NOTES AND CORRESPONDENCE

Imbalance in a Mesoscale Vortex within a Midlatitude, Continental Mesoscale Convective System

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ABSTRACT

The authors examine the degree of hydrostatic and gradient balances in a mesoscale convective vortex (MCV) in the stratiform region of a mesoscale convective system (MCS) that crossed Oklahoma on 1 August 1996. Results indicate that the MCV was partially unbalanced because the cool layer at the base of its core was too cool and too shallow to balance the tangential winds about the MCV's axis. The apparent imbalance may have been due to strong, unsteady forcing on the vortex; insufficient or unrepresentative data; approximations used in the analysis; or reasons that are unknown.

1. Introduction

Mesoscale convective vortices (MCVs) are generally considered to be balanced, or nearly balanced, circulations. Much evidence supports this consideration. MCVs persist for hours to days, and many researchers have successfully simulated MCVs and similar vortices in numerical models founded on various assumptions of balance (e.g., Hack and Schubert 1986; Raymond and Jiang 1990; Davis and Weisman 1994). However, whether balance is a defining trait of all MCVs or whether the degree of balance varies substantially from one MCV to the next is unclear. Only a few purely empirical studies specifically address the question of balance (e.g., Trier and Davis 2002), and, as far as we are aware, none of these includes an explicit evaluation of the simplest forms of balance that might widely apply to MCVs: hydrostatic and gradient.

Our objective in this paper is to present an evaluation of the hydrostatic and gradient balances in a single MCV generated by a mesoscale convective system (MCS) in the central Great Plains of the United States on 1 August 1996. The MCV of 1 August 1996 was a particularly good candidate for study because a thermodynamical sounding was made near the vortex's vertical axis just after it matured and at approximately the time the vortex was deepest. The rarity of such core soundings may partly explain why observations have not been widely used to explore balance in MCVs.

2. Data and methods

Horizontal wind is from soundings taken by the National Oceanic and Atmospheric Administration (NOAA) Profiler Network (NPN), from radiosondes launched semidaily by the National Weather Service (NWS), and from radiosondes launched every 3 h from four sites in Oklahoma as part of 1996's Enhanced Seasonal Observing Period (ESOP-96) of the Global Energy and Water Cycle Experiment's (GEWEX's) Continental-Scale International Project (GCIP). Temperature and humidity are from NWS and GCIP soundings.

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To produce gridded fields of wind, we used a two-pass Barnes analysis (Barnes 1973; Koch et al. 1983) on data from the NPN in a manner identical to that used by Knievel and Johnson (2002). Grid points were 75 km apart, and the response function was chosen to capture 90% of the signal of phenomena with wavelengths of 300 km (twice the average distance between profilers in the densest part of the NPN) and less than 10% of the signal of phenomena with wavelengths shorter than 85 km, so virtually no coherent convective signal exists in the analyzed data. In some cases it proved useful to average kinematical data and their derivatives over 3 h and a $2° \times 2°$ area centered on the MCV in the middle troposphere.

Radar data are NOWrad composites of reflectivity with temporal and spatial intervals of 15 min and 2 km. Each pixel for a specific point at a specific time is the highest value detected in a column by any Weather Surveillance Radar-1988 Doppler (WSR-88D) in the network.

Determining the MCV's location and size was not straightforward. There is no universally accepted approach, probably because no single approach tried so far works well with every dataset. We diagnosed the center of the MCV to be at the center of the observable cyclonic motion in loops of composite radar reflectivity—that is, where the velocity of elements in the reflectivity field was zero in a system-relative frame of reference. Our diagnoses were consistent with observations from the NPN. Methods based on satellite data in the infrared and visible bands were impossible due to cirri in the upper troposphere that obscured midlevel clouds. Because the kinematical data were coarse, we could only estimate the size of the MCV at certain times when the vortex was best observed by the NPN. Over a range of times, our estimation of the radius of maximum wind is 0.75°–1.50° latitude (83–167 km).

