Numerical Simulation of Radial Cloud Bands within the Upper-Level Outflow of an Observed Mesoscale Convective System

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ABSTRACT

Turbulence affecting aircraft is frequently reported within bands of cirrus anvil cloud extending radially outward from upstream deep convection in mesoscale convective systems (MCSs). A high-resolution convection permitting model is used to simulate bands of this type observed on 17 June 2005. The timing, location, and orientation of these simulated bands are similar to those in satellite imagery for this case. The 10–20-km horizontal spacing between the bands is also similar to typical spacing found in a recent satellite-based climatology of MCS-induced radial outflow bands.

The simulated bands result from shallow convection in the near-neutral to weakly unstable MCS outer anvil. The weak stratification of the anvil, the ratio of band horizontal wavelength to the depth of the near-neutral anvil layer (5:1 to 10:1), and band orientation approximately parallel to the vertical shear within the same layer are similar to corresponding aspects of horizontal convective rolls in the atmospheric boundary layer, which result from thermal instability. The vertical shear in the MCS outflow is important not only in influencing the orientation of the radial bands but also for its role, through differential temperature advection, in helping to thermodynamically destabilize the environment in which they originate.

High-frequency gravity waves emanating from the parent deep convection are trapped in a layer of strong static stability and vertical wind shear beneath the near-neutral anvil and, consistent with satellite studies, are oriented approximately normal to the developing radial bands. The wave-generated vertical displacements near the anvil base may aid band formation in the layer above.

1. Introduction

Bands of anvil cirrus extending radially outward from regions of deep convection (Fig. 1) are a common cloud characteristic near the outer edge of divergent upper-level outflows of mesoscale convective systems (MCSs). Lenz et al. (2009, hereafter L09) document such banding events, lasting an average of 9 h, in approximately ½ of a sample of 136 large MCSs over the central United States during the 2006 warm season. L09 suggest the practical importance of these bands by noting that at least one observation of light (moderate) commercial aviation turbulence was recorded in their vicinity for 93% (44%) of their MCS cases.

Knox et al. (2010) illustrate similar cirrus bands in a wide range of atmospheric phenomena that, in addition to MCSs, includes tropical cyclone outflows and jet stream cirrus in midlatitude cyclones. While environments of the these bands share common characteristics including strong vertical and horizontal shears, which can support various dynamic instabilities, Knox et al. (2010) point out that there is no current consensus regarding their formation mechanism.
Both L09 and Knox et al. refer to these bands as "transverse bands," with discussion in the latter suggesting that the terminology may have arisen from observations of the bands being oriented approximately normal to jet stream winds. However, this is not always the case (e.g., Knox et al. 2010, their Fig. 11). Within MCSs and tropical cyclones, band orientation approximately locally outward from the main cirrus cloud shield appears to be more generic. Thus, in the current paper we refer to these banded cloud features as "radial bands."

Another aspect of these cirrus bands in MCS outflows revealed by L09 is their tendency to occur on only one side of individual MCSs (their Fig. 5). To the extent that environmental vertical and/or lateral shears influence band formation, the above result may be related to the well-known asymmetry in midlatitude MCS outflow jets. Fritsch and Maddox (1981) pointed out that the preference for these anticyclonic jets in a given sector of an MCS resulted from a similarity of the outflow direction with that of background flow at the detrainment level. Such sectorization of radial cirrus bands is often absent in tropical cyclone outflows (e.g., Heymsfield et al. 2006; Knox et al. 2010), which could be a manifestation of weaker background flow.

The 17 June 2005 MCS case (Fig. 1) is an example of a radial band event associated with numerous turbulence reports on the north side of the system (Trier and Sharman 2009, hereafter TS09). TS09 used a convection-permitting model to simulate the mesoscale environment in which turbulence during the 17 June MCS was observed. They noted that the gradient Richardson number, 

$$R_i = \frac{N_m^2}{|\partial V/\partial z|^2},$$

where the numerator is the moist static stability and the denominator depends on vertical wind shear, had strong regional variations within the MCS anvil. Within the northern part of the anvil, where outflow was not opposed by background westerlies, both dynamic ($0 < R_i < 1$) instabilities, such as Kelvin–Helmholtz instability (e.g., Nappo 2002, section 6.2), and moist static ($R_i < 0$) instability were supported.
However, the horizontal resolution in TS09 was inadequate to resolve the radial bands of Fig. 1.

In the current study we extend the results of TS09 by adding a fine-resolution nested grid that resolves banded features within the MCS upper-level outflow. Figure 2 illustrates the development of radial bands in the simulated brightness temperature $T_b$, for the region that contains the black rectangle in Fig. 1. Here, we have coarsened the model output to the $\sim$4-km satellite pixel size to facilitate comparison with Fig. 1. The horizontal location, orientation (southwest–northeast), and overall pattern of the simulated radial bands (Fig. 2) are similar to those in the satellite observations (Fig. 1). Using results from TS09 and this new simulation we propose mechanisms for the generation of the observed radial bands.

