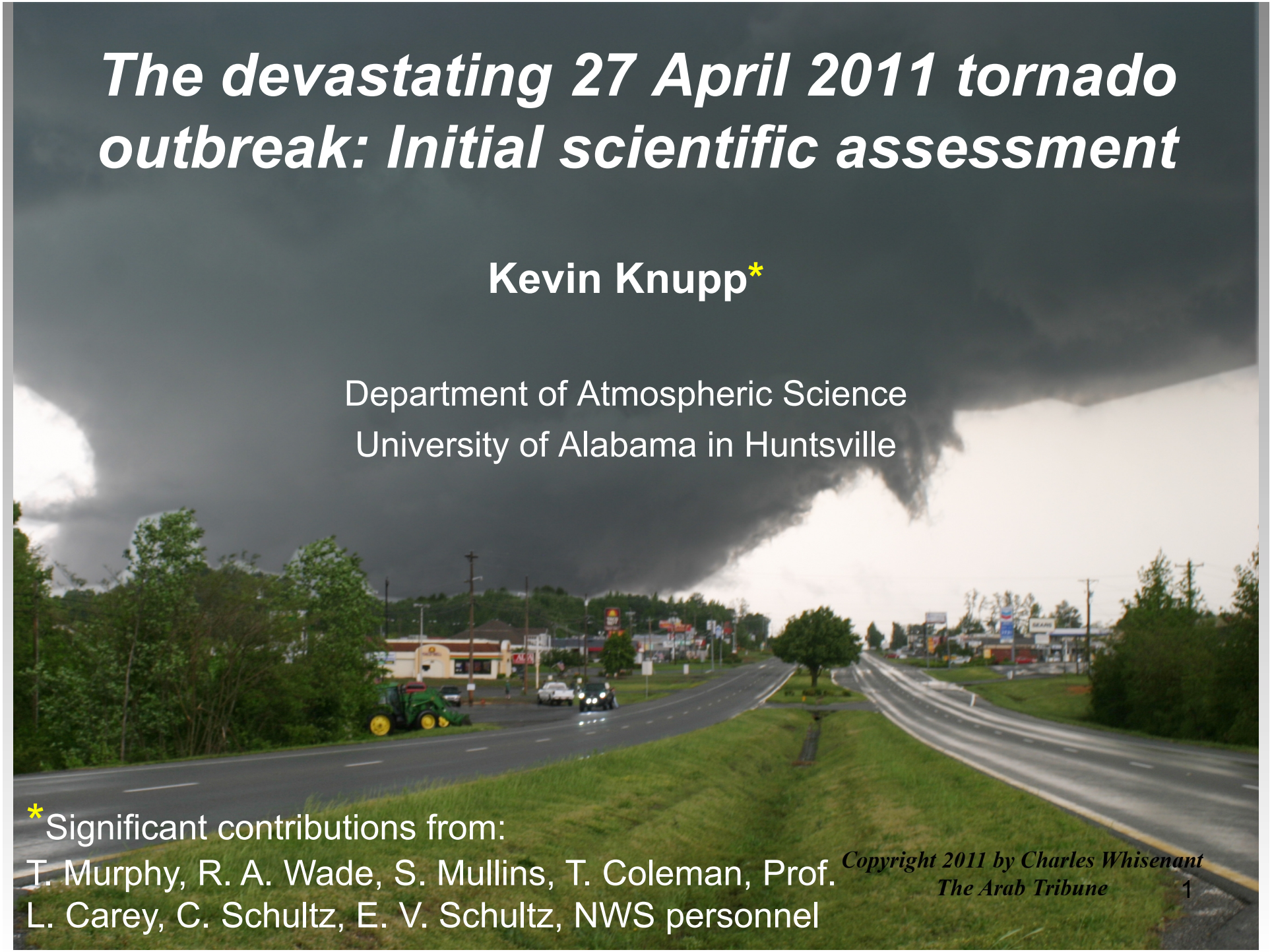
The devastating 27 April 2011 tornado outbreak: Initial scientific assessment

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

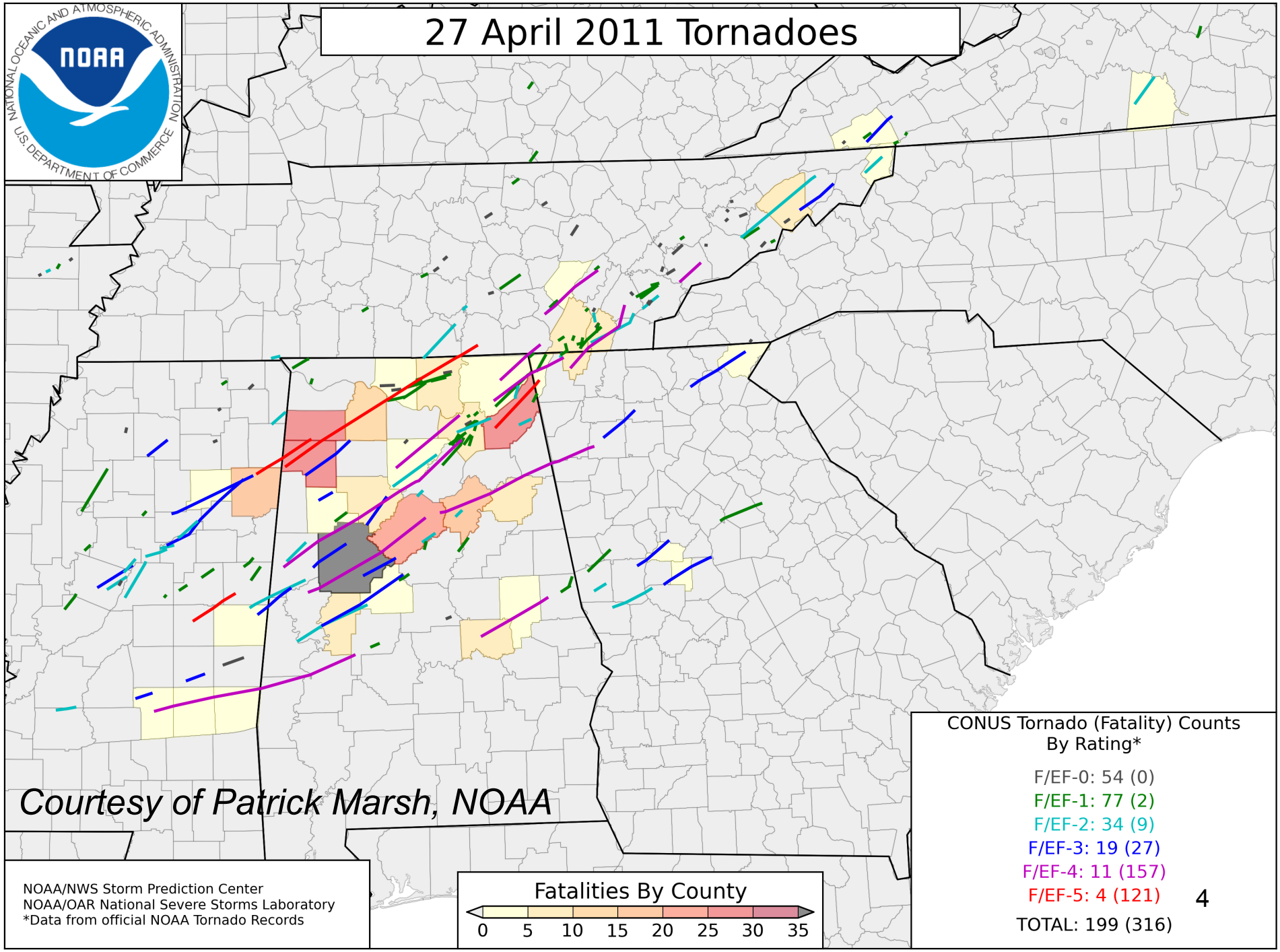
Copyright 2011 by Charles Whisenant
The Arab Tribune

