The devastating 27 April 2011 tornado outbreak: Initial scientific assessment

Kevin Knupp*

Department of Atmospheric Science
University of Alabama in Huntsville

* Significant contributions from:
T. Murphy, R. A. Wade, S. Mullins, T. Coleman, Prof.
L. Carey, C. Schultz, E. V. Schultz, NWS personnel
Outline of this talk

• A scientific overview of the 27 April 2011 outbreak
  – Overview
  – Some interesting features
  – Some fascinating measurements by UAH platforms
• Some comparisons with the 3-4 April 1974 outbreak
  – Similarities/differences
Brief summary of the disaster, 4/27/11

- Applies to calendar day 27 April 2011
  - Midnight to midnight CDT
- 199 tornadoes primarily in 6 states
  - 62 confirmed tornadoes in Alabama (40 within the HUN CWA
    - 2 EF-5 tornadoes (4 total in outbreak)
    - 7 EF-4 tornadoes in AL, 11 total
    - Many tornadoes were wide (>800 m)
- 319 weather related fatalities in the outbreak area
- 248 weather related fatalities in Alabama
  - 234 tornado related fatalities in AL
- Insured losses for entire outbreak (April 25-28) estimated at $4B, $11B total
  - Costliest tornado (convective storm) event in U.S. history
  - Estimated 10 million cubic yards of debris removed
In Alabama:

• Historic outbreak, especially for a single state
• 238 fatalities and 62 tornadoes in Alabama
• 10 violent (EF-4/EF-5) tornadoes
• 1.06% of the area of AL directly impacted.
1.06% of AL was impacted: 1 square mile grid – 1% is large!
1 square mile grid – 1% is large!

Tornado, 0.1 mi wide, 10 mi long

13 grid boxes are affected!
Primary region of interest (~230,000 km²)
1. 148 tornadoes in 24 hr
2. Many were violent (stronger than F-3)
3. Large area of tornadic activity – Michigan (and Canada) to Alabama
4. BTW, note the locations of the long-track tornadoes!
## Comparison of 4/3/74 and 4/27/11

<table>
<thead>
<tr>
<th>Date</th>
<th>Tornado area times EF scale (km²)</th>
<th>Date</th>
<th>Tor path length (EF-4 &amp; EF-5) (km)</th>
<th>Date</th>
<th>U.S. fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/24/10</td>
<td>2830</td>
<td>4/3/74</td>
<td>1326</td>
<td>4/3/74</td>
<td>307 (315)</td>
</tr>
<tr>
<td>4/11/65</td>
<td>1632</td>
<td>2/21/71</td>
<td>688</td>
<td>2/21/71</td>
<td>226</td>
</tr>
<tr>
<td>4/30/54</td>
<td>1495</td>
<td>5/31/85</td>
<td>417</td>
<td>3/21/52</td>
<td>218</td>
</tr>
</tbody>
</table>
# Distribution of tornado intensity

## 27 April 2011 vs. 3-4 April 1974

<table>
<thead>
<tr>
<th>(E)F-Scale</th>
<th>Number 27 April 2011</th>
<th>Number 3-4 April 1974</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>48</td>
<td>21</td>
</tr>
<tr>
<td>1</td>
<td>74</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>187 (199)</strong></td>
<td><strong>148</strong></td>
</tr>
</tbody>
</table>

27 April had:
- a) Longer & wider tornadoes
- b) Longer duration
- c) Greater contrast in parent convective systems

Notes:
Were all weak (F0, F1) tornadoes detected in 1974? Not likely.
- Doppler radar not available to indicate where to look for F0, F1
- EF-scale vs F-scale
Number of tornadogenesis events per 30 min period

- Early Morning QLCS
- Midday QLCS
- Afternoon supercell storms

MCV

- No. EF-5
- No. EF-4
- No. EF-3
- No. EF-2
- No. EF-1
- No. EF-0

Todd Murphy
Tornado damage width vs. path length, 4/27/11

- Width (m) vs. Length (km)
- EF-0 to EF-5 categories indicated with different colors and shapes
- Milestones: 50 km, 100 km, 200 km
- Todd Murphy
Radar Overview

3+ tornado episodes over Alabama

Early morning QLCS
- 29 tornadoes

Mid morning lone supercell
- 1 tornado

Mid-day QLCS
- 7 tornadoes (N AL)

Afternoon supercells
- 26 tornadoes
Early Morning MCV

- 16 tornadoes produced by MCV passage – mainly affected Lake Guntersville Park/Marshall County
- Good dual-Doppler coverage by ARMOR/KHTX radars (baseline ~65 km)
- Vorticity analysis:
  - concentration in low levels
  - multiple peaks & horizontal structure transitions
  - aligned well w/ tracks
- Dual-pol parameters suggest hydrometeor sorting

Provided by Stephanie Mullins
Radar Data

• **KHTX:**
  – 88D, S-band, super resolution level-II
  – 0.5, 1° beam width, 250 m gates
  – VCP 212 (full volumes)