2. Numerical model and experiment design

We use 0400 UTC 17 June 2005 ($t = 7$ h) output from the Advanced Research Weather Forecast (ARW-WRF) model (Skamarock et al. 2005) simulation of TS09 with $\Delta x, y = 3$ km to initialize a new simulation over the same $600 \times 500 \times 64$ domain, D1 (Fig. 3a). In addition, the new simulation places a two-way interactive horizontal nest, D2, in the path of the northern outflow of the MCS (Fig. 3a). D2 has $1250 \times 550$ horizontal grid points with 600-m spacing. The vertical grid spacing is the same as in D1 and is $\sim(60–170)$ m in the lowest kilometer, $\sim350$ m within the outer anvil cloud (11.5–13.5 km MSL), and $\sim500–1500$ m from 15 to 31 km MSL.

The model is integrated for 7.5 h with lateral boundary conditions obtained from hourly Rapid Update Cycle (RUC) (Benjamin et al. 2004) 13-km native hybrid coordinate analyses and 1° hourly FNL pressure-level analyses as described in TS09. The model physical parameterizations are identical to those discussed in more detail in TS09 and include the Janjic (1990, 1994) PBL scheme, the Thompson et al. (2008) bulk microphysics parameterization, and the Rapid Radiative Transfer Model (RRTM) longwave (Mlawer et al. 1997) and Dudhia (1989) shortwave radiation schemes. Subgrid vertical mixing in the model is handled by the PBL scheme, whereas horizontal mixing is determined using a Smagorinsky first-order closure (Skamarock et al. 2005).

3. Results

The 12.1-km MSL moist static stability $N_m^2$ calculated from Durrant and Klemp [1982, their Eq. (36)] but modified to account for ice latent heating–cooling, is superimposed on $T_b$ in Fig. 2. The $T_b$ calculation assumes 1) the zenith angle is zero, 2) $T_b$ is roughly the temperature at unity optical depth into the cloud, and 3) the cloud absorption coefficient (Dudhia 1989) is constant. At 0600 UTC (2 h after initialization of the inner nest), similar to observations (Fig. 1a), radial bands occur near the anvil edge over northeast Kansas (Fig. 2a).

In the model, this weak banding originates within a localized region of $N_m^2 < 0$ (Fig. 2a). Over the next 2–4 h radial bands redevelop within a much larger mesoscale region of small $N_m^2$ that approaches from the southwest (Figs. 2b–d). Animations revealed that individual bands were identifiable for up to $\sim 2$ h and moved approximately with the mean anvil wind (Fig. 3a).

Differential radiative forcing from longwave cooling at cloud top and warming at cloud base (e.g., Houze 1993, section 5.3.1.2) can contribute to thermodynamic destabilization of anvils. In the current case, the parent MCS convection is not significantly affected by cloud–radiative feedbacks (Figs. 3a,c). However, in Figs. 3b and 3d, where $T_b$ is displayed at full horizontal resolution (as in the remainder of the paper), the control run clearly has more widespread and prominent anvil radial bands than does a simulation in which cloud–radiative feedbacks are neglected. The bands originate from regions where $N_m^2 < 0$, which are more extensive in the control run. However, the mesoscale patterns of $N_m^2$ are similar (Figs. 3b,d) and thermodynamic destabilization with some banding also occurs when cloud–radiative feedbacks are deactivated (Fig. 3d), indicating that additional mechanisms focus regional destabilization in this case.