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

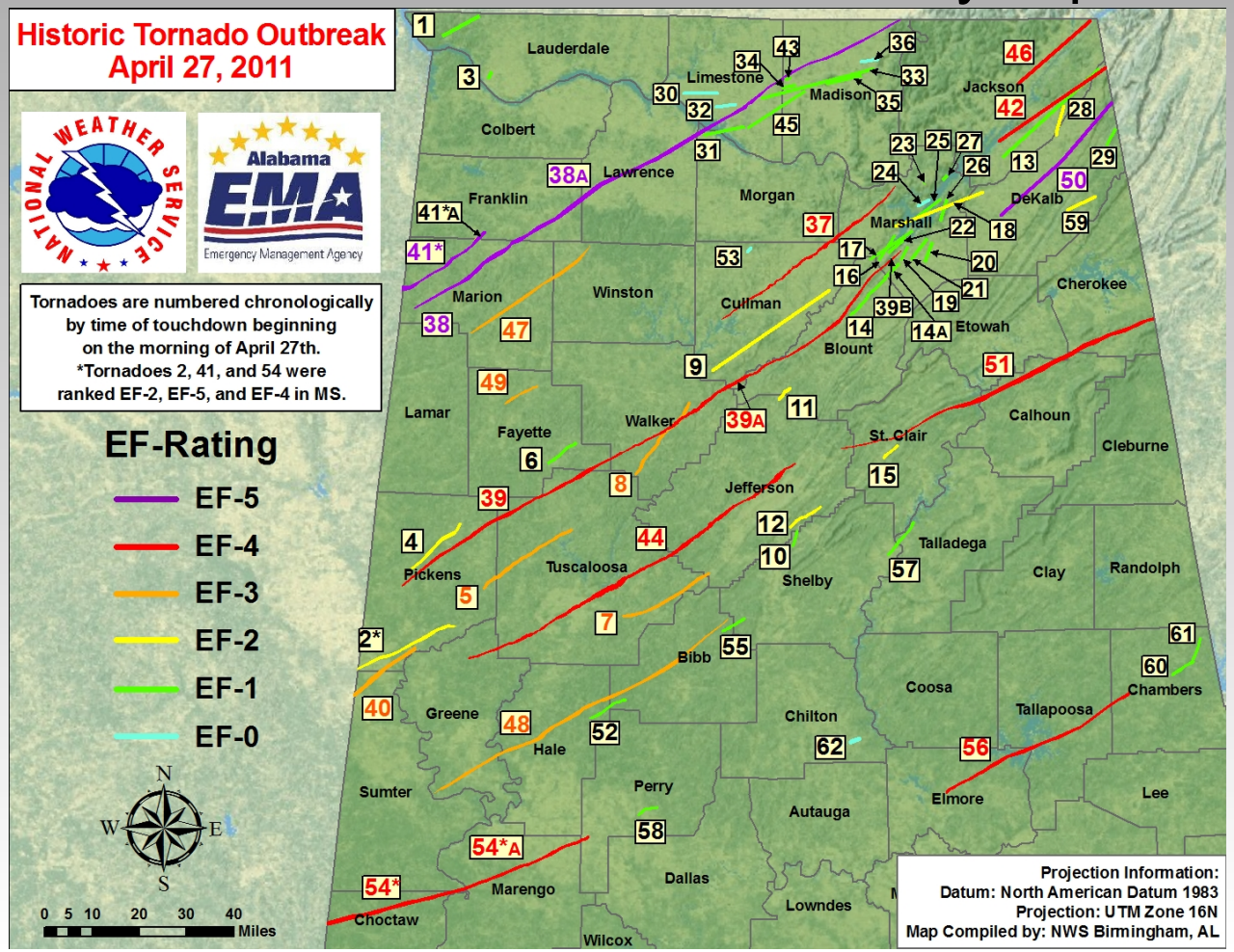
Brief summary of the disaster, 4/27/11

- Applies to calender 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

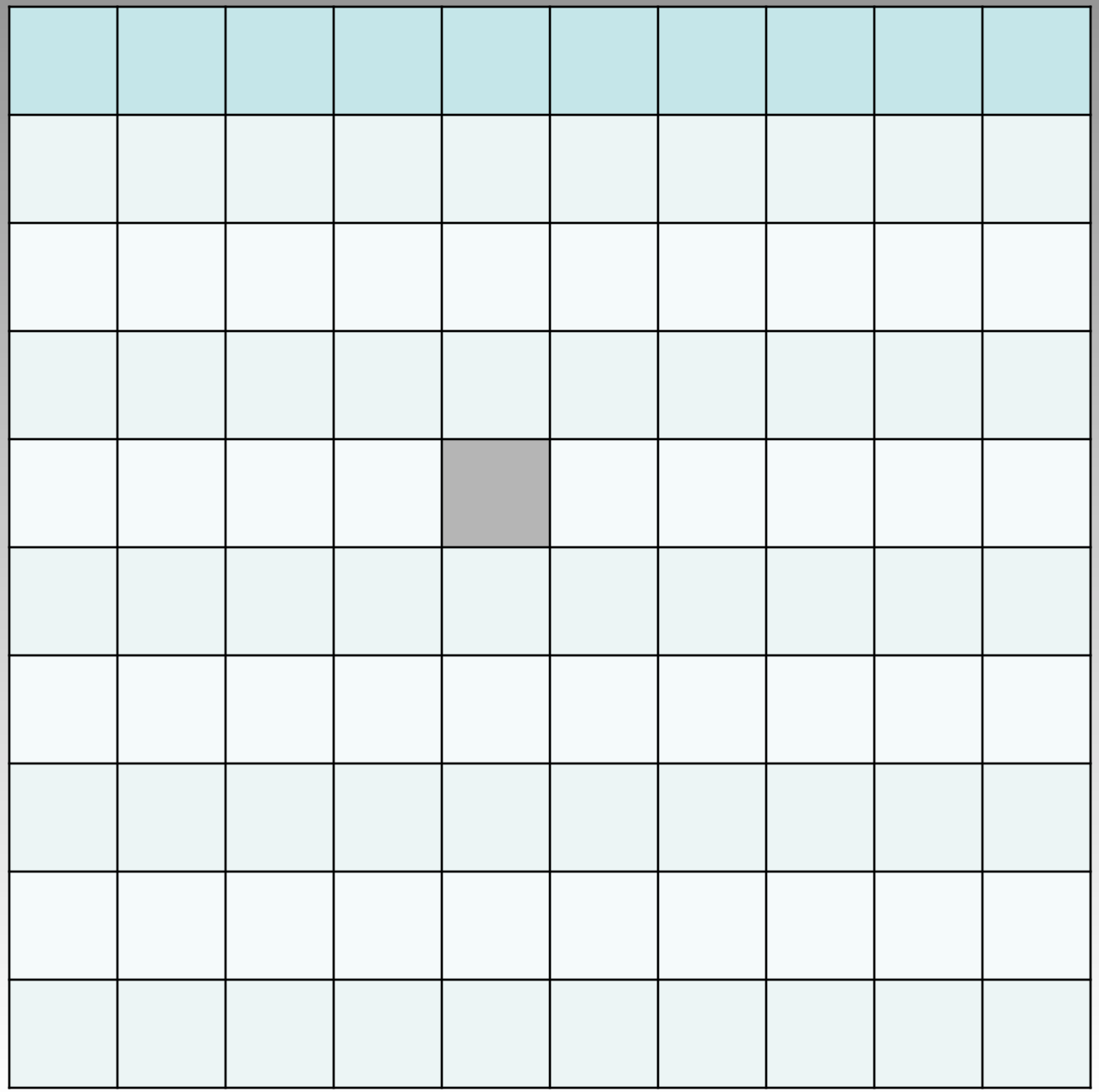

27 April 2011 Tornadoes
Courtesy of Patrick Marsh, NOAA
NOAA/NWS Storm Prediction Center
NOAA/OAR National Severe Storms Laboratory
*Data from official NOAA Tornado Records
Fatalities By County
0 5 10 15 20 25 30 35
CONUS Tornado (Fatality) Counts
By Rating*
F/EF-0: 54 (0)
F/EF-1: 77 (2)
F/EF-2: 34 (9)
F/EF-3: 19 (27)
F/EF-4: 11 (157)
F/EF-5: 4 (121)
TOTAL: 199 (316)

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.

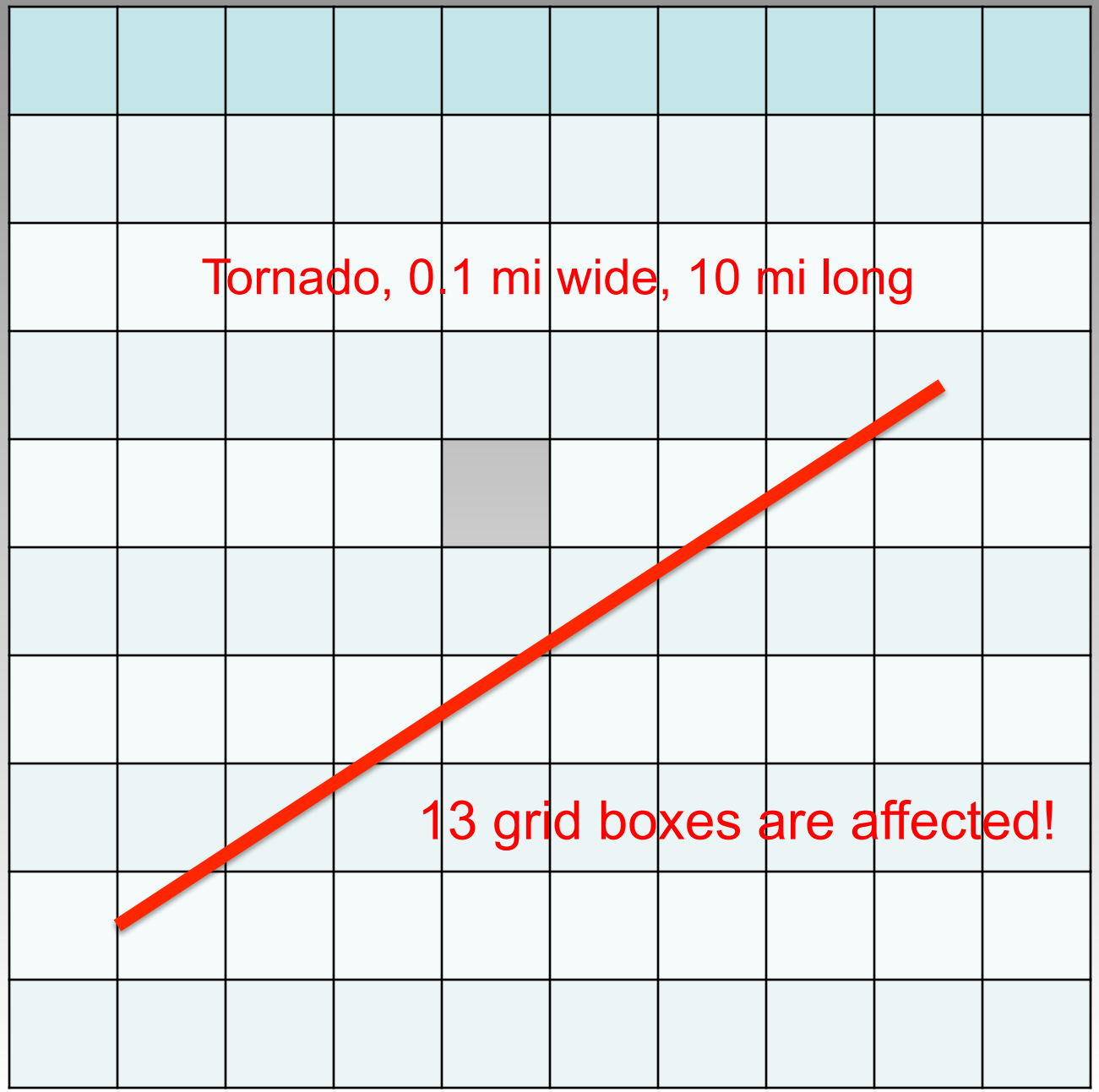


1.06% of AL was impacted: 1 square mile grid – 1% is large!

