CORRESPONDENCE

Comments on "Observations of Wall Cloud Formation in Supercell Thunderstorms during VORTEX2"

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1. Introduction

In a recent article, Atkins et al. (2014, hereafter AGN) nicely synthesize mobile radar and stereo photogrammetric data in a study of the wall clouds observed in the 5 June and 11 June 2009 supercells intercepted by the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2). They conclude that the lifting of rain-cooled air originating in the storms' forward-flank precipitation regions contributed to wall cloud formation, as Rotunno and Klemp (1985) found in a numerical simulation of a supercell thunderstorm. However, AGN also conclude that a dynamic pressure deficit associated with rotation within the 5 June wall cloud contributed significantly to cloud lowering. Moreover, it was found that both wall clouds comprised air parcels from not just the forward-flank precipitation region, but also from the environmental inflow, and that some other parcel trajectories into the 5 June wall cloud originated from the rear-flank downdraft (RFD). Below we offer an alternative interpretation of some of their results.

2. The lowering of the cloud base owing to rotation

AGN use the linearized ideal gas law to relate pressure, density, temperature, and water vapor perturbations [see their Eq. (1)]. Though neglecting the effects of water vapor on pressure perturbations is fairly inconsequential, neglecting density perturbations has a drastic effect on the temperature perturbation associated with a given pressure perturbation. AGN's Eq. (1), subject to their assumptions, becomes

$$T' = \frac{T_s p'}{p_{as}}, \tag{1}$$

where T' and p' are the temperature and pressure perturbations, respectively; and T_s and p_{as} are the base-state temperature and pressure, using AGN's symbology. AGN infer 2.2°C of cooling for a 6–7-hPa pressure drop, which implies a lowering of the cloud base by approximately 270 m. Equation (1) predicts $T' \sim 30$ K in a strong tornado (assuming $p' \sim 100$ hPa), which would correspond to temperatures near or below freezing within many tornadoes.

Unavoidably, density perturbations accompany temperature perturbations. For the problem at hand, the first law of thermodynamics provides the relationship between pressure and temperature changes:

$$q = c_p \frac{dT}{dt} - \alpha \frac{dp}{dt}. \tag{2}$$

The variables q, c_p, T, α, and p are the specific heating rate, specific heat at constant pressure, temperature, specific volume, and pressure, respectively. For $q = 0$,

$$\frac{dT}{dp} = \frac{\alpha}{c_p}. \tag{3}$$

This expression is perhaps used most often to obtain the lapse rate of temperature within a vertically displaced parcel, but it also can be used as a general expression to link pressure and temperature changes that occur during any dry adiabatic process, such as the dynamic lowering

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of pressure that occurs as vorticity increases. A temperature change of $\Delta T = -0.7°C$ is obtained for $\Delta p = -7$ hPa, $c_p = 1005\,\mathrm{J\,kg^{-1}\,K^{-1}}$, and $\alpha = 1\,\mathrm{m^3\,kg^{-1}}$ (α needs to be averaged during the process). The temperature change is less than one-third of that estimated by AGN; the implied lowering of the cloud base is similarly reduced to less than one-third of the AGN estimate. AGN's overestimate of the temperature drop and cloud-base lowering stems from the erroneous constant-density assumption.

3. Nonuniqueness of retrieved pressure fields

The pressure retrieval employed by AGN likely involves inverting (on a given horizontal plane)

$$\nabla_h^2 p' = \frac{\partial^2 p'}{\partial x^2} + \frac{\partial^2 p'}{\partial y^2}, \tag{4}$$

where the rhs of Eq. (4) is obtained from the dual-Doppler-derived three-dimensional wind field and the Navier–Stokes equations, such that

$$\frac{\partial p'}{\partial x} = -\overline{\rho}\left(\frac{\partial u}{\partial t} + \mathbf{v}\cdot\nabla u - fv - F_u\right), \tag{5}$$

$$\frac{\partial p'}{\partial y} = -\overline{\rho}\left(\frac{\partial v}{\partial t} + \mathbf{v}\cdot\nabla v + fu - F_v\right), \tag{6}$$

where $\overline{\rho} = \overline{\rho}(z)$ is a reference density profile, f is the Coriolis parameter, $\mathbf{v} = (u, v, w)$ is the velocity, and (F_u, F_v) are the horizontal components of turbulent drag (usually neglected or parameterized from the velocity field).