To assess the degree of balance in the MCV of 1 August 1996, we retrieved a temperature profile in balance with observed wind in the MCV, then compared that diagnosed profile to an observed profile in the MCV's core. The procedure demanded a number of approximations and compromises. The only complete sounding near the core of the MCV was above Purcell, Oklahoma (B6 in Fig. 1a), at 1800 UTC. However, no GCIP sounding site was unaffected by the MCS at that time, so a more realistic far-field boundary condition for the retrieval was an average of soundings above Dodge City, Kansas (DDC), Little Rock, Arkansas (LIT), and Shreveport, Louisiana (SHV), taken at 0000 UTC 2 August, 6 h later (Fig. 1a). We did not include in the average any soundings from Springfield, Missouri, and other regional sites where local influences such as recent thunderstorms obscured the synoptic signal. As an additional complication, observations by the NPN at 1800 UTC were unrepresentative of the mesoscale wind, perhaps because convective circulations in cumulonimbi skewed the data (Knievel and Johnson 2002), so we chose to retrieve the balanced temperature profile based on wind observed at 1500 UTC. The retrieval involved three steps. First, we approximated the MCV with an axisymmetric, nondivergent vortex constructed from the azimuthal average of the tangential component of the observed winds. Second, we used the far-field sounding and wind field at each altitude to calculate the pressure field inward from the perimeter of the approximated vortex to its axis. Third, we forced the temperature field into hydrostatic balance, based on the pressure field. Steps two and three were repeated until the fields converged to a solution. A more detailed explanation of this method, including formulas, can be found in section 4b of the paper by Nolan et al. (2001).

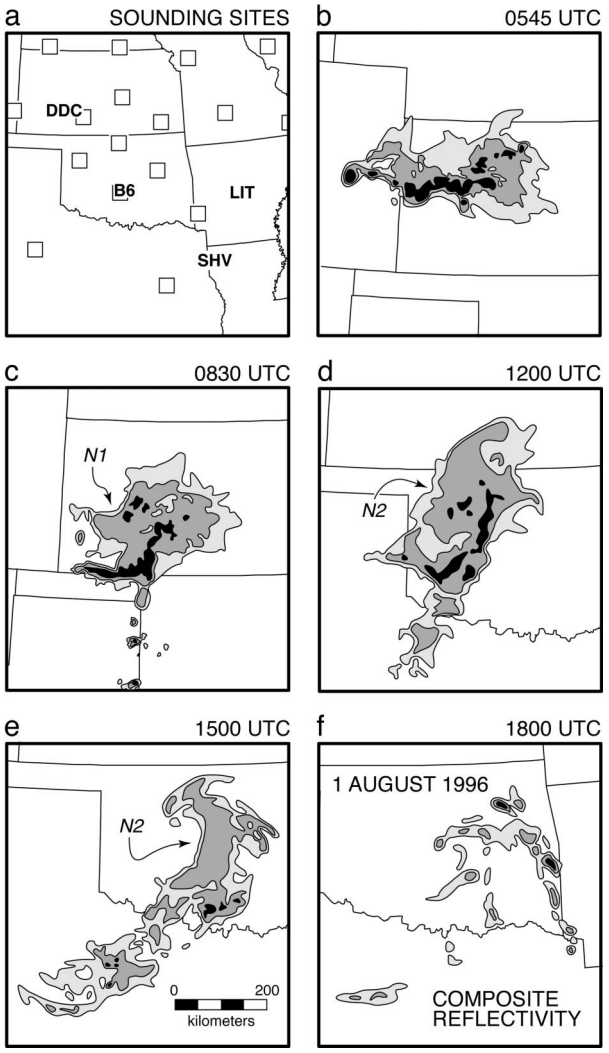

FIG. 1. (a) Sounding sites and composite base-scan radar reflectivity on 1 Aug 1996. NPN sites are marked by open squares, and the names of rawinsonde sites are abbreviated. Reflectivity is depicted at (b) 0545, (c) 0830, (d) 1200, (e) 1500, and (f) 1800 UTC. Contours are of 15, 30, and 45 dBZ. Only reflectivity due to the MCS and nearby cumulonimbi is shown. Notches are marked by N1 and N2.