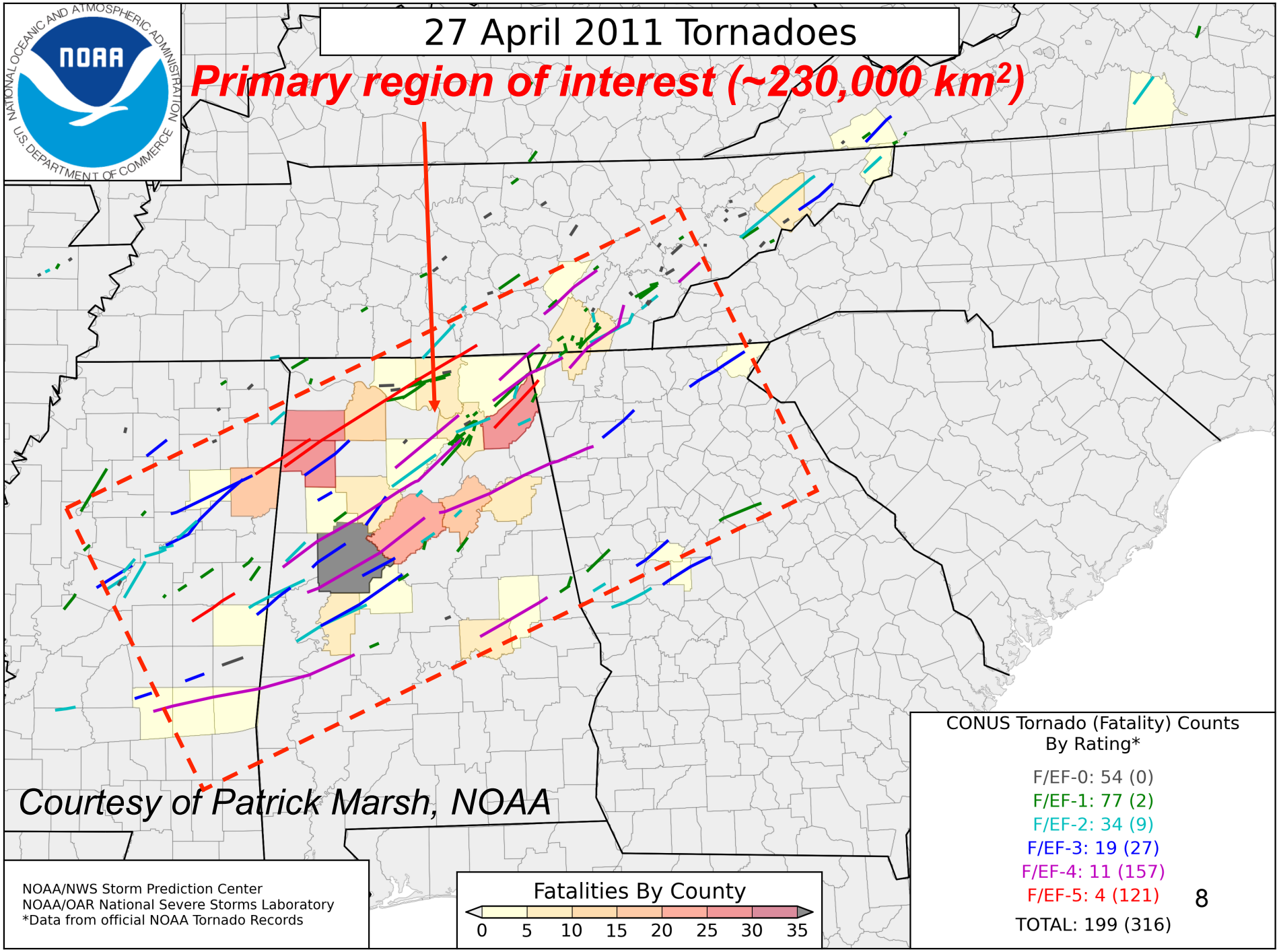


10x10 grid

1 square mile grid – 1% is large!



10x10 grid


27 April 2011 Tornadoes
Primary region of interest (~230,000 km²)
Courtesy of Patrick Marsh, NOAA
NOAA/NWS Storm Prediction Center
NOAA/OAR National Severe Storms Laboratory
*Data from official NOAA Tornado Records
Fatalities By County
0 5 10 15 20 25 30 35
CONUS Tornado (Fatality) Counts
By Rating*
F/EF-0: 54 (0)
F/EF-1: 77 (2)
F/EF-2: 34 (9)
F/EF-3: 19 (27)
F/EF-4: 11 (157)
F/EF-5: 4 (121)
TOTAL: 199 (316)

Same domain as in previous slide superimposed on the 3-4 April 1974 outbreak map

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

date	Tornado area times EF scale (km^2)	date	Tor path length (EF-4 & EF-5) (km)	date	U.S. fatalities
4/27/11	**4447**	**4/27/11**	**1502**	**4/27/11**	**319**
4/24/10	2830	4/3/74	1326	4/3/74	307 (315)
4/3/74	2635	4/11/65	788	4/11/65	305
4/11/65	1632	2/21/71	688	2/21/71	226
4/30/54	1495	5/31/85	417	3/21/52	218

Distribution of tornado intensity

27 April 2011 vs. 3-4 April 1974

(E)F-Scale	Number 27 April 2011	Number 3-4 April 1974
0	48	21
1	74	31
2	31	30
3	19	35
4	11	24
5	4	6
Totals	187 (199)	148

27 April had:

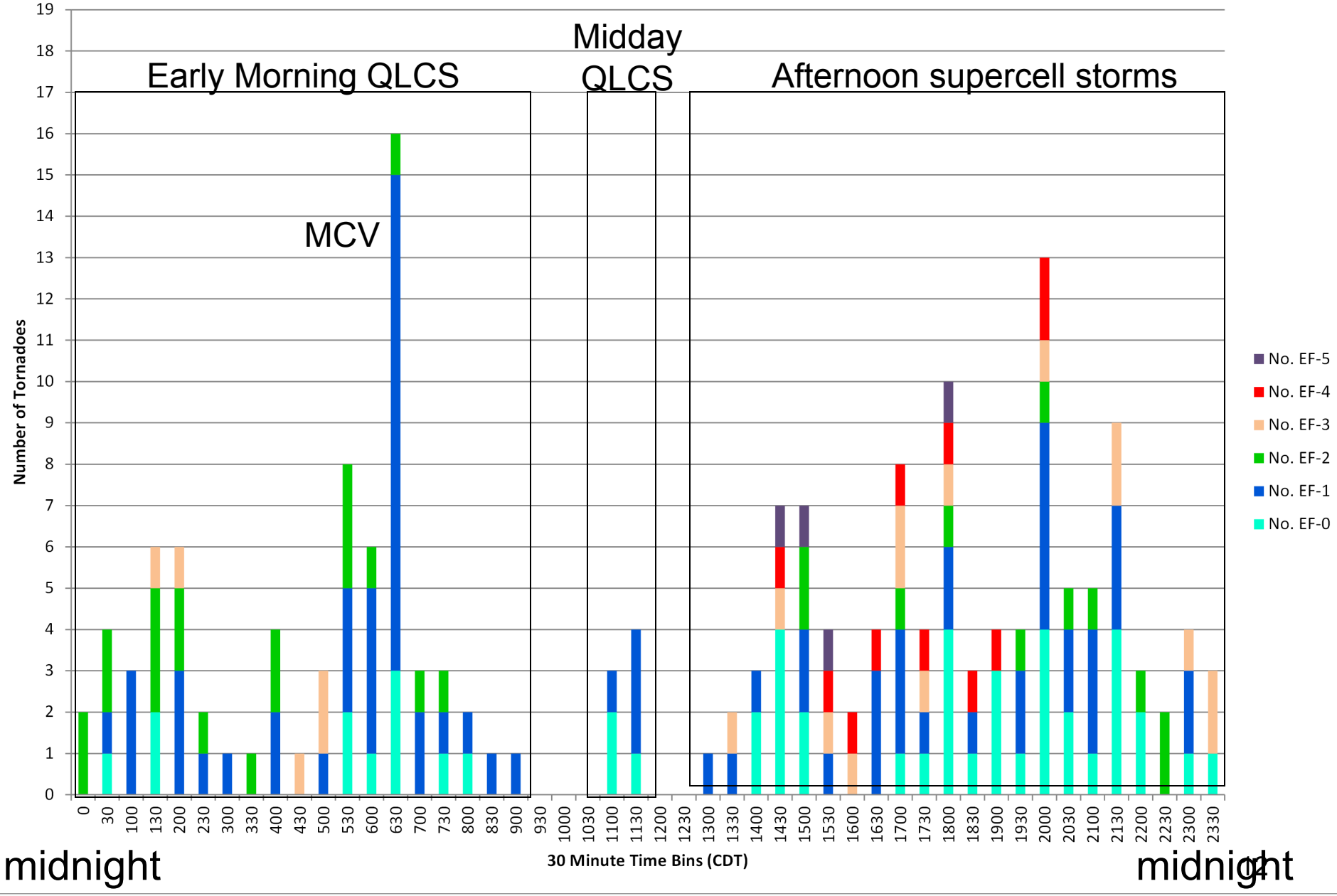
a) Longer & wider tornadoes
b) Longer duration
c) Greater contrast in parent convective systems

Notes:

Were all weak (F0, F1) tornadoes detected in 1974? Not likely.