Though AGN do not say what boundary conditions were used, in our experience, Eq. (4) is usually solved by applying Neumann boundary conditions on the horizontal boundaries of the dual-Doppler domain (e.g., Hane and Ray 1985) because $\partial p'/\partial x$ and $\partial p'/\partial y$ are known along the boundaries via Eqs. (5) and (6). Dirichlet boundary conditions (such as $p' = 0$ along the boundaries) are typically not a viable option; although $p' = 0$ might be a satisfactory assumption along the southern and eastern boundaries of a dual-Doppler wind synthesis region surrounding a storm, this assumption is less credible along the western and northern boundaries because these boundaries are likely to reside in cool outflow and high pressure.

If Neumann boundary conditions are used, then the retrieved p' field is not unique; it is only known to within a constant in a given horizontal plane. [Note, however, that horizontal gradients of p' are unique, as is the field of $p' - \langle p' \rangle$, where $\langle p' \rangle$ is the horizontal average of the retrieved p' at each level (e.g., Hane and Ray 1985).] Assuming AGN used Neumann boundary conditions, the magnitude of the retrieved pressure perturbations (e.g., AGN's Figs. 2b and 4b) cannot be interpreted as pressure deficits relative to the environment without first adding a constant to the pressure fields. Though the constant is unknown, one strategy would be to require $p' \sim 0$ along the southern and eastern boundaries of the dual-Doppler domain.

In AGN's Figs. 2b and 4b, it appears that p' might be too negative (i.e., a positive constant might need to be added to the retrieved p' field), given the minimum p' of -8 to -10 hPa (these pressure perturbations are several hPa lower than those occurring in numerically simulated supercell wall clouds, even in high-resolution simulations) and how limited the areal extent of positive p' is within the cool outflow. Concerning this second point, where positive p' exists, its magnitude is very weak, with virtually no regions within the outflow having $p' > 1$ hPa.

4. Dynamic versus nonhydrostatic pressure perturbations

AGN (p. 4829) refer to the diagnosed pressure perturbations as "nonhydrostatic dynamic" pressure perturbations. We believe this terminology could create some confusion.

The dynamic pressure perturbation, as defined by Klemp and Rotunno (1983), among others, is related to the wind field via

$$\nabla^2 p_d' = -\nabla\cdot(\overline{\rho}\mathbf{v}\cdot\nabla\mathbf{v}) + \overline{\rho} f \zeta, \tag{7}$$

where ζ is the vertical vorticity and the variation of f with latitude has been neglected. Given this definition of p_d', the total pressure perturbation is the sum of p_d' and a pressure perturbation due to the buoyancy (B) field, p_b', that is, $p' = p_d' + p_b'$, where

$$\nabla^2 p_b' = \frac{\partial \overline{\rho} B}{\partial z}. \tag{8}$$

Alternatively, p' can be decomposed into hydrostatic (p_h') and nonhydrostatic (p_{nh}') parts, that is, $p' = p_h' + p_{\mathrm{nh}}'$. In this framework, following Davies-Jones (2003),

$$\frac{\partial p_h'}{\partial z} = -\rho' g \tag{9}$$

and

$$\nabla^2 p_{\mathrm{nh}}' = -\nabla_h^2 p_h' - \nabla\cdot(\overline{\rho}\mathbf{v}\cdot\nabla\mathbf{v}) + \overline{\rho} f \zeta, \tag{10}$$

where g is the acceleration due to gravity and ρ' is the density perturbation ($\rho' = -B\rho/g$).

Although p'_d and p'_{nh} are similar in some circumstances [e.g., see Fig. 2.6 in Markowski and Richardson (2010), which depicts p'_d and p'_{nh} fields associated with a density current], in other situations p'_d and p'_{nh} are dissimilar [e.g., see Fig. 2.7 in Markowski and Richardson (2010), which depicts p'_d and p'_{nh} fields associated with a rising warm bubble]. Reference to a nonhydrostatic dynamic pressure perturbation does not seem appropriate because only part of the nonhydrostatic pressure perturbation is related to p'_d; the rest is attributable to p'_b, which is virtually certain to be nonzero beneath a thunderstorm updraft. Moreover, AGN have retrieved the *total* pressure perturbation (to within a constant).