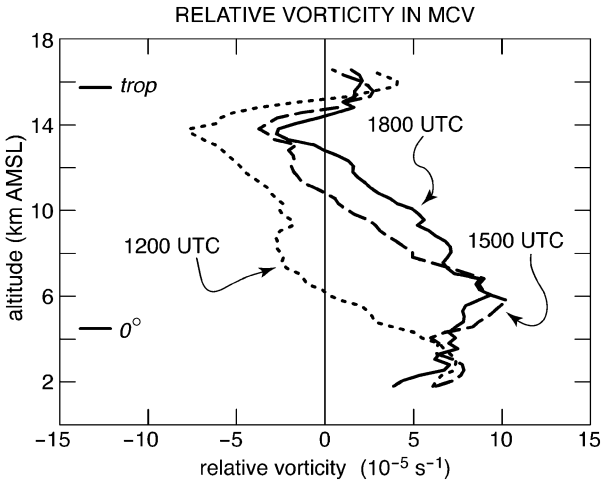

FIG. 2. Relative vertical vorticity (10^{-5} s^{-1}) in the MCV at 1200 (dotted), 1500 (dashed), and 1800 UTC (solid) on 1 Aug 1996. Profiles are for a 2° × 2° area centered on the MCV in the middle troposphere, averaged over 3 h ending at the time labeled. The altitudes of the tropopause and 0°C in the environment are indicated along the left tick marks.

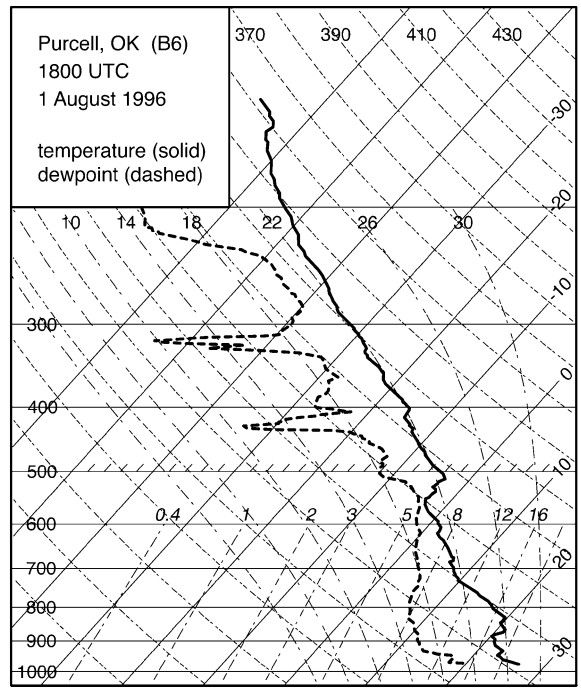

FIG. 3. Sounding at Purcell, OK (B6), at 1800 UTC 1 Aug 1996 plotted on a skew *T*–ln*p* diagram. Temperature is solid and dewpoint is dashed. This sounding was near the center of the MCV (see Fig. 1).

(Hereafter, *balance* means *hydrostatic and gradient balances* unless otherwise stated.)

3. The MCS and MCV

The MCS of 1 August 1996 epitomized MCSs that generate MCVs. The system formed in northwestern Kansas when three clusters of cumulonimbi merged. Initially the MCS was approximately symmetric along its major axis (Fig. 1b). The system then became asymmetric, a notch developed at the back of the stratiform region (*N1* in Fig. 1c), and the convective line bowed into the shape of an *S*. After the first notch became indistinguishable, a second notch formed at the back of the MCS (*N2* in Figs. 1d and 1e). Eventually reflectivity on the MCS's northern end took on the shape of a hammer head (Fig. 1e). The stratiform region broke into spiral bands that slowly dissipated over more than 12 h, while scattered, new cumulonimbi grew in the remnants of the bands (Fig. 1f).

From 0900 to 1800 UTC, the 9 h during which the MCV was well observed by the NPN, the MCV deepened and strengthened as the MCS matured and dissipated (Fig. 2). Eventually the vortex occupied almost the entire troposphere, perhaps even reaching the ground (Knievel and Johnson 2002). Convergence, tilting, and unresolved effects within the total wind contributed the most to the MCV's growth, although their respective contributions varied with time (Knievel and Johnson 2003). Available data weakly suggest that, of the resolved mesoscale sources, tilting may have supplied the most vertical vorticity during the vortex's initial stages. Convergence predominated during its maturity.