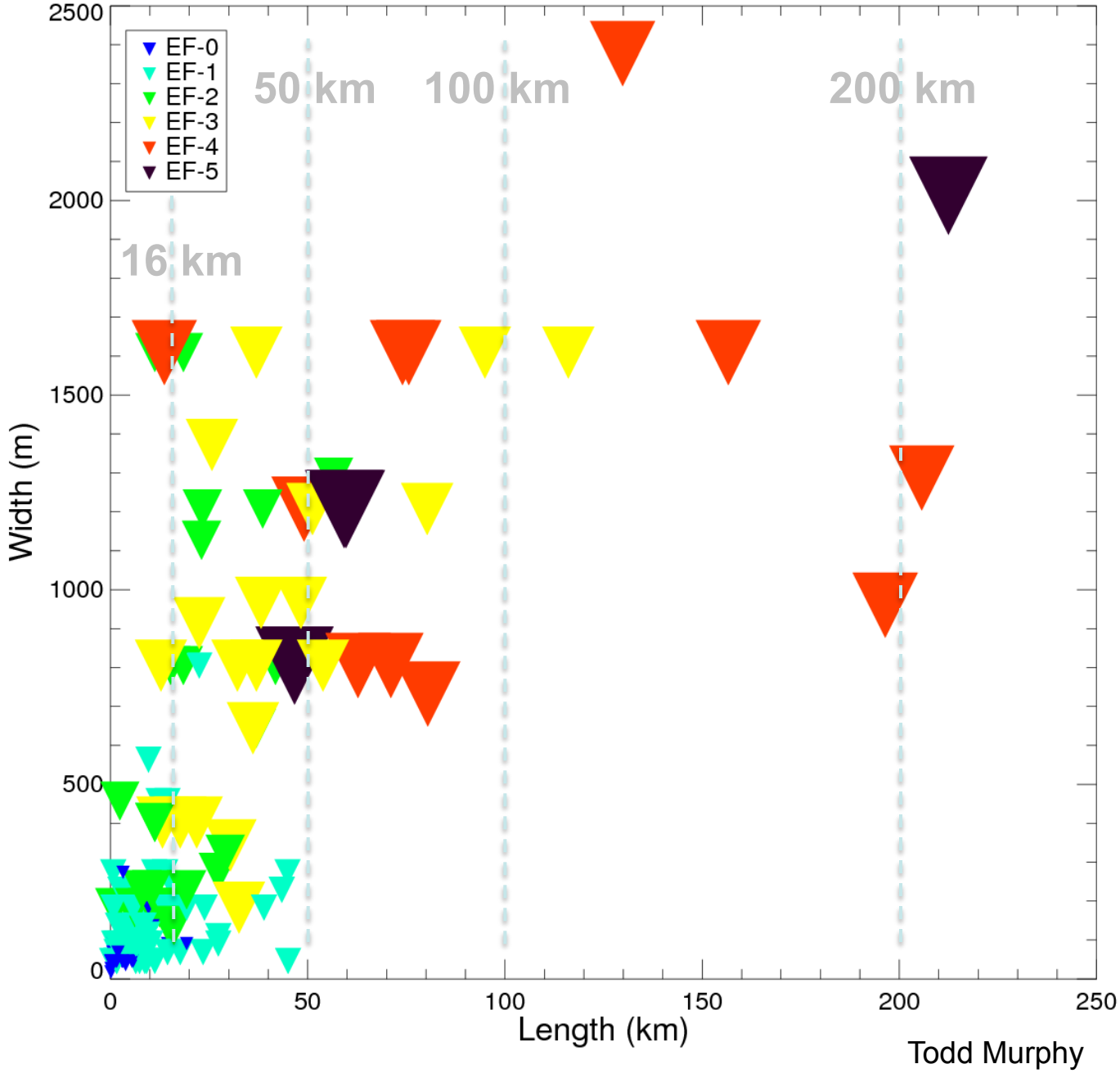
- Doppler radar not available to indicate where to look for F0, F1
- EF-scale vs F-scale

