2.6 THE DEGREE OF BALANCE IN A MIDLATITUDE, CONTINENTAL MESOSCALE CONVECTIVE VORTEX

JASON C. KNIEVEL *
National Center for Atmospheric Research, Boulder, Colorado

DAVID S. NOLAN
University of Miami, Miami, Florida

JAMES P. KOSSIN
Space Science and Engineering Center, University of Wisconsin, Madison, Wisconsin

RICHARD H. JOHNSON
Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

Mesoscale convective vortices (MCVs) are generally considered to be balanced, or nearly balanced, circulations. However, few published empirical studies address the question of balance, and none of these includes an explicit evaluation of the simplest forms of balance that can widely apply to MCVs: hydrostatic and gradient. Whether all MCVs are balanced or whether the degree of balance within them varies considerably from one vortex to the next has implications for the simulation and forecasting of severe weather, especially excessive rainfall and violent wind.

In this paper we present an evaluation of the hydrostatic and gradient balances in an MCV generated by a mesoscale convective system (MCS) in the central Plains of the United States on 1 August 1996. (Henceforth, *balanced* means wind and mass are simultaneously in hydrostatic and gradient balances, unless otherwise stated.)

2. DATA AND METHODS

Data for our research are a combination of observations available operationally and observations available as part of a field project in the central Plains.

Horizontal wind is from soundings taken by the National Oceanic and Atmospheric Administration (NOAA) Profiler Network (NPN), radiosondes launched semi-daily by the National Weather Service (NWS), and radiosondes launched every three hours 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 soundings taken by the NWS and GCIP sondes.

To produce gridded fields of wind, we used a two-pass Barnes analysis (Barnes 1973; Koch et al. 1983) on data from the NPN. 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.

Radar reflectivity is from composite base scans with temporal and spatial intervals of 15 min and 2 km. Each pixel for a specific point and time is the highest value detected in a column by any 1988 Doppler generation of Weather Surveillance Radar (WSR-88D).

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 data set. We diagnosed the center of the MCV to be at the center of the observable cyclonic motion in composite radar reflectivity. Methods based on satellite data were impossible due to cirri in the upper troposphere. 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, the radius of maximum wind was approximately 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, OK (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, KS (DDC), Little Rock,

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* *Address correspondence to:* Dr. Jason Knievel, NCAR, P.O. Box 3000, Boulder, CO 80307-3000; knievel@ucar.edu