TS09 describe one such mechanism that is summarized here using Fig. 4, which is a southwest–northeast-oriented vertical cross section originating from near the MCS outflow source and terminating in the outer anvil region (cf. Fig. 3a). At the height of the outer anvil [$\sim(11.5–13.5)$ km MSL], where moist and dry adiabatic lapse rates are nearly equal, $N_m^2$ is nearly proportional to $\partial \theta_e / \partial z$, where $\theta_e$ is the equivalent potential temperature. As a large and intense deep convective line decays after 0600 UTC (TS09, their Fig. 8) $\theta_e$ surfaces are displaced upward downstream, leading to horizontal $\theta_e$ gradients at the northeast edge of the mesoscale anvil updraft by 0745 UTC (Fig. 4a). These isentropes are steepened further by differential horizontal advection from the vertical shear contributing to $\partial \theta_e / \partial z < 0$ ($N_m^2 < 0$) downstream by 0830 UTC (Fig. 4b).
FIG. 2. Simulated brightness temperature $T_b$ and smoothed contours of 12.1-km MSL moist static stability $N_{ms}$ each calculated using the RIP software for model output (users’ guide available online at http://www.mmm.ucar.edu/wrf/users/docs/ripug.htm) over the southeastern 2/3 of D2 in Fig. 3a, which corresponds to the black rectangular region in Fig. 1: (a) 0600, (b) 0845, (c) 0945, and (d) 1045 UTC 17 Jun. The brightness temperature is smoothed using a $7 \times 7$ gridpoint running mean to approximate the resolution of the satellite image in Fig. 1. Here $N_{ms}$ is contoured in intervals of $2 \times 10^{-5}$ s$^{-1}$ with negative values dashed. The dashed red rectangles in (b) and (c) locate the regions of analysis in Figs. 5a and 5b, respectively. The solid white rectangle in (b) locates the region of analysis in Figs. 6a and 6b.
Though less striking than at later times, the simulated radial cloud bands (Fig. 2) are most dynamically active in their initiation stages. We analyze the bands at 0845–0945 UTC (shortly after onset) because this best elucidates their genesis mechanisms. Figures 5a and 5b indicate that their alignment within the 90 km × 60 km red rectangular regions of Figs. 2b and 2c is nearly along the vertical shear vector in an anvil layer from 11.5 to 13 km MSL. Despite the strong magnitude of the vertical shear (1.2–2.5 × 10⁻² s⁻¹), the small angle between the shear direction and band orientation indicates that Kelvin–Helmholtz instability is unlikely to be the cause of band generation.

The formation of the bands in neutral to weakly convectively unstable stratification and their orientation nearly parallel to the vertical shear are aspects similar to horizontal convective roll vortices (HCRs) in the atmospheric boundary layer (e.g., Kuettner 1971; LeMone 1973; Etling and Brown 1993; Weckwerth et al. 1997), which themselves are often manifestations of thermal instability (Hill 1968; Asai 1970, 1972). HCRs in studies by Ferrare et al. (1991) are within 15° of the vertical shear vector through the depth of the atmospheric boundary layer (ABL), similar to the simulated radial bands in our near-neutral anvil (Figs. 5a, b).

This analogy in the current case is supported further by counterrotating vortices in the anvil (Fig. 5c) within a 6-km averaged vertical cross section oriented across the bands (WE in Fig. 5a). Enhancements of the total cloud condensate that contribute to the $T_b$ minima of the bands occur within and above the ascending branch of the vertical circulation implied by the meridional (approximately along-band) component of vorticity ($\partial u/\partial z - \partial w/\partial x$) displayed in Fig. 5c.

To quantify band characteristics (including horizontal scale) $T_b$ power spectra are calculated for the example regions of Figs. 5a and 5b. Since the bands are aligned approximately north–south in these locations, we estimate the spectral density $\Phi_{T_b}$ in the east–west direction only using

![Control Simulation (Full Physics)](image1)

![No Cloud-Radiative Feedback Simulation](image2)

FIG. 3. (left) ARW-WRF model domains D1 and D2, 0800 UTC 17 Jun 2005 maximum simulated radar reflectivity in a vertical column, and 12.5-km MSL horizontal winds for (a) the control simulation and (c) a simulation in which cloud–radiative feedbacks are deactivated. (right) Simulated brightness temperature (at full horizontal resolution) and 12.1-km MSL smoothed moist static stability (contoured in intervals of $2 \times 10^{-5}$ s⁻¹ with negative values dashed) at 0930 UTC 17 Jun 2005 for (b) the control simulation and (d) a simulation in which cloud–radiative feedbacks are deactivated. The plotting domain in (b) and (d) is the high-resolution Dₓ,ᵧ = 600-m model inner nest D2 in (a) and (c), which has a horizontal grid spacing 5 times smaller than D1. The line CA in (a) denotes the location of the centerline of the horizontally averaged SW–NE-oriented vertical cross sections displayed in Fig. 4.
from Frehlich and Sharman (2008), where $T_b(l\Delta, j)$ are brightness temperature fluctuations (after linear detrending), $\Delta k = 2\pi/M\Delta$ is the spectral resolution, $\Delta = 600$ m is the model horizontal grid spacing, and the overbar in (1) denotes a $y$ average.

A band of enhanced power with wavelengths between 10 and 20 km (Fig. 5d) indicates typical horizontal spacings between the bands. This is $\sim[(16–33)\Delta]$, which confirms the bands are horizontally well resolved (Skamarock 2004). Moreover, the 10–20-km wavelengths are typical of spacing between MCS-induced radial bands revealed by satellite data (L09).

HCR studies (e.g., LeMone 1973; Weckwerth et al. 1997) have noted a scaling influenced by the depth of the near-neutral ABL with HCR wavelengths exceeding ABL depths by factors of 2–10. The radial band spacing exceeds the $\sim$1.5–2-km depth of the near-neutral anvil cloud layer (Fig. 5c) by a factor of 5–10, which is broadly consistent with the HCR studies.