Number of tornadogenesis events per 30 min period



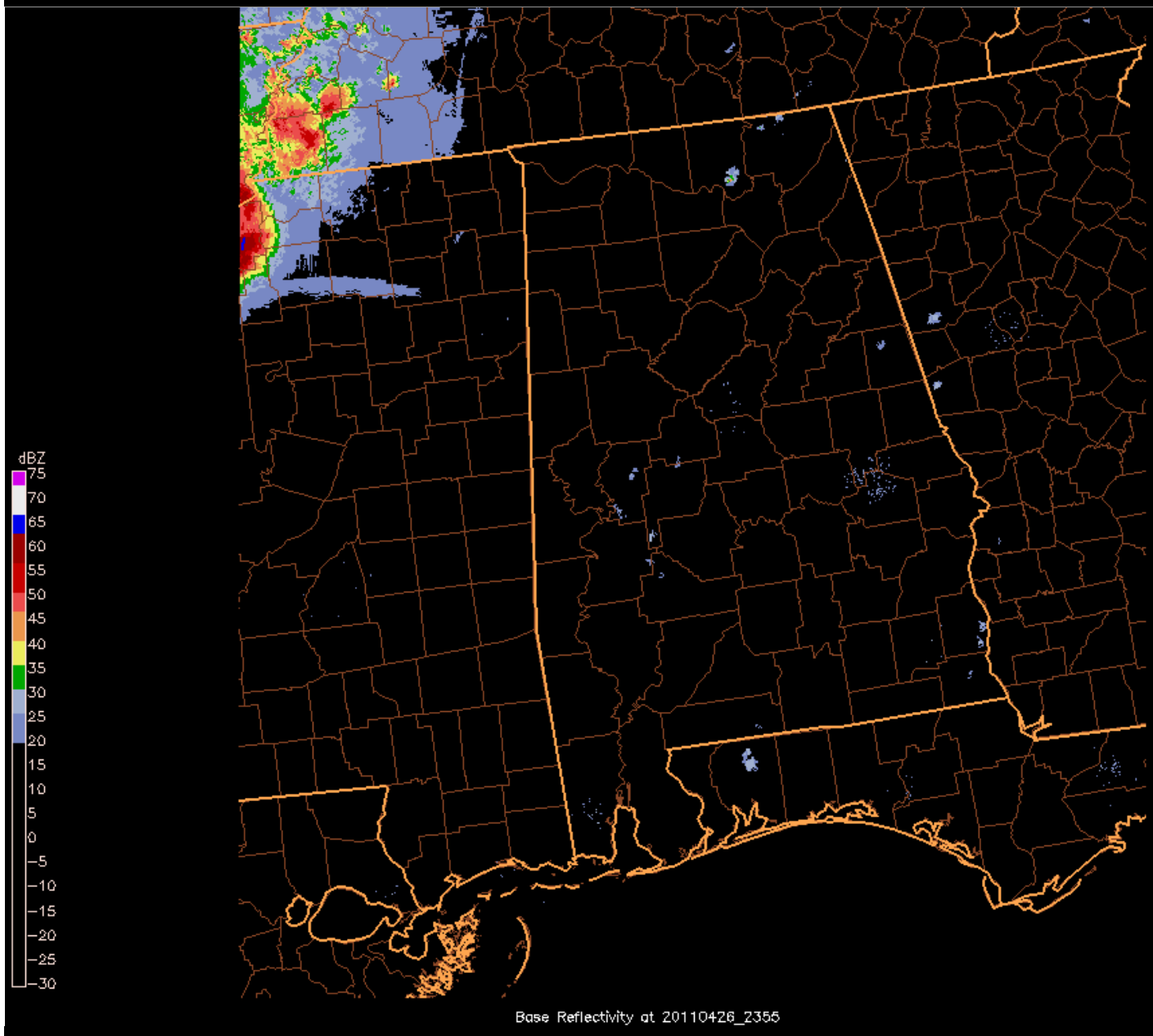
Todd Murphy

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



Todd Murphy

Radar Overview



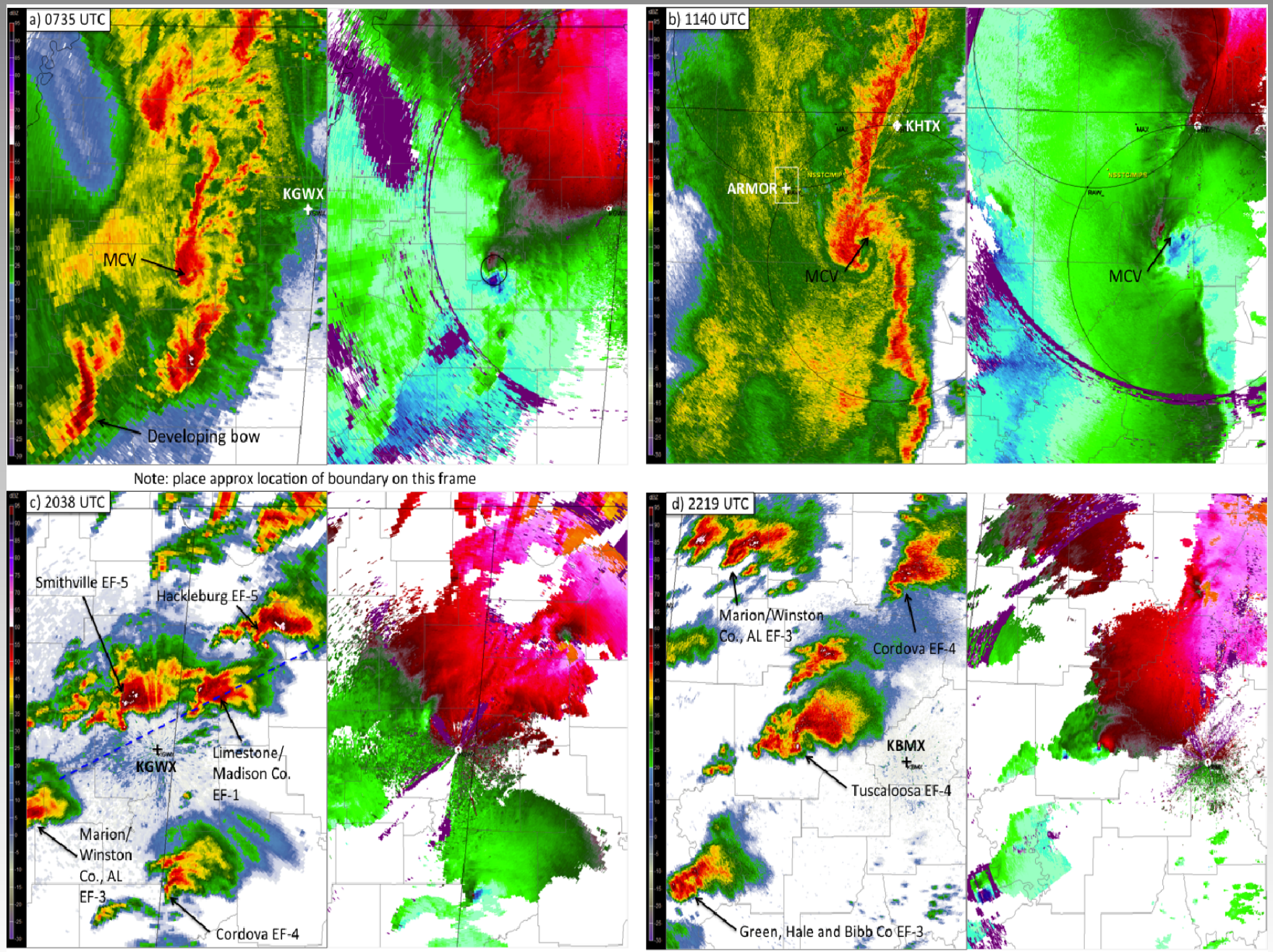
3+ tornado episodes over Alabama

Early morning QLCS
- 29 tornadoes

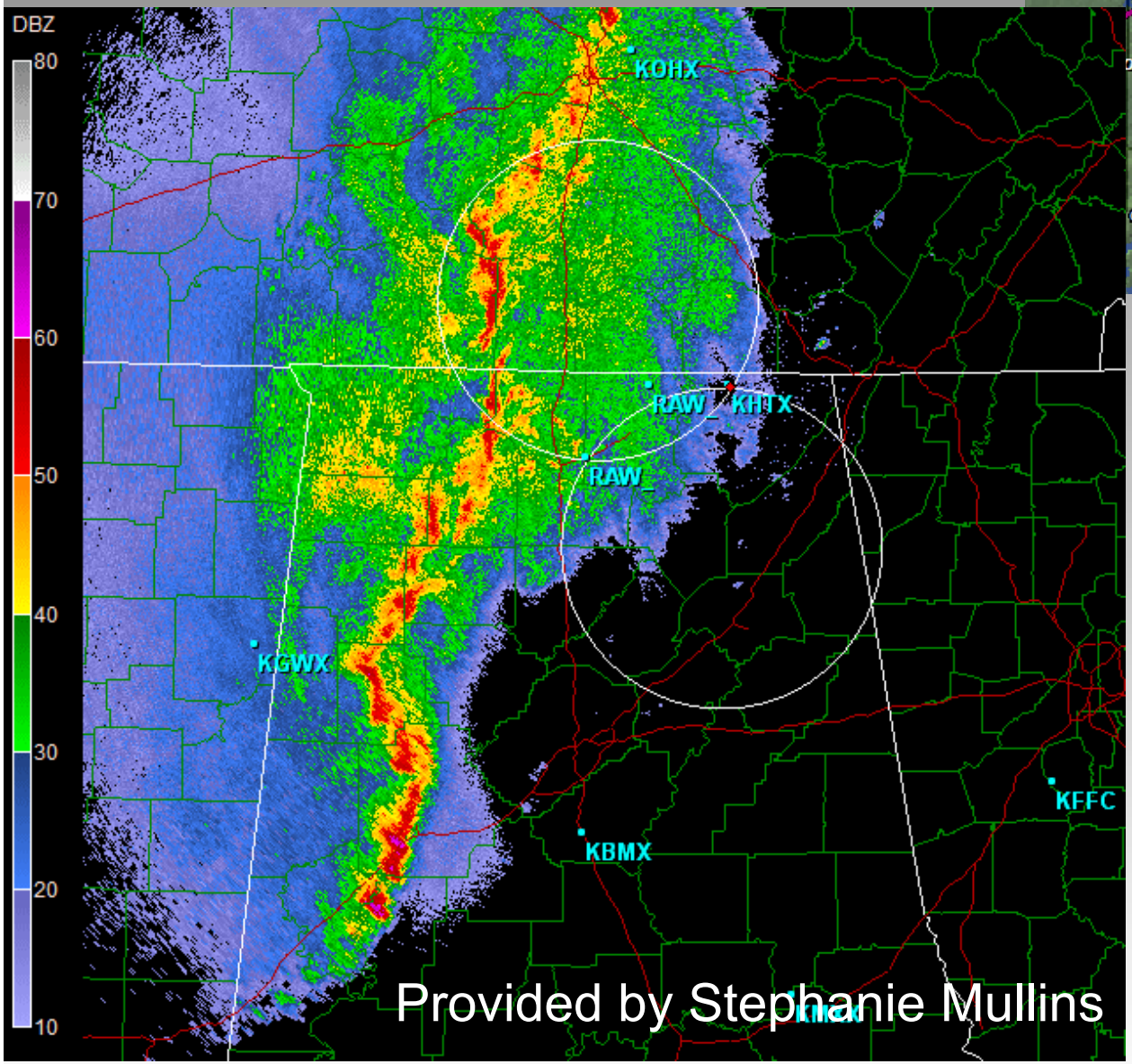
Mid morning lone supercell
- 1 tornado

Mid-day QLCS
- 7 tornadoes (N AL)

Afternoon supercells
- 26 tornadoes

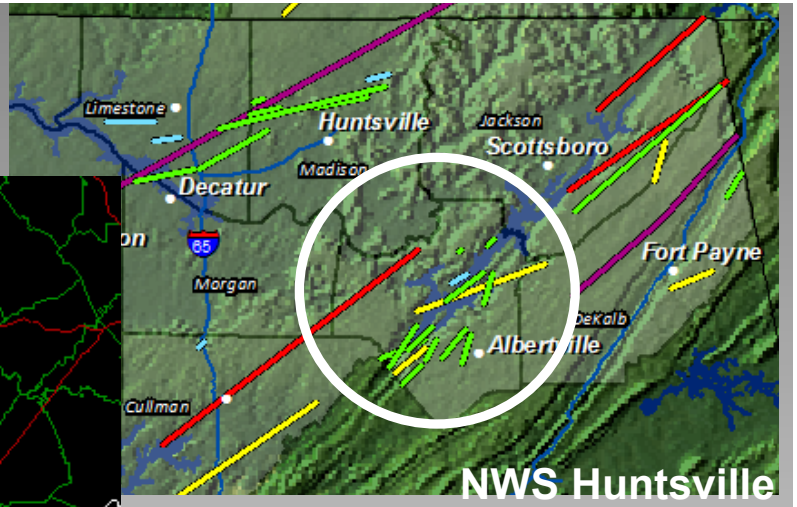

a) 0735 UTC
KGWX
MCV
Developing bow
b) 1140 UTC
KHTX
ARMOR
MCV
MCV
Note: place approx location of boundary on this frame
c) 2038 UTC
Smithville EF-5
Hackleburg EF-5
KGWX
Limestone/
Madison Co.
EF-1
Marion/
Winston
Co., AL
EF-3
Cordova EF-4
d) 2219 UTC
Marion/Winston
Co., AL EF-3
Cordova EF-4
KBMX
Tuscaloosa EF-4
Green, Hale and Bibb Co EF-3

Early Morning MCV



Provided by Stephanie Mullins

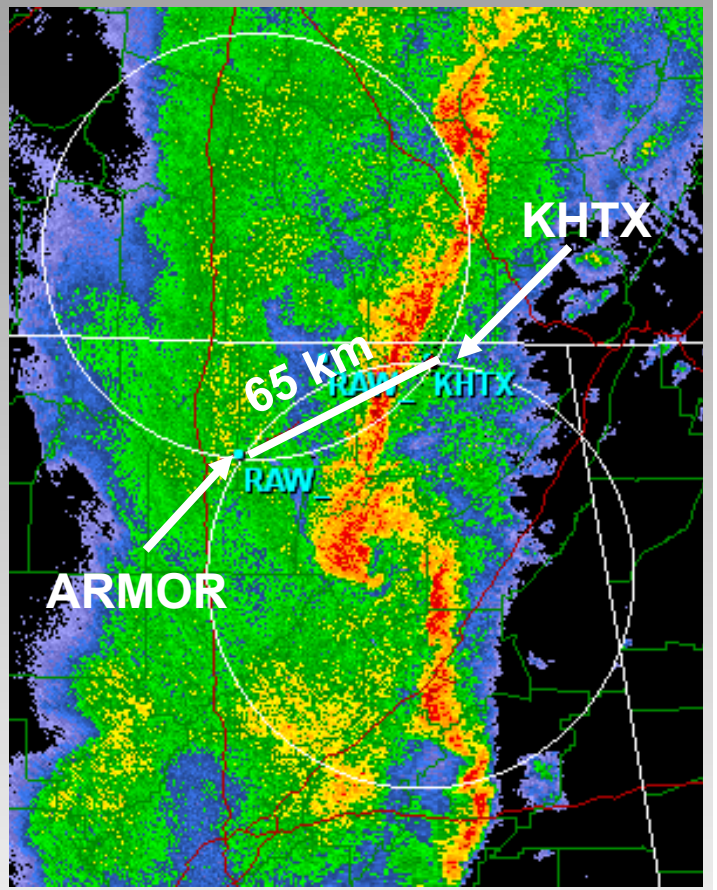
KHTX 10-13 UTC (5-8 am CDT)



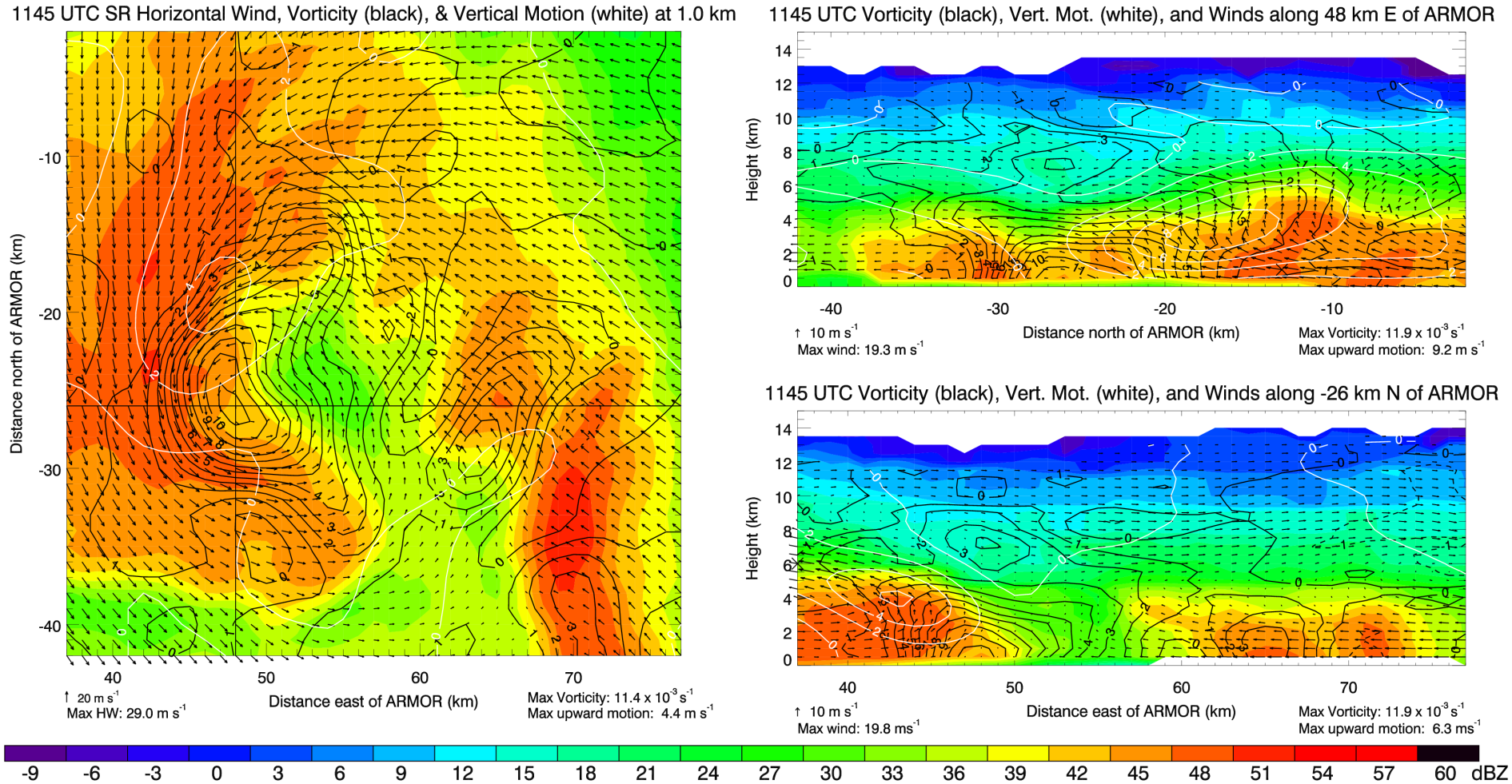
- 16 tornadoes produced by MCV passage – mainly affected Lake Guntersville Park/Marshall County
- Good dual-Doppler coverage by ARMOR/KHTX radars (baseline ~65 km)
- Vorticity analysis:
  - →concentration in low levels
  - →multiple peaks & horizontal structure transitions
  - →aligned well w/][tracks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