• **ARMOR:**
  – Advanced Radar for Meteorological and Operational Research (UAH/WHNT)
  – C-band, dual-pol
  – 1° beam width, 250 m gates
  – Sector volumes: 0.7, 1.3, 2.0, 2.7, 3.4, 4.2, 4.9, 5.8, 6.9, 7.7, 8.8, 10.0, 11.7, 13.5, 15.5, 17.5° tilts

• **Baseline:** ~65 km
• Maximum vorticity \((12 \times 10^{-3} \text{ s}^{-1})\) at lowest level (1 km)
• Maximum updrafts <10 m s\(^{-1}\)
• Z values greater than 40 DBZ are confined to levels <4 km AGL

Credit: Stephanie Mullins
Fundamental question: What is the physical connection between the tornadoes and MCV?
a) ARMOR $Z_e$ (1622 UTC) and tornado tracks

b) Close-up of $Z_e$ and $\rho_{hv}$

c) $Z_e$ from the X-band Profiling Radar (6 Hz sampling)

Large vert gradient in $Z_e$

$>40$ dB in 500 m

Credit: Ryan Wade
EF-1 tornado associated with QLCS
11:50 – 12:05 PM CDT
(Midday tornado #6, previous slide)

Damage path began on the downslope portion of Drake Mtn.
The numbered locations indicate areas where damage was more concentrated and enhanced.
Science questions for the midday event

How did tornadoes form in this environment (within strong updraft at the leading edge of a QLCS)?

Why did the tornadoes form in this general area as the QLCS passed through? Was a shear instability involved?

External forcing? Was the pre-storm boundary layer “primed” in some way. Clear air radar observations suggest this was the case.

The atmosphere was extremely conducive to the generation of vorticity on 27 April, and many contrasting storms types produced tornadoes.
Round 3: Afternoon Supercells

- The earlier convective episodes & cloud cover tended to stabilize the boundary layer in North Alabama.
- There were some questions about the potential severity of the afternoon round in N. AL.
- However, the early convection and cloud cover actually reinforced the temperature gradient over North Alabama, which was a focal point for the “train” of supercells.
Afternoon Supercells

• Energy Helicity Index (EHI) is one of the better single indices used for tornado prediction since it combines both CAPE and helicity (instability & wind shear)

• EHI values were near 10 (EHI values greater than 2 have been associated with significant tornadoes)

22 UTC 0-1 km EHI

Unprecedented values in AL

Dr. Tim Coleman
Afternoon Supercells

KHTX Reflectivity
In many tornado outbreaks, a few storms generate most of the significant tornadoes.
The appearance is typical of most of the violent tornadoes on this day: downshear tilt (24 m/s trans. spd.)
Supercell structure:
- Classic
- Strong updrafts
- Effective lofting of debris
- Mostly isolated
- Mesoscale organization?
- 90% of all supercells produced a tornado

\[ \rho hv < 0.65 \]

\[ w > 40 \text{ m/s} \]
ARMOR reflectivity (left) and correlation coefficient (correlation between horizontal and vertical polarization) showing the massive debris signature (tornado marked by circle)

EF-5 Hackleburg tornado directly approaching the photographer (4:30 pm)

Very low cloud base (cool, moist air on the N side of the boundary)
Thermal boundary and Hackleburg storm

1. The Hackleburg storm formed along a well-defined thermal boundary that extended from NE MS to northern AL and the MIPS
2. The Hackleburg storm produced the strongest and longest-track tornado
3. The Hackleburg storm generated this tornado very quickly

Conclusion?
Unusual storm features due to extreme environment

Horizontal vortex tubes

- Many of the violent tornadoes on 27 April 2011 had horizontal vortices around them, sometimes several at one time.
- These vortices are likely due to the extreme helicity of the ambient flow into the tornado, and the horizontal stretching of this horizontal vorticity, causing a central pressure deficit.
- This pressure deficit, especially in a high RH environment, could produce adiabatic cooling and horizontal vortices.
The Tuscaloosa-Birmingham storm

a) Pic of tornado over Tuscaloosa
   • Horiz vortices were common in violent tornadoes

b) Z image of storm 20 km NE of TSC
   • Most severe damage occurred here
   • Debris ball: 69 dBZ

c) Corresponding Vr image:
   • 57 m/s outbound,
   • -72 m/s inbound
   • Very impressive for R = 63 km and h = 800 m AGL
   • Lofted a 37 ton rail car for 120 m
Unusual storm features due to extreme environment

Horizontal vortex tubes – Tuscaloosa tornado
Examples of extreme surface damage

1) Culvert torn out from paved road (upper right pic) (Smithville, MS EF-5)
2) Grass and dirt scoured up to 0.5 m deep (lower right pic) (Philadelphia, MS EF-5)
3) Ford Explorer lofted for 900 m (Smithville, MS EF-5)
4) Earthen storm shelter eroded and nearly destroyed (Rainsville, AL EF-5)
5) 37 ton rail car lofted for 120 m (Tsc-Bhm EF-4+)
6) Stripping of pavement was common in many T’s
Some unique features worthy of a more detailed scientific effort

- Tornadoes produced by QLCS’s
- Tornadoes associated with an MCV
- Detailed structure of the boundary along which the Hackleburg storm propagated
- Impact of topography on tornadogenesis and intensity change
- Impact of gravity waves
- Complex vortical structures of the strong tornadoes
- Debris signatures
Questions?
Research questions

– Why were storms so efficient (90%) in producing tornadoes?
– Why were so many tornadoes long tracked, wide, and intense?
– What mechanisms produced an impressive mesoscale convective vortex (MCV) and the flurry of ~16 tornadoes associated with it over Marshall and DeKalb counties?
– Why was debris effectively lofted to relatively high altitudes?
– Why did the violent tornadoes exhibit rapidly-evolving horizontal vortices along their periphery?

