NOTES AND CORRESPONDENCE

The Observed Inflow Structure of a Thunderstorm with a Mesocyclone

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ABSTRACT

Inbound and outbound passes were made with an instrumented aircraft at a variety of altitudes in the inflow region of a severe thunderstorm containing a mesoscale vortex. The streamwise vorticity, helicity, and geostrophic thermal advection were estimated from these data. The increased helicity in the inflow region may explain the marked decrease in turbulence observed in this region.

1. Introduction

Marwitz (1972) observed that substantial veering of strong subcloud winds was associated with supercell storms. Klemp and Wilhelmson (1978) confirmed this observation with numerical simulations of thunderstorms. Barnes (1968) suggested that the origin of rotation in severe thunderstorms was the tilting of streamwise vorticity in the inflow air. Theoretical studies by Davies-Jones (1984) have shown that updraft rotation in supercell storms originates from this streamwise vorticity. Weisman and Klemp (1982) have confirmed through numerical simulations that supercells develop only when the combination of shear and buoyancy as represented by the bulk Richardson number is less than 50.

Helicity is the scalar product of velocity and vorticity (V · \(\nabla \times \mathbf{v}\)). For pure helical or Beltrami flow the velocity and vorticity vectors are aligned and hence the stretching and tilting terms in the vector vorticity equation are balanced by the advection terms. Kraichman (1973) and Andre and Lesieur (1977) suggested that pure helical flow blocks the cascade of turbulent energy from large to small scales, thereby resulting in more coherent and dynamically stable flows. Lilly (1983, 1986a,b) hypothesized that the coherency and dynamic stability of supercell thunderstorms were related to helicity.

Davies-Jones et al. (1990) suggested that storm-relative helicity in the inflow region of thunderstorms can be used to forecast the rotational characteristics of

\[\text{Fig. 1. Aircraft track on 12 May 1985. Time is central standard time. Note position of vortex at (35, 5).}\]

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thunderstorms. Numerical simulation of thunderstorms by Droegemeier et al. (1993) has shown that helicity is related to long-lived storms and that storm-relative helicity is a slightly better predictor of storm type than bulk Richardson number. Storm-relative helicity is

\[ H_s = \int_0^{CB} (V_r \cdot \nabla \times V)dz, \]  

(1)

where \( V_r \) is the velocity of the inflow air relative to the storm and \( \nabla \times V \) is the vorticity vector. The streamwise component of vorticity \( \xi \) is approximated by \( \partial v / \partial z \), and CB is cloud-base height. It is noteworthy that \( V_r \cdot (\partial v / \partial z) i \) is directly related to thermal advection assuming geostrophic flow.

This paper will present direct observations in the inflow region of a severe thunderstorm that contained two mesocyclones [defined by Brandes et al. (1988) to be areas where vertical vorticity exceeds 0.01 s\(^{-1}\)]. From these data we estimate the streamwise vorticity and helicity in the environment and in the inflow beneath the updrafts where horizontal acceleration occurred in response to the mesolow. Comments on the origin and role of helicity will also be presented.

2. Observations

On 12 May 1985 (as part of PRE-STORM, the Preliminary Regional Experiment for STORM-Central) the Wyoming King Air aircraft made a number of inbound and outbound passes (Fig. 1) in the subcloud region of a thunderstorm that contained two mesocyclones and produced severe weather (wind and hail). The reflectivity and vector wind based upon dual-Doppler analysis at 1.1 km (all heights are MSL) are presented in Fig. 2. The vortices at (35, 5) and (45, 17) are readily apparent in both the reflectivity hook echoes and wind vectors. The aircraft flew closest to the southwestern mesocyclone (35, 5), hereafter referred to as the “vortex.” The maximum vertical component of vorticity in the vortex was 0.030 s\(^{-1}\). In the subcloud inflow region south and east of the vortex, convergence was readily apparent.

The flight track and data from the aircraft were pro-
Fig. 3. Vertical profile of aircraft data relative to moving vortex. Note position of cloud base and 20-dBZ reflectivity contour: (a) equivalent potential temperature, (b) indicated turbulence, (c) u component of winds, and (d) v component of winds.

Projected into the vertical cross section oriented along the 140° radial and moved relative to the vortex (Fig. 3). The analyzed flight data from 2020 to 2050 CST were centered on the dual-Doppler scan of 2035 CST. Figure 3a displays the vertical profile of the equivalent potential temperature \( \theta_e \). The \( \theta_e \) in the subcloud layer was rather uniform at about 342 K and decreased rapidly to 325 K about 200 m above cloud base. The vertical profile of the cube root of eddy dissipation rate (TURB) is presented in Fig. 3b. These data were obtained with an MRI (Meteorological Research, Inc.) universal turbulence meter (MacCready 1964). The mechanically induced turbulence in the lowest 300 m was 4 cm\(^{2/3}\) s\(^{-1}\). In the last 20 km or 1000 s of the inflow trajectory, the turbulence decreased to less than 1 cm\(^{2/3}\) s\(^{-1}\). We have long known that the updrafts at cloud base were not turbulent (Auer and Sand 1966). These are thought to be the first data that indicate the turbulence decays in a time period of only 1000 s.