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



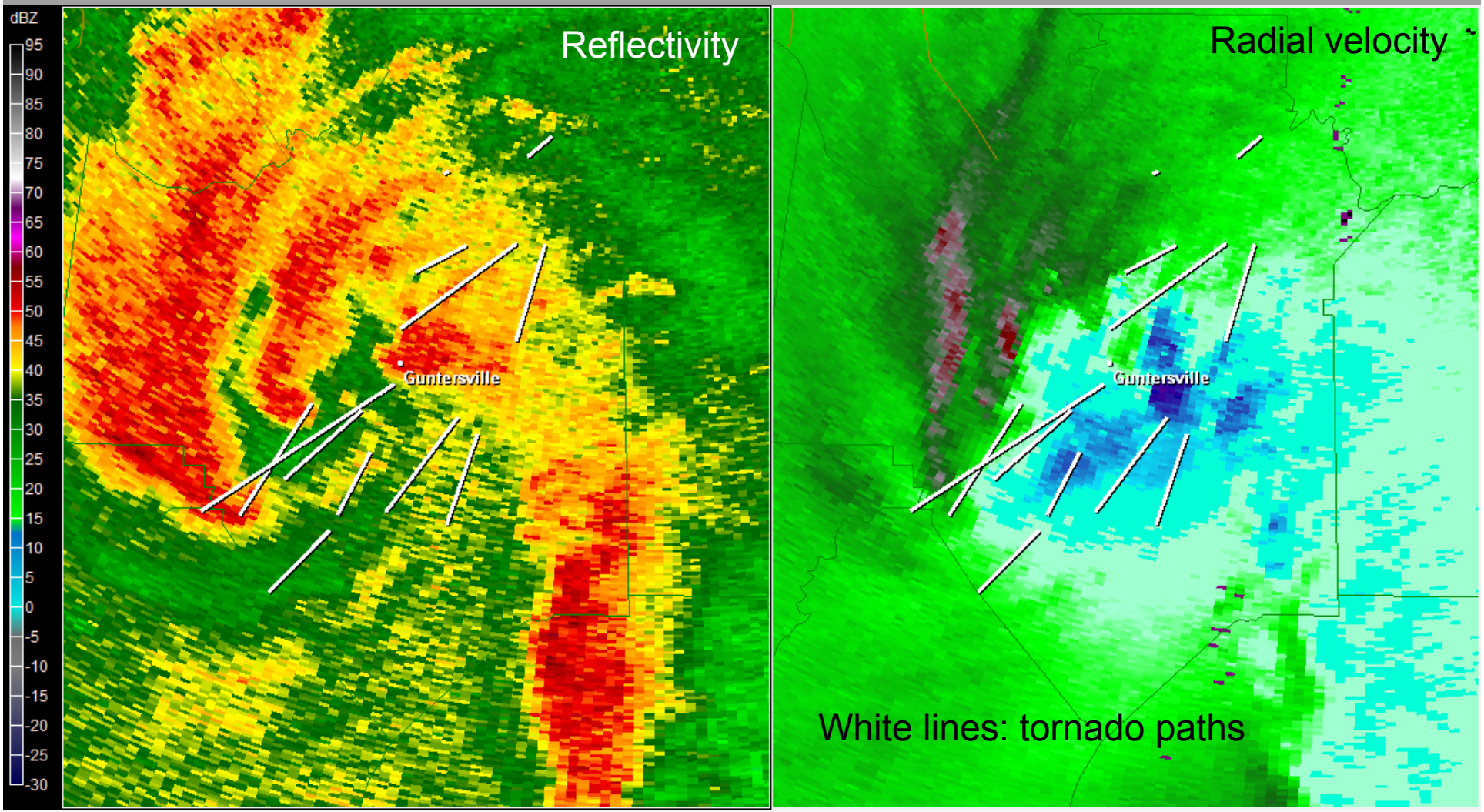
Dual Doppler analysis of the MCV at 1145 UTC



- Maximum vorticity (12 x 10^{-3} 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

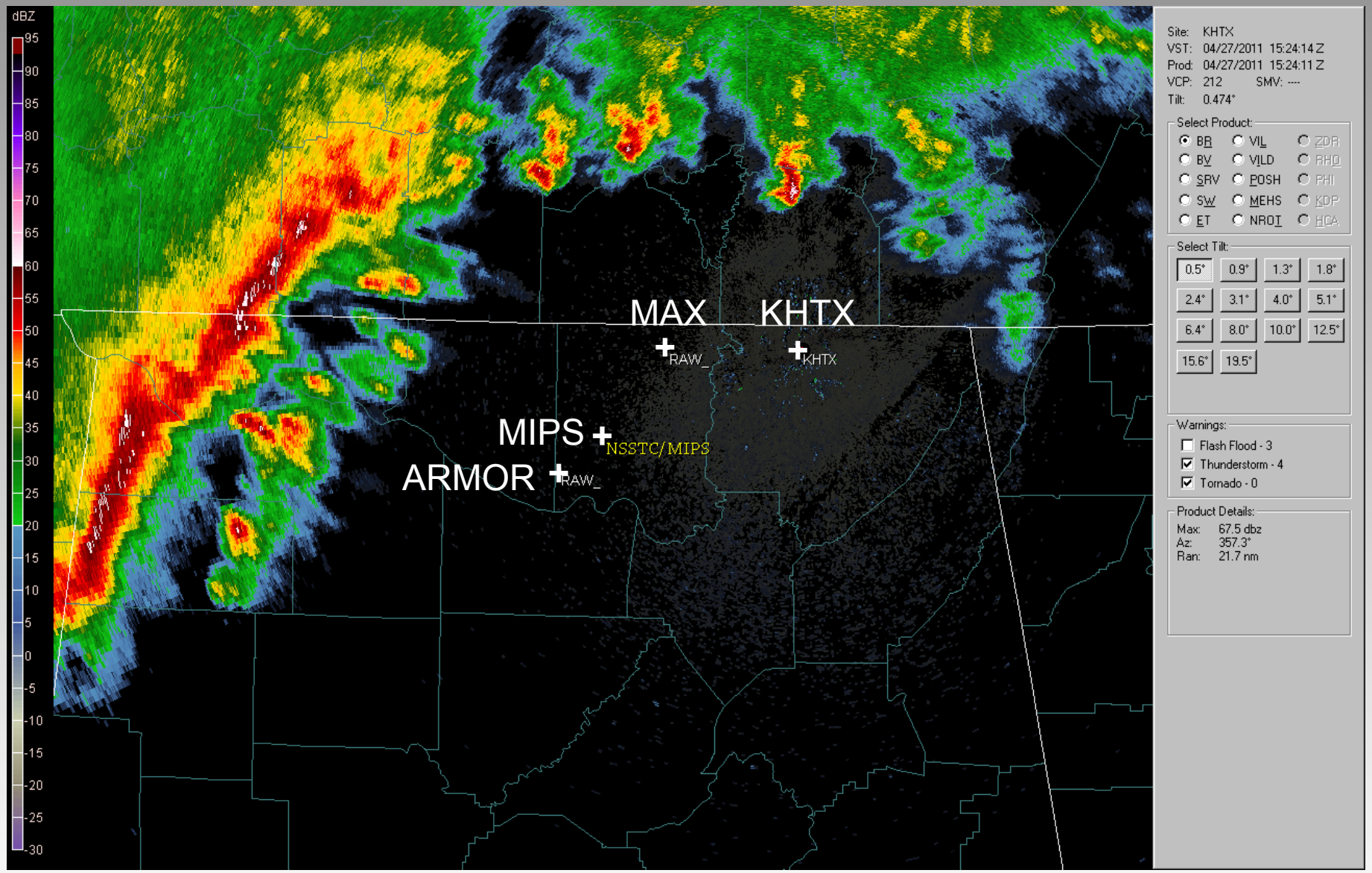
Credit: Stephanie Mullins

Fundamental question: What is the physical connection between the tornadoes and MCV?

