiative transfer processes thus enhance the baroclinicity being produced by surface processes and turbulent transport.

Time sequences of $\overline{q_c}$, $\overline{q_r}$, TKE_{max}, and w_{max} are shown in Figure 3. The solid lines represent values taken from the simulation with radiative transfer, the dashed lines from the simulation without radiative transfer. The mean quantities of q_c and q_r are horizontal domain averaged values of the integrated column liquid water values, i.e.

$$\overline{q_1} = \frac{\int\int\left[\int_o^{\infty} \rho q_1 dz\right] dxdy}{\int\int dxdy} \tag{1}$$

where the subscript 1 refers to either cloud water or rain water. The similar time structure of the water averages between the two cases indicates that the essential formation mechanism is the same, but is more effective when radiative transfer is included. The $\overline{q_c}$ is about 50% greater when radiative transfer is included, while $\overline{q_r}$ is approximately double. Rain water is removed as precipitation at the surface even over the ocean surface. These results show clearly that radiative transfer has a large effect on the production of cloud and rain water and on the entire water budget.

The turbulence and vertical velocity maximum values also have similar structure for both cases with similar magnitudes. The TKE_{max} occurs over land at hour 6, which is one hour after local noon. This is due to the normal buoyancy source term over heated land. Incoming solar radiation heats the land surface, creating the buoyancy source. The smaller values of shortwave radiation reaching the surface in the radiative transfer case account for the slightly smaller values of the maximum TKE. The increase late in the day for the radiative transfer is due to the slower stabilization of the atmosphere as longwave heating at cloud base maintains turbulence and slows the cooling of the surface temperatures over land. Also, the heating at cloud base can be an effective source of turbulence, which decouples the surface layer from the cloud layer making surface dissipation of turbulence less effective in that instance. This effect has been seen in observations and documented by various researchers (Duynkerke and Driedonks 1989).

Including radiative transfer in the cloud model significantly affects the thermodynamic structure, the momentum fields, and the water budget. The effects are through complex interactions of the radiative flux divergence with the moisture, and the feedback to the thermodynamics which then forces the momentum fields, resulting in the generation of greater circulation. Stronger circulation then results in greater cloud amounts with stronger feedback to the radiative transfer.

References

Chen, S., and W. R. Cotton. 1988. The Sensitivity of a Stimulated Extratropical Mesoscale Convective System to Longwave Radiation and Ice-Phase Microphysics. *J. of Atmos. Sci.* **45**:3897-3910.

Cione, J. J., S. Raman, and L. J. Pietrefesa. 1991. The Effect of Gulf Stream-Induced Baroclinicity on U.S. East Coast Winter Cyclones. *Mon. Wea. Rev.* **121**:421-430.

Duynkerke, P. G., and A.G.M. Driedonks. 1989. Turbulent Structure of a Shear-Driven Stratus-Topped Atmospheric Boundary Layer: A Comparison of Model Results with Observations. *J. of Atmos. Sci.* **45**:2343-2351.

Holt T., and S. Raman. 1990. Marine Boundary Layer Structure and Circulation in the Region of Offshore Redevelopment of a Cyclone during GALE. *Mon. Wea. Rev.* **118**:392-410.

Lin, T.-L. 1990. A Theory of Cyclogenesis Forced by Diabatic Heating. Part II: A Semigeostrophic Approach. *J. of Atmos. Sci.* **47**:1755-1777.

Reddy, N. C., and S. Raman. Scales and Spectra of Turbulence over the Gulf Stream during an Offshore Cyclogenesis. *Bound.-Layer. Meteorol.*, in press.

Slingo, J. M., U. C. Mohanty, M. Tiedtke, and R. Pearce. 1988. Prediction of the 1979 Summer Monsoon Onset with Modified Parameterization Schemes. *Mon. Wea. Rev.* **116**:328-346.

Tripoli, G. J., and W. R. Cotton. 1989. Numerical Study of an Observed Orogenic Mesoscale Convective System. Part 2: Analysis of Governing Dynamics. *Mon. Wea. Rev.* **117**:305-328.