5. Source regions of the air parcels within the wall clouds

For the 5 June 2009 wall cloud, AGN (p. 4826) found that ‘‘the primary source region is the forward flank’’ and that ‘‘two secondary source regions are the inflow and rear-flank downdraft.’’ We wonder whether the pink trajectories in AGN’s Fig. 5a, identified as inflow trajectories, might have been rained into. One challenge in displaying trajectories atop a reflectivity image is that the reflectivity only can be displayed at one instant (2200 UTC), whereas the trajectories represent the positions of air parcels over a 10-min period (2150–2200 UTC). The inflow trajectories in the figure panel pass through the edge of the 2200 UTC reflectivity field. Thus, it seems possible that these parcels, like the forward-flank parcels, might also have been cooled and humidified by evaporation. Given that mesocyclone-strength rotation seems unlikely to lead to an appreciable drop in cloud base per section 2, it would seem that such inflow parcels must have been cooled and humidified if they were observed to develop condensation at altitudes hundreds of meters below the ambient cloud base (see AGN’s Fig. 1).[1]

Numerous inflow trajectories also were found to feed the 11 June 2009 wall cloud (see AGN’s Fig. 14a). However, these trajectories appear to be behind the outflow boundary per AGN’s Fig. 13, which implies they likely have been cooled and humidified too. Indeed, the mobile mesonet observations in AGN’s Fig. 15 indicate potential temperatures and water vapor mixing ratios of 301–303 K and 10.8–11.1 g kg^{-1}, respectively, in the region of these trajectories. The environmental inflow sounding shown in AGN’s Fig. 16 has a surface potential temperature and water vapor mixing ratio of 36.2°C (309.4 K) and 10.4 g kg^{-1}, respectively. It might be more appropriate to characterize the air parcels following the inflow trajectories as outflow parcels, given their potential temperature deficits of 6–8 K.

We are not surprised that some parcels on the rear flank of the 5 June 2009 wall cloud were found to descend rather than rise through the wall cloud. These are presumably not the parcels that led to the *formation* of the wall cloud. Rather, it seems likely that these parcels were forced to descend in a developing occlusion downdraft (Klemp and Rotunno 1983). Such a cascading waterfall of sinking *and evaporating* cloud tags on the rear side of a wall cloud is commonly observed by storm chasers, and in fact is evident in the Lyndon State University camera B video from the 11 June 2009 storm[2] (there are no photogrammetric observations to the rear of the 5 June 2009 storm). The ‘‘rear-flank’’ trajectory in AGN’s schematic (their Fig. 8) suggests that subsaturated (i.e., extracloud) parcels enter the wall cloud during their descent. However, it seems much more likely that parcels that end up in the wall cloud after being drawn downward from above would be saturated (i.e., within cloud) during their descent.

6. Summary

We believe AGN overestimated the contribution to wall cloud formation from rotation and its dynamic lowering of pressure. The magnitude of the pressure deficits (relative to the environmental pressure) retrieved by AGN from the dual-Doppler wind fields also may be too large, depending on how lateral boundary conditions were handled. Furthermore, many, if not most, of the trajectories feeding the wall clouds that were identified as having come from the environmental inflow were likely cooled and humidified by evaporating precipitation prior to ascending into the wall clouds.

[1] In our experience, most of the trajectories passing through a supercell’s forward-flank precipitation region at low levels ultimately can be found to come from the inflow environment to the east of the radar echo if taken sufficiently far backward in time, so there can be some ambiguity in the terms ‘‘inflow’’ and ‘‘outflow’’ (and, of course, a fraction of the *outflow* from the forward-flank precipitation region is *inflow* to the wall cloud).

[2] This video is available at http://meteorology.lyndonstate.edu/vortex2/videos/vidb_61109_190147.mov.

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