At 1800 UTC the sounding taken at Purcell, Oklahoma, near the center of the vortex displays a deep, highly subsaturated layer below the melting level and a lapse rate of temperature that is pseudoadiabatic in the upper half of the troposphere (Fig. 3). In between is an isothermal layer from 510 to 550 hPa. Overall, the sounding is consistent with those found in stratiform regions of other MCSs, except that near the ground the cold pool had been modified by warming from sunshine through breaks in the dissipating stratiform clouds.

The Rossby radius of deformation during the MCS's lifetime is an indication of what fraction of the atmosphere's response to heating was in the form of convergent, vortical flow that helped spin up the MCV. At 0800 UTC, the Rossby radius in the immediate environment of the MCS was approximately 276 km (Knievel and Johnson 2003). After that, increasing vorticity in the strengthening MCV drove down the Rossby radius. By 1200 UTC, it was approximately 136 km, then changed little through 1500 UTC. Because the Rossby radius was slightly smaller than the area being heated by the stratiform region, we might expect to see some signs of balance in the system.

4. Assessment of balance

The core of the MCV of 1 August 1996 comprised a cool layer surmounted by a warm layer (solid line in Fig. 4). This is the gross structure one would expect in a vortex that originates in the diabatically heated stratiform region of an MCS (Hertenstein and Schubert 1991). It is also what one would expect in a vortex that

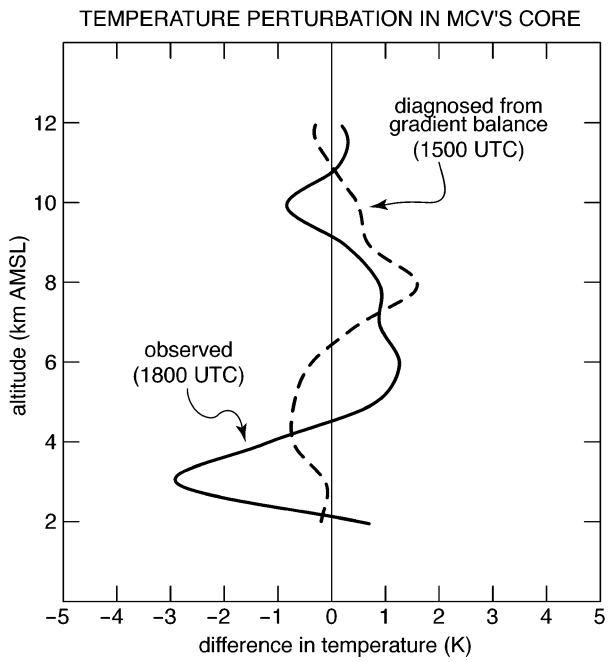

FIG. 4. Balanced and observed temperature perturbations within the MCV. Both perturbations (K) are with respect to far-field soundings at 0000 UTC on 2 Aug 1996. The solid line is the observed profile from near the MCV's axis at 1800 UTC on 1 Aug. The dashed line is a retrieved profile in hydrostatic and gradient balances with the MCV's wind field at 1500 UTC. Data are plotted every kilometer and smoothed.

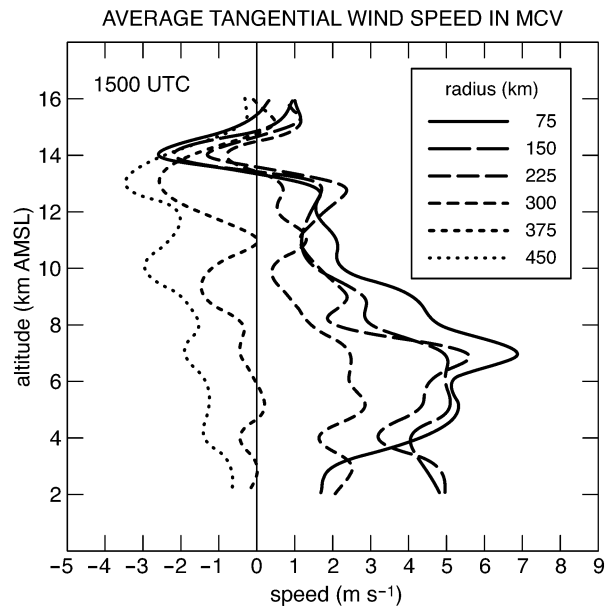

FIG. 5. Azimuthally averaged tangential wind speed (m s^{-1}) within the MCV at 1500 UTC on 1 Aug 1996. Data are plotted every kilometer and smoothed. Positive speed means cyclonic wind.

is balanced (Bartels et al. 1997). However, a closer examination of the detailed structure of the cool and warm layers reveals a marked deviation from complete balance.