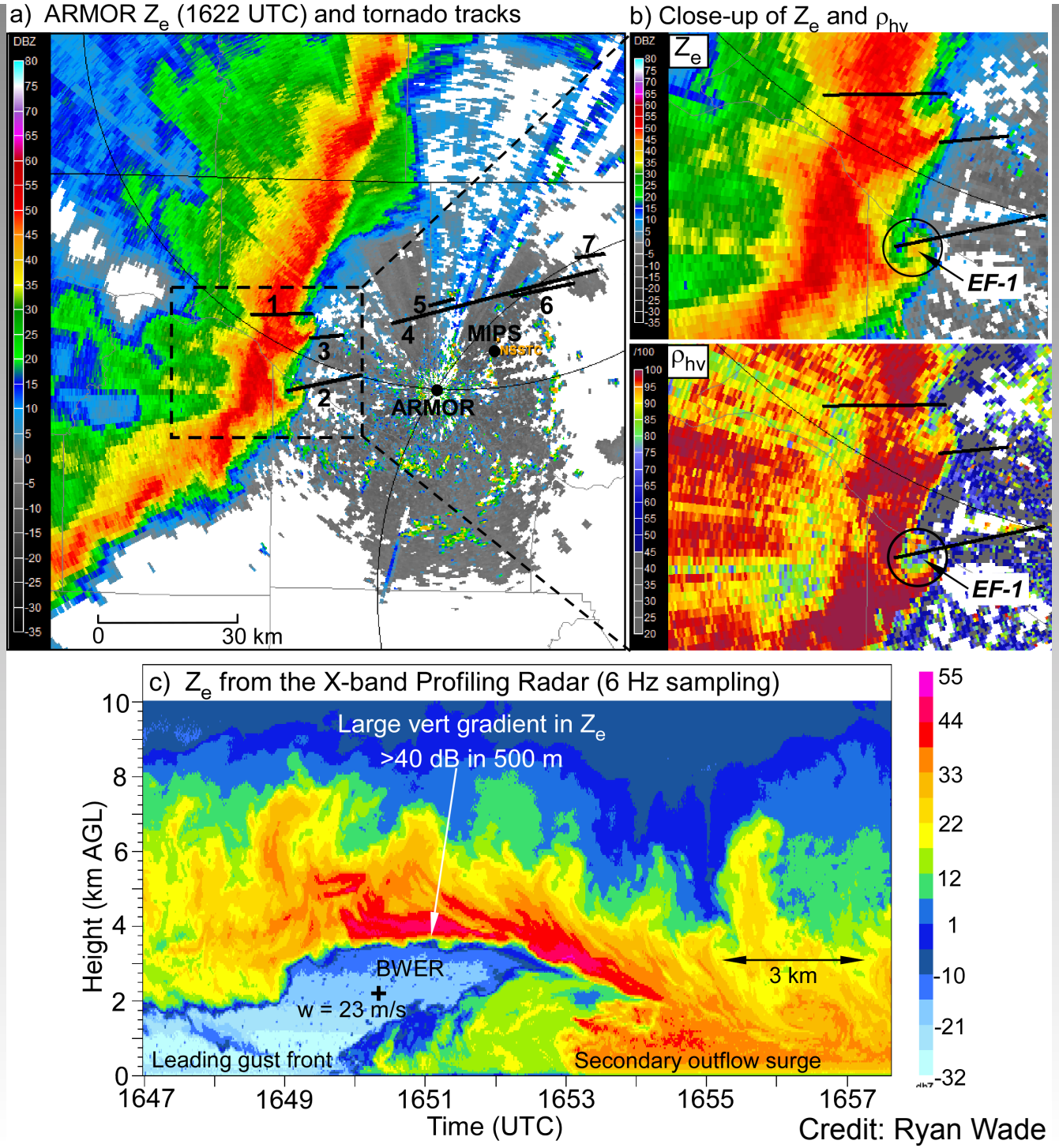


1134 UTC – KHTX Reflectivity & Velocity

Round 2: Mid-Day QLCS

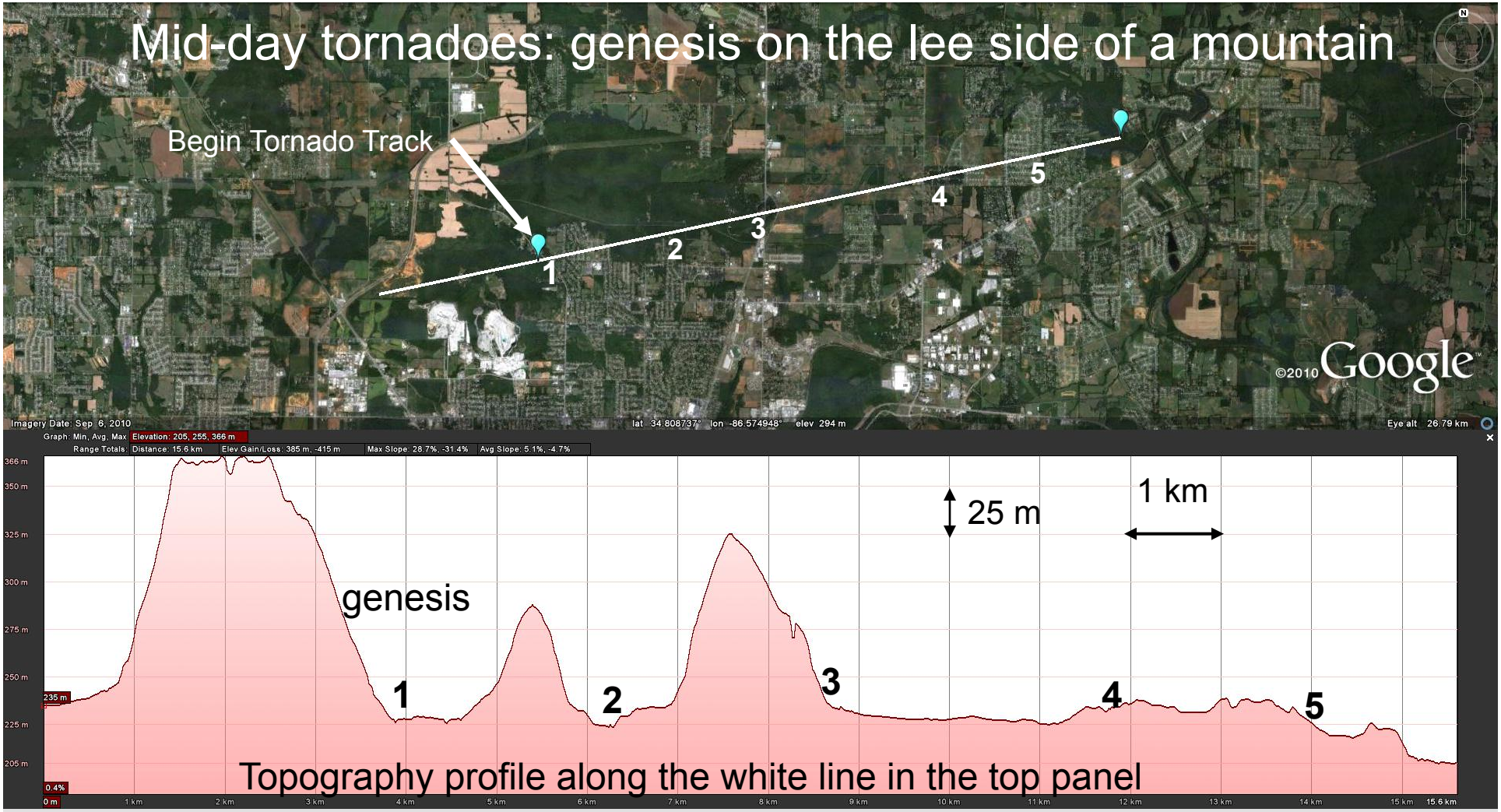


1524 - 1841 UTC – KHTX Reflectivity



Credit: Ryan Wade

Mid-day tornadoes: genesis on the lee side of a mountain



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)?

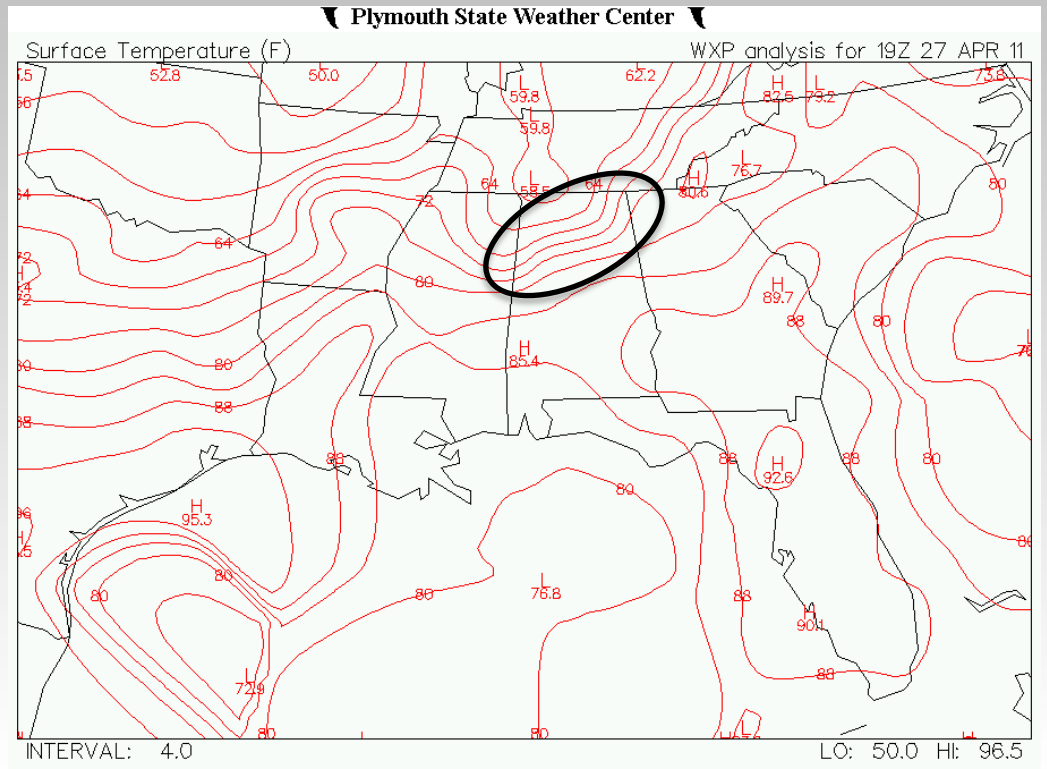
Why did the tornadoes form in this general area as the QLCS passed through? Was a shear instability involved?

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.