The longitudinal (\( u' \)) and lateral (\( v' \)) component of the horizontal winds in the inflow region and relative to the 140° radial from the moving vortex are presented in Figs. 3c and 3d, respectively. The \( u' \) component is 20 m s\(^{-1}\) in the lowest level, and the high momentum air appears to be drawn upward toward cloud base. Changes in the \( v' \) component indicate considerable veering of the wind with height in the subcloud layer.

A rawinsonde was released at Sulphur, Oklahoma, (SUL) at 2046 CST. SUL is located 90 km southeast of the vortex. The hodograph of the subcloud winds observed at SUL and observed by the aircraft in

Fig. 4. Hodograph of winds at SUL and from the aircraft in the inflow region. Motion of the vortex is V.
Table 1. Summary of data in thunderstorm inflow region.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Time (CST)</th>
<th>Location (km)</th>
<th>(v_c) (m s(^{-1}))</th>
<th>(\xi) ((\text{s}^{-1}))</th>
<th>(v_c \cdot \xi r) (m s(^{-1}))</th>
<th>(\frac{dT}{dt}) (°C h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Doppler</td>
<td>2035</td>
<td>0</td>
<td>0</td>
<td>0.030*</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Aircraft</td>
<td>2020–2050</td>
<td>southeast at 25</td>
<td>20</td>
<td>0.020</td>
<td>0.40</td>
<td>3.6</td>
</tr>
<tr>
<td>SUL</td>
<td>2046</td>
<td>south-southeast at 90</td>
<td>12</td>
<td>0.013</td>
<td>0.16</td>
<td>1.3</td>
</tr>
</tbody>
</table>

* Vertical component of vorticity in vortex (\(\xi\)).

The inflow are presented in Fig. 4. The observed movement of the vortex was toward 050° at 8 m s\(^{-1}\), and this vector is also plotted in Fig. 4. The mean relative speed of the inflow winds between 0.5 and 1.25 km were 13 and 20 m s\(^{-1}\) at SUL and in the inflow, respectively. The streamwise components of the vorticity at SUL and in the inflow were 0.013 and 0.020 s\(^{-1}\), respectively. These values are summarized in Table 1. Note that the values of \(\xi\) at SUL and in the inflow were about half the maximum vertical component of vorticity in the vortex.

The vertical vorticity equation in natural coordinates is as follows:

\[
\frac{d\xi}{dt} = -\xi \nabla \cdot V + J(p, \alpha) + \frac{\partial w}{\partial n} + \xi \frac{\partial w}{\partial s} \tag{2}
\]

where \(\xi\), \(\eta\), and \(\xi\) are the vertical, lateral, and streamwise components of vorticity, respectively. Term 1 is the divergence term, 2 is the solenoidal term, 3 is the lateral tilting term, and 4 is the longitudinal tilting term. The vertical vorticity in the vortex developed primarily from term 4 and doubled between SUL and the vortex through convergence and vertical stretching (term 1). Terms 2 and 3 may have acted to further enhance low-level vertical vorticity.

It is interesting to note that the streamwise component of vorticity (\(\xi\)) increased somewhat between SUL and the inflow region and that the mean inflow winds accelerated from 12 to 20 m s\(^{-1}\). The longitudinal contribution to helicity (\(V_c \cdot \xi r\)) increased from 0.16 to 0.40 m s\(^{-2}\) between SUL and the inflow region. Lilly (1986a,b) hypothesized that helicity stabilizes flow against turbulent decay. The helicity and the increased helicity may explain the marked decrease in turbulence along streamlines observed during the 1000 s it took for the turbulent inflow air to be ingested into the thunderstorm through the cloud base.

It is also noteworthy that the estimated relative thermal advection, assuming geostrophic winds, increased from 1.3°C h\(^{-1}\) at SUL to 3.6°C h\(^{-1}\) in the subcloud inflow region. The assumption of geostrophy was tested by assuming steady state and estimating the Rossby number (inertial acceleration/Coriolis force). The estimated inertial acceleration and Coriolis force between SUL and the inflow region (see Fig. 4) were both 0.0017 m s\(^{-2}\). The Rossby number was therefore 1.0, and hence, the assumption of geostrophy is not valid. Nevertheless, the warm-air advection in the inflow over SUL was 1.3°C h\(^{-1}\). It could well be that long-lived supercells are a result of the thermal energy advection and/or the helicity. A simple test would be to assume a wind profile with negative helicity (i.e., cold-air advection) and see if the left-handed supercell is as long-lived as the normal right-handed supercell.

REFERENCES


Barnes, S., 1968: On the source of thunderstorm rotation. ESSA Tech. Memo NSSL. 38. NSSL, Norman, OK.