In a balanced vortex, the strongest tangential winds are at the same altitude as the top of the cool layer—or, alternatively, the bottom of the warm layer—in the vortex's core (Bartels and Maddox 1991; Bartels et al. 1997). If the MCV of 1 August 1996 were completely balanced, based on the tangential wind at 1500 UTC (Fig. 5), the top of the cool layer would have been at 6.5 km above mean sea level (AMSL). Instead, it was 2 km lower (Fig. 4). Moreover, not only was the cool layer too shallow to balance the wind, it was also too cool.

The most pedestrian of the possible explanations for the apparent imbalance in the MCV is that the necessarily imperfect method of creating Fig. 4 misrepresented the actual fields of mass and wind in and near the vortex. In particular, if the MCV were highly tilted, then the single sounding at 1800 UTC may not have accurately recorded the true depth and strength of the cool layer. However, evidence that corroborates Fig. 4 suggests this explanation alone cannot account for the entirety of the apparent imbalance. First, clear signs of the strong, shallow, lower-tropospheric cool layer also appear in 6-h temperature changes observed at two other GCIP sites as the MCV passed over them (not shown). There is reason, then, to believe that both the core profile and the far-field profile used to construct Fig. 4 are representative, respectively, of the MCV and its environment. Second, the observed transition from cool to warm core was very near the altitude of 0°C in the environment (Fig. 3), which is consistent with temperature changes due to nonradiative cooling and heating within stratiform anvils (Houze 1982; Johnson and Young 1983). Finally, the vertical and horizontal distributions of tangential wind at 1500 UTC (Fig. 5), from which the balanced temperature profile was retrieved, are consistent with observations of wind in the MCV at other times for which we deemed observations to be reliable (not shown). The most likely deficiency in Figs. 4 and 5 is a general underrepresentation of the magnitude of tangential wind. Observations from the NPN were coarse compared with the size of the MCV, so its circulation may have been stronger than was detected. Indeed, manual tracking of individual elements in the radar data suggests that data from the NPN may have underresepresented the MCV's vortical wind speed by perhaps 25% or so. This could account for at least some of the discrepancy in the strengths of the diagnosed and observed temperature perturbations in Fig. 4, but not for the discrepancy in the depths of the cool layers.

One reason the MCV of 1 August 1996 may have been unbalanced is that it was being strongly and unsteadily forced during most of the period of detailed analysis. Possibly the MCV simply did not have time to achieve balance before it left the densest part of the NPN, because extensive raining clouds in the MCS's dissipating stratiform region continued strongly to heat and cool the troposphere through 1500 UTC

(Figs. 1b–e). In the few hours following 1500 UTC, the areal extent of the stratiform region markedly decreased (Fig. 1f), and by 1700 UTC, strong convergence into the MCV had greatly weakened (Knievel and Johnson 2002). A natural assumption is that, in the absence of strong forcing after 1700 UTC, the MCV may have been evolving toward balance, but not quickly enough to be apparent in the observations. Without forcing, an MCV adjusts toward balance in roughly f^{-1}, the inverse of the Coriolis parameter. This would have been about 3.3 h for the MCV of 1 August 1996.

This hypothesis that the MCV did not have time to achieve balance, but was tending toward it, is not supported by all the evidence, however. As already mentioned, in a balanced vortex, the maximum tangential wind speeds (and vorticity due to curvature) are at the top of the cool layer. Therefore, if a vortex's maximum tangential wind speeds begin much higher or lower than the top of its cool layer, any adjustment toward balance must involve a shift of the maximum speeds to lower or higher altitudes, respectively. As the MCV of 1 August 1996 matured, its maximum tangential wind speeds were above the top of the cool layer, so they should have shown signs of descending if the vortex were adjusting toward balance. They did not. From 1200 to 1500 UTC, vorticity was largest just below 6.0 km AMSL (Fig. 2). By 1700 UTC vorticity was largest between 6.0 and 7.0 km AMSL (not shown), although vorticity below 4.5 km AMSL did increase over that time, maybe in response to cooling in the lower troposphere. It is also worth noting that numerical simulations of MCVs can produce balanced or nearly balanced vortices even in the presence of strong diabatic forcing, which is another reason to look elsewhere for an explanation of the apparent imbalance in the subject MCV.