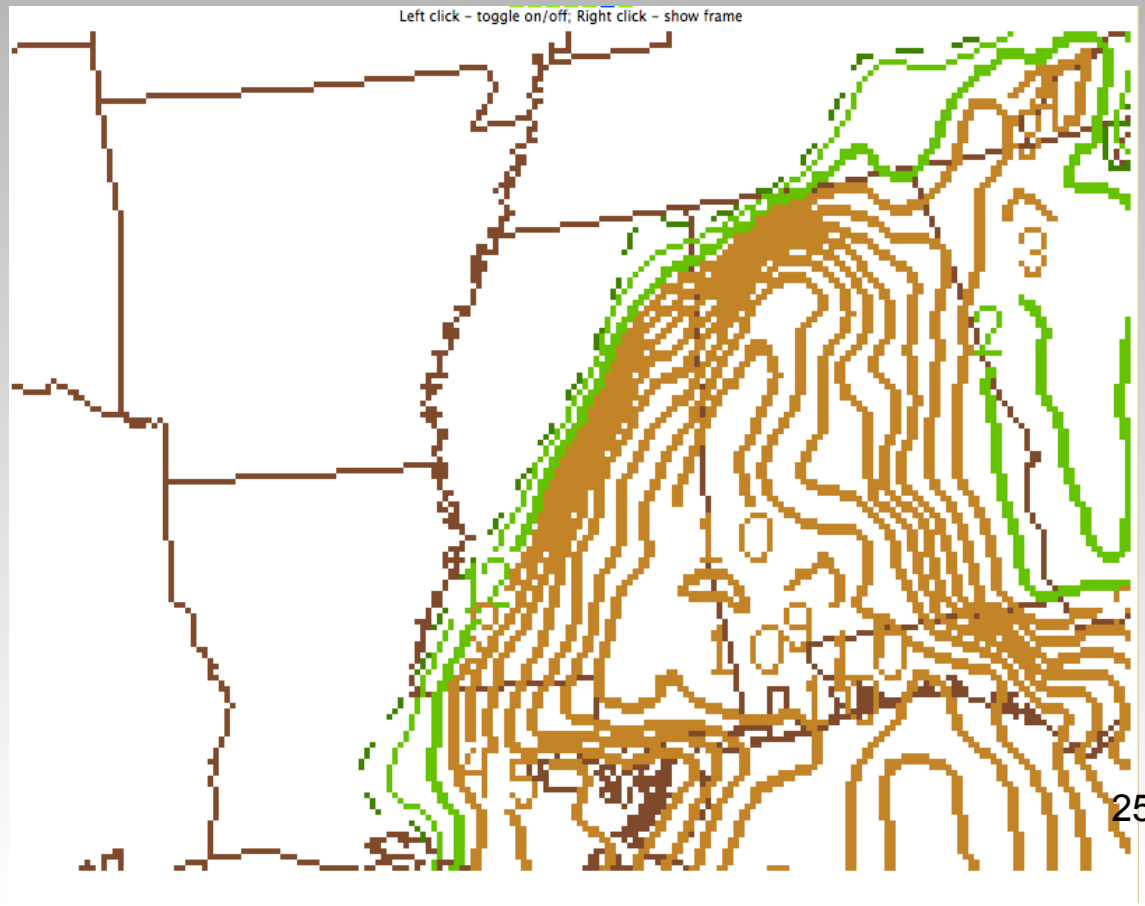


Afternoon Supercells

- 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

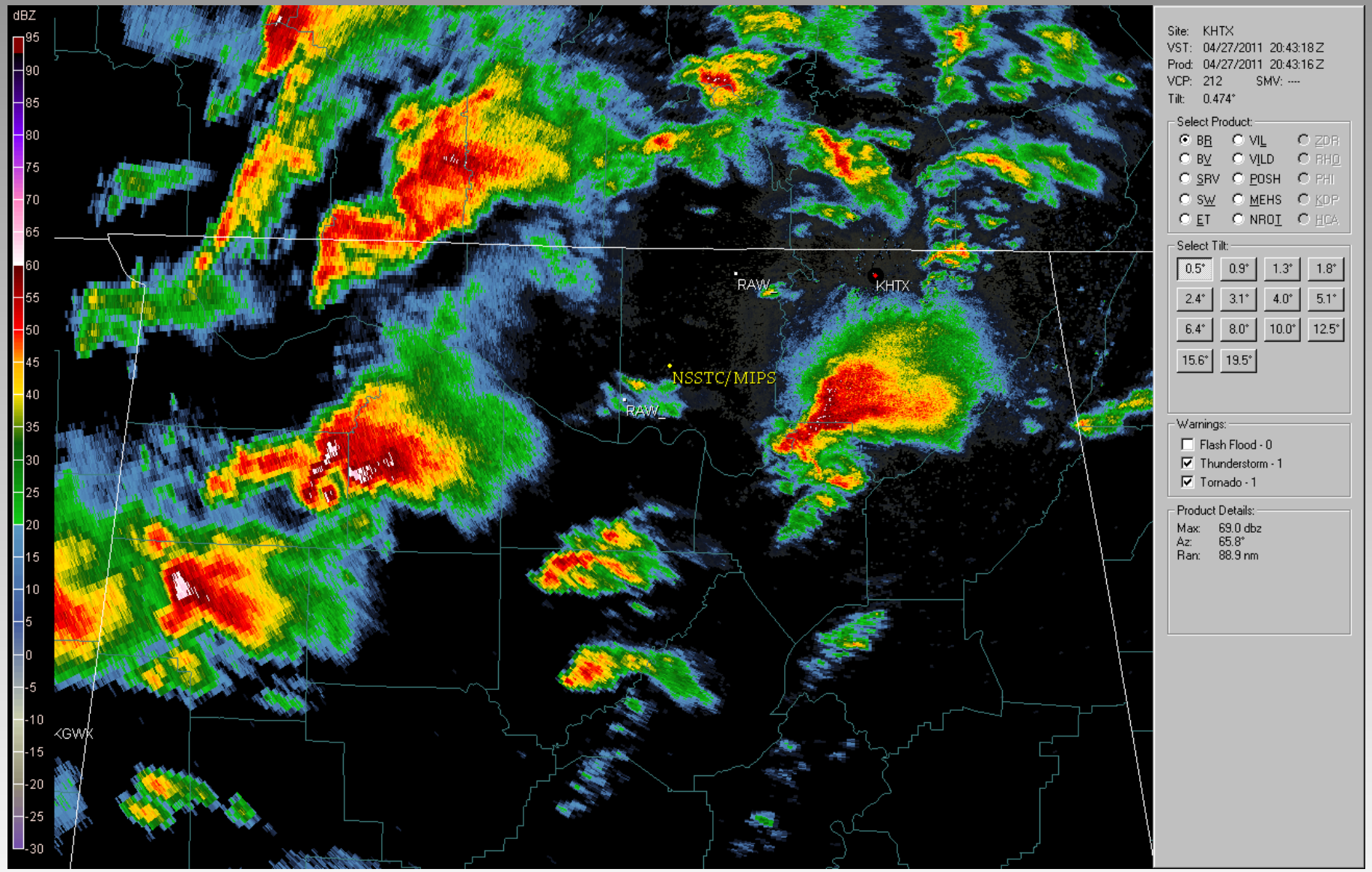
22 UTC 0-1 km EHI

Unprecedented values in AL

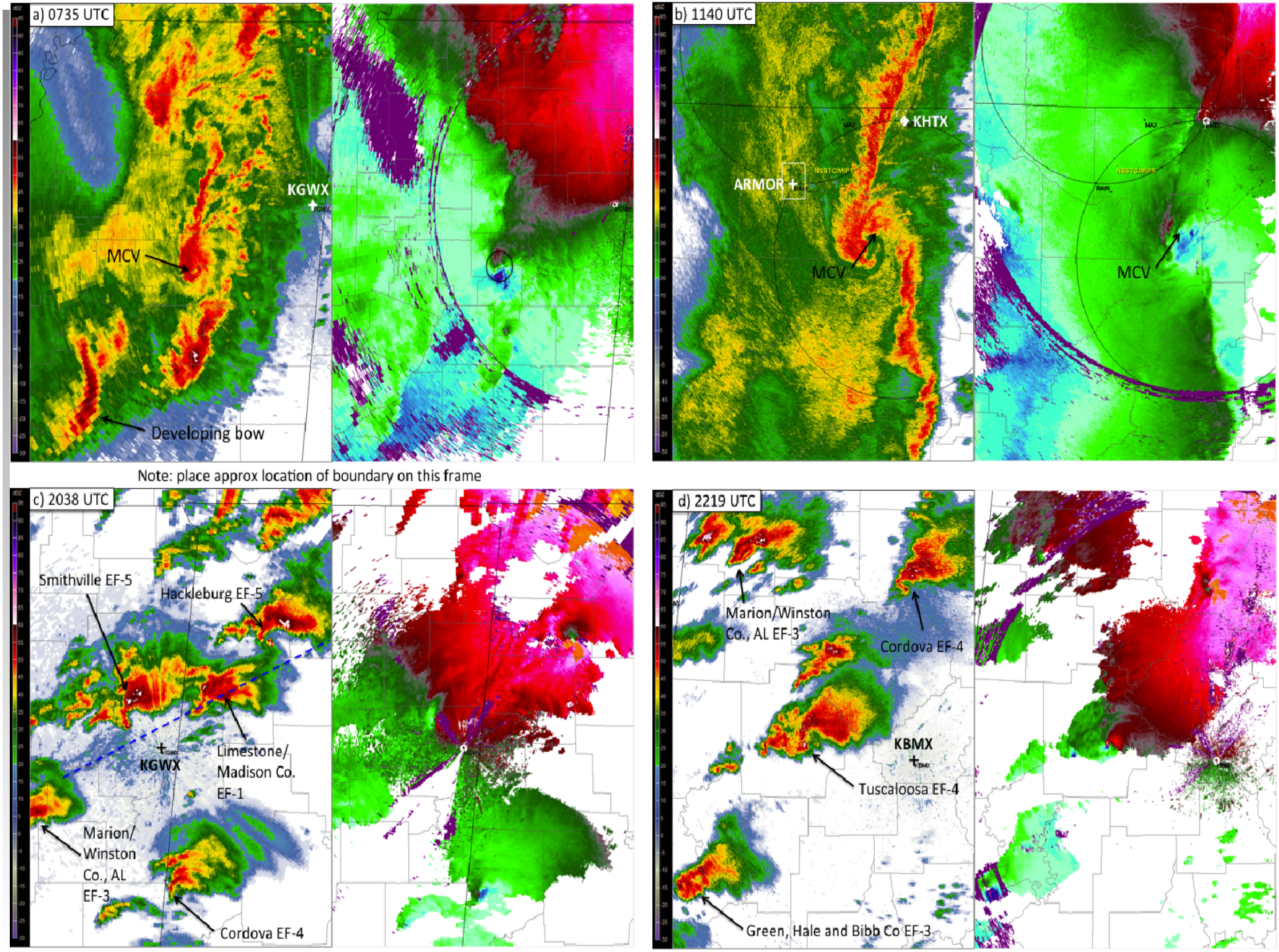


Dr. Tim Coleman

Afternoon Supercells