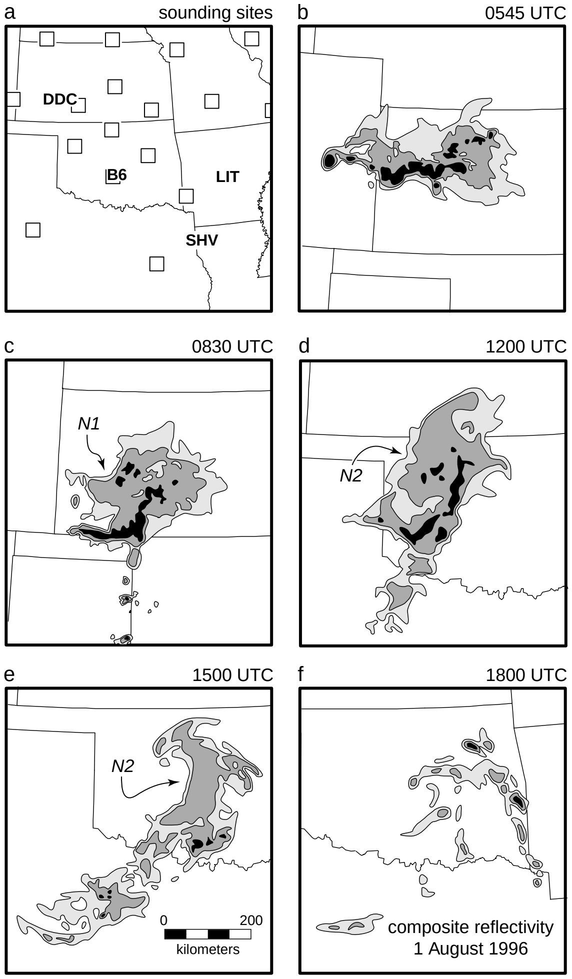

Figure 1: Observation sites and composite base-scan radar reflectivity on 1 August 1996. In the first panel, NPN sites are marked by open squares and the names of rawinsonde sites are abbreviated. Reflectivity is depicted at (b) 0545, (c) 0830, (d) 1200, (e) 1500, and (f) 1800 UTC. Contours are of 15,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

AR (LIT), and Shreveport, LA (SHV) taken at 0000 UTC 2 August, 6 h later (Fig. 1a). As an additional complication, wind observations at 1800 UTC were unrepresentative, so we chose to retrieve the balanced temperature profile from wind observations at 1500 UTC. The retrieval involved three steps. First, we approximated the MCV with an axisymmetric, non-divergent vortex constructed from the azimuthal average of observed tangential winds. Second, we used the far-field sounding and wind field at each altitude to calculate the pressure field inward from the perimeter to the core. 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 can be found in subsection 4b of the paper by Nolan et al. (2001).

3. OVERVIEW OF THE MCS AND MCV

The MCS of 1 August 1996 epitomized MCSs that generate MCVs. The system formed when three clusters of cumulonimbi merged between 0345 and 0415 UTC. For 1 h 15 min the MCS was approximately symmetric about its vector of motion (Fig. 1b). Its evolution to asymmetry began at 0715 UTC, when 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. At 1100 UTC the MCS overtook in western Oklahoma a broad and seemingly unorganized north-south band of cumulonimbi. Between 1145 and 1530 UTC a second notch formed at the back of the MCS (*N2* in Figs. 1d and e). Then reflectivity on the MCS's northern end took on the shape of a hammer head (Fig. 1e), and the stratiform region broke into spiral bands. From 1545 UTC on 1 August through 0315 UTC on 2 August, the spiral bands slowly dissipated, and 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 2002a). Convergence, tilting, and unresolved effects within the total wind contributed the most to the MCV's growth (Knievel and Johnson 2002b).

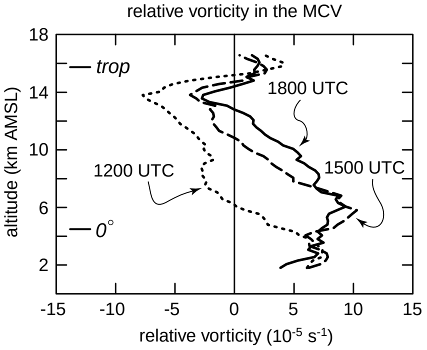

Figure 2: Relative vorticity (10^{-5} s^{-1}) in the MCV at 1200 (dotted), 1500 (dashed), and 1800 UTC (solid) on 1 August 1996. Profiles are for a $2^\circ \times 2^\circ$ area centered on the MCV in the middle troposphere, averaged over 3 h ending at the time labeled. The altitudes of the tropopause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

4. ASSESSMENT OF BALANCE

The core of the MCV of 1 August 1996 comprised a cool layer surmounted by a warm layer (Fig. 3). This is the 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 is balanced (Bartels

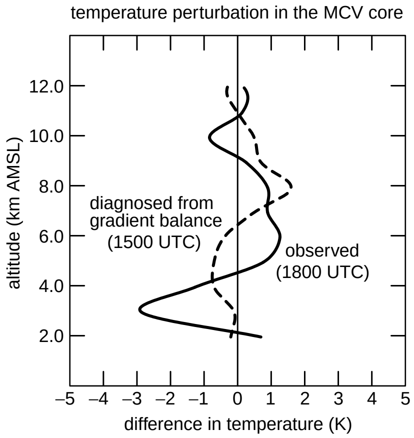

Figure 3: Balanced and observed temperature perturbations within the MCV. Both perturbations (K) are with respect to far-field soundings at 0000 UTC on 2 August 1996. The solid line is the observed profile from near the MCV's core at 1800 UTC on 1 August. The dashed line is a retrieved profile in hydrostatic and gradient balances with the MCV's wind field at 1500 UTC. Data are plotted every kilometer and smoothed.

et al. 1997). However, a closer examination of the detailed structure of the two 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. 4) the top of the cool layer should have been at about 7 km above mean sea level (AMSL). Instead, it was about 2 km lower (Fig. 3). Moreover, not only was the cool layer too shallow to balance the wind, it was also too cool.