5. Comparison with previous research

It is not easy to evaluate Fig. 4 in the context of previous research because, as already mentioned, few studies have addressed balance in MCVs. Bartels and Maddox (1991) did present persuasive evidence of an MCV in approximate gradient balance. They found that the MCV of 14 May 1984 had a cooled core whose top was nearly at the same altitude as the MCV's largest tangential wind speeds. Other MCVs appear to have been more like that of 1 August 1996, with maximum tangential wind speeds (or vorticity) at significantly higher altitudes than the observed tops of the cool layers—or what one might reasonably infer to be the tops of the cool layers—in the vortices' cores (e.g., Brandes 1990; Chong and Bousquet 1999).

Bartels et al. (1997) *assumed* balance for some of their treatment of the MCV of 9 June 1988. However, their assumption may not have been entirely compatible with their data. Tops of cool layers in the stratiform regions of MCVs tend to be very near the altitude of 0°C (Houze 1982; Johnson and Young 1983). That altitude was at 590 hPa, or approximately 4.5–4.6 km AMSL, in the environment of the MCS of 9 June 1988, yet Bartels et al. diagnosed from the observed wind field a cool-layer top of 6.3 km AMSL in order to model their MCV's potential vorticity perturbation. It is more likely that their MCV had a cool layer too shallow to be in gradient balance with the tangential wind, which is what we conclude about the MCV of 1 August 1996.

6. Synthesis

We evaluated the hydrostatic and gradient balances in an MCV generated by an MCS in the southern Great Plains of the United States on 1 August 1996. For the evaluation, we first azimuthally averaged the observed tangential wind around the vortex, then diagnosed from this average wind a core temperature profile in balance with it. Finally, we compared the diagnosed profile with the observed profile in the core of the MCV.

The comparison revealed that the MCV of 1 August 1996 was not balanced, even late in its life cycle. However, the extent of the imbalance was not extreme. The diagnosed, balanced temperature profile and the observed profile display the same gross structure: a cool core surmounted by a warm core. The differences between the two profiles are in the depths and magnitudes of the temperature perturbations: the observed cool layer in the MCV was too strong and too shallow to balance the vortex's tangential wind. Stated another way, the observed tangential wind was too weak and its highest wind speeds were at too great an altitude to balance the distribution of mass in the MCV's core.

Among the possible explanations for the apparent imbalance are the imperfections in the methods of analysis; insufficiencies in the relatively scant thermodynamical data available for the vortex; the NOAA Profiler Network's underrepresentation of the MCV's wind; and the fact that unsteady heating and cooling from cumulonimbi were continuing to force the vortex during the period of detailed analysis, perhaps not allowing the MCV to become balanced, even if that was its tendency.

A simple test of hydrostatic and gradient balances, such as the one herein, seems a fitting starting point in the examination of mass and wind in an MCV. However, more complex treatments may also be applied to such vortices. Nonlinear balance, in particular, has proven quite fruitful in both diagnostic and prognostic simulations of MCVs (e.g., Raymond and Jiang 1990; Davis and Weisman 1994; Davis et al. 1996; Olsson and Cotton 1997; Trier and Davis 2002). It is based on the assumption that the nondivergent component of wind is much larger than the irrotational component. Mass and wind are related by a balance equation that is derived from the divergence equation in a manner whereby terms involving irrotation and vertical velocity are neglected. In some circumstances it is possible that an MCV not in gradient balance may still be balanced ac-

cording to another definition, such as nonlinear balance. It seems unlikely, though, that in the case of the MCV of 1 August 1996, differences among definitions of balance alone could explain all of the imbalance apparent from the available observations.

In the end, just how similar the distribution of mass in an observed MCV must be to that in an idealized, perfectly balanced vortex before the former may be called *balanced* is open to debate. The distribution of mass in the MCV of 1 August 1996 was grossly similar to that in the balanced vortex we diagnosed, but we consider the differences between the two to be significant.

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