The thermal–shear instability that supports daytime HCRs is associated with widespread heating from below. In contrast, thermal–shear instability that supports the radial bands in the anvil is nonstationary. The radial bands originate within these localized regions of $N^2_m < 0$ but extend significantly downshear into regions where the anvil is weakly stratified (Figs. 5a,b). Not surprisingly, the 0.5–2 m s$^{-1}$ maximum vertical velocities within the anvil (Fig. 6b) generally decay northeastward along the bands at greater distances from the buoyancy source. A vertical cross section along an example radial band (denoted AB in Figs. 6a,b) shows that the horizontal advection implied by strong (25–30 m s$^{-1}$) along-band winds (Fig. 6c) can account for the lengthening of the bands northeastward beyond their convectively unstable $\text{Ri}(N^2_m)$ origination regions (cf. Fig. 3b).

Near the time of radial band onset, 2–3 m s$^{-1}$ magnitude vertical motion features move north-northeast at $\sim$10 m s$^{-1}$ toward and beneath the developing bands (Fig. 6a). The $\sim 90^\circ$ phase shift between potential temperature perturbations and these vertical velocity features in the cross section normal to their orientation (Fig. 6d) confirms they are associated with high-frequency gravity waves. L09 similarly note that gravity wave signatures in satellite data often appear perpendicular to radial bands. The gravity waves together with the radial bands form a “checkerboard” pattern at times in satellite imagery from the current case (Fig. 7).

The gravity waves in the simulation are trapped within the subanvil layer of strong static stability and vertical wind shear (Fig. 6d), which is overlaid by near-neutral stability in the anvil. The wave source (not shown) is the MCS convection located a few hundred kilometers upstream (Fig. 3a). The appearance of roll-like radial bands together with trapped gravity waves below is not surprising since both are favored by the near-neutral conditions within the anvil. Here, the majority of updraft maxima within the anvil cloud (11.5–13.5 km) along AB (Figs. 6a,b) are situated almost directly above upwardly displaced potential temperature surfaces associated with
the trapped gravity waves (Fig. 6d). Thus, while not clearly necessary, the gravity waves below the bands may play a role in band formation by helping to excite the thermodynamic instability that is generated by other processes including differential radiative forcing and mesoscale differential advection in the upper-level outflow. The bands are then organized by the shear.

4. Summary and discussion

We have described a high-resolution numerical simulation of radial cloud bands in the northern upper-level outflow of an observed MCS, which had aircraft reports of at least moderate turbulence (TS09). Though such bands are relatively common within MCS anvils (L09), to the authors’ knowledge the current work contains the first documentation and analysis of them in a numerical simulation. The timing, location, and orientation of the simulated bands are similar to those in satellite images of this case, and their spacing is similar to that found in the L09 satellite climatology.

We conclude that analogous to horizontal convective rolls in the boundary layer, which are aligned approximately parallel to the vertical shear vector, the radial
bands within the outer MCS anvil are manifestations of convective instability in vertical shear. This supports speculation by Dixon et al. (2000) that convective rolls can organize cloud striations in the free troposphere. We also present evidence that gravity waves beneath the anvil could aid in their formation, consistent with the noted presence of gravity waves in satellite studies of radial bands (L09).

Our results show the vertical shear in the MCS outflow is important not only in determining the alignment of the bands but also in facilitating the mesoscale thermodynamic destabilization in the anvil through differential thermal advection. This thermodynamic destabilization mechanism for band formation requires only that the relative humidity is sufficient to produce clouds and that horizontal equivalent potential temperature gradients exist with significant vertical shear in the plane of these gradients. Thus, we speculate that this mechanism together with differential radiative forcing could contribute in other phenomena containing cirrus bands (Knox et al. 2010), including tropical cyclone outflows and jet stream cirrus in midlatitude cyclones.

The current mechanism predicts that radial band formation–decay in MCS anvils should be episodic and linked to strengthening and weakening phases of parent deep convection. These events resulted in a ∼3-h periodicity in anvil $N_A^2$ time series of the current simulated case (TS09, their Fig. 17). In both observations (Fig. 1) and the simulation (Fig. 2) particularly prominent band formation occurs while the parent deep convection is declining. Additional satellite and modeling studies are needed to determine whether the episodic nature of the
bands in this case study occurs more generally. Idealized simulations over a range of environments are also necessary to better isolate band formation mechanisms hypothesized in this study. Though we do not specifically address the relationship of the radial bands to turbulence, we believe we have taken a first step in understanding the connection by illustrating the genesis stages of such bands. It remains to be determined whether the weak-to-moderate radial band convection at the MCS anvil edge in our simulations can explain the turbulence reported by aircraft.

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