– How did external influences, such as boundaries, gravity waves, topography, and differential surface roughness affect tornadogenesis and/or tornado intensity change?
3. Unusual storm features due to extreme environment
   A. Horizontal vortex tubes – Cullman EF4 tornado
Cullman storm
Cullman storm at 2021 UTC

Multiple Doppler (3) radar analyses will be conducted on this storm.

2021 UTC – ARMOR Reflectivity also shows the reflectivity “feed”.

Looking NNW
4. Afternoon Supercells

Dual Doppler analysis in progress (Chris Schultz)

Cullman storm at 2015 UTC

KHTX reflectivity factor

What is this?
4. Afternoon Supercells

B. March of the Supercells

EF-5 tornado, Hackleburg to Madison Co.

200 km path length

>1.5 km path width

Dual Doppler within the lowest 2 km is available after this time

ARMOR Z, 2130 UTC

Debris ball is apparent, also clear $\rho_{hv}$ signature (not shown)

View looking S
Some details of the afternoon supercells

Cullman EF4 Tornado

- First tornadic supercell to form in Alabama
- Went very quickly from an insignificant thunderstorm to tornadic supercell in the high shear, high CAPE environment

1925 - 2037 UTC – ARMOR Reflectivity
5. Possible topography/land cover effects

A. Friction changes

- Wind blows faster over water/cropland than over forest/urban areas
- Sometimes sharp boundaries between the two can produce circulation
External influences on tornadogenesis:

1. Topography was apparently influential in one of the mid-day QLCS tornadoes. More later?

2. Gravity wave interactions may have been prevalent:
   a) Feeder flow into the first Cullman storm tornado. Gravity wave interactions involved in the genesis of the second EF-4 tornado?
   b) Gravity wave interactions were apparent prior to the development of the Jackson county EF-4 tornado (see next frame).
   c) Other cases will likely emerge upon further analysis.

Remember the importance of the boundary layer!
ARMOR $\rho_{hv}$ centroid and tornado track debris signature was persistent

Hackleburg EF-5

Cullman EF-4

Chris Schultz and Larry Carey
Gravity Wave Interactions?

MAX Reflectivity 2122-2156 UTC

Horizontal lines of weak to moderate reflectivity interact with the storm just prior to tornadogenesis (white line = tornado track)

KHTX Reflectivity 2120-2157 UTC

Interactions occurred in the southern MAX-KHTX dual-Doppler lobe.

Great case study potential – determine importance (if any) of wave interactions in this environment

Talk by Todd Murphy
Summary and future research

• Thermodynamic boundary influences
  – The thermal boundary was well sampled by MIPS and radiosonde in advance of the Hackleburg EF-5 storm
  – Profiler and radar measurements of a thermal boundary and its relation to an EF-5 tornado.

• Terrain influences and impact on tornadogenesis and tornado intensity changes
  – Tornadoes of varying intensity moved over significant tree-covered topography. High-quality aerial images will be valuable in documenting terrain impacts.
  – Terrain influences on tornadoes
• **Gravity wave interactions**
  
  – Gravity wave interactions appeared to be significant in some cases. Wave features appeared to initiate storms
    
    • Interactions of wave features with existing storms were associated with tornadogenesis or intensity change

  – *Gravity wave influences on tornadoes and tornadogenesis*
Summary and Future work (cont.)

• Dual-polarization and Z debris signatures
  – Abundant opportunity to relate $\rho_{hv}$ to debris type by comparing with aerial images
  – Papers already submitted

• *Detailed analysis of a large MCV and its influence in tornadogenesis*
  – High quality dual Doppler analysis of a large MCV with banded structures

Acknowledgement: This research is supported by the National Science Foundation under the RAPID program
• Boundary layer influences on tornadoes
BL stability affects the wind profile via turbulent momentum transport

Mixed layer – low shear

Stable layer – high shear

2 March 2012:
1. Tornado storms occurred when the BL was weakly stable
2. The afternoon BL was highly convective
3. As a result, how did 0-1 km SRH change?
Be sure to keep up with our research deployments or research news by following the UAHuntsville Severe Weather Group on Facebook:

http://www.facebook.com/UAHsevereweather

Do you have pictures or videos of the tornadoes that occurred on April 27? Please send them to:

tornado@nsstc.uah.edu
The forgotten (lone) storm, 9:26 AM CDT
(tornado observed near E Limestone school ~10 min later)

Looking west from County Line & Mill Rds

Laminar cloud base

Sc inflow

Funnel cloud