The most pedestrian explanation for the apparent imbalance in the MCV of 1 August 1996 is that the necessarily imperfect method of creating Figure 3 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, too much other evidence corroborates Figure 3 to make this a likely explanation. First, signs of the anomalously 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). This suggests that both the core profile and the far-field profile used to construct Figure 3 respectively are representative 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. 2), which is exactly what one would expect of temperature changes due to non-radiative cooling and heating within stratiform anvils (e.g., Houze 1982; Johnson and Young 1983). Finally, tangential wind at 1500 UTC (Fig. 4), from which the balanced temperature profile was retrieved, is consistent with observations of wind at other times (not shown).

One reason the MCV of 1 August 1996 may have been unbalanced is that it was being strongly 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 raining clouds in the MCS's dissipating stratiform region continued to strongly heat the troposphere through 1500 UTC (Figs. 1b–e). Large, middle-tropospheric convergence into the MCV through 1500 UTC (Knievel and Johnson 2002a) signifies that the MCV was certainly not balanced at that time. 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 stopped (Knievel and Johnson 2002a). 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 should adjust 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.

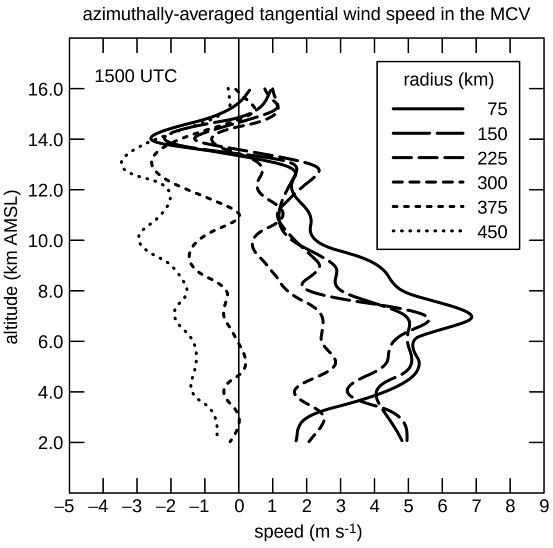

Figure 4: Azimuthally-averaged tangential wind speed (m s^{-1}) within the MCV at 1500 UTC on 1 August 1996. Data are plotted every kilometer and smoothed.

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 the maximum tangential wind speeds start out much higher or lower than the top of the cool layer, any adjustment toward balance must involve a descent or ascent of these winds, 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. Instead, they ascended. From 1200 to 1500 UTC, the average altitude of maximum vorticity was just below 6.0 km AMSL (Fig. 2). By 1700 UTC its altitude was between 6.0 and 7.0 km AMSL (not shown). Vorticity below 4.5 km AMSL did increase over that time, maybe in response to cooling in the lower troposphere.

5. OTHER APPLICABLE FORMS OF BALANCE

In a general sense, a vortex is balanced if its mass and wind fields are diagnostically related. The simplest forms of balance widely applicable to vortices of the size and altitude of MCVs are hydrostatic and gradient, so a test for these balances is a fitting starting point in the examination of mass and wind in an MCV. However, more complex treatments, such as nonlinear balance (e.g., Raymond and Jiang 1990; Davis and Weisman 1994; Olsson and Cotton 1997) may also be applied to such vortices. An MCV that is not in gradient balance may still be balanced according to another definition. It seems unlikely, though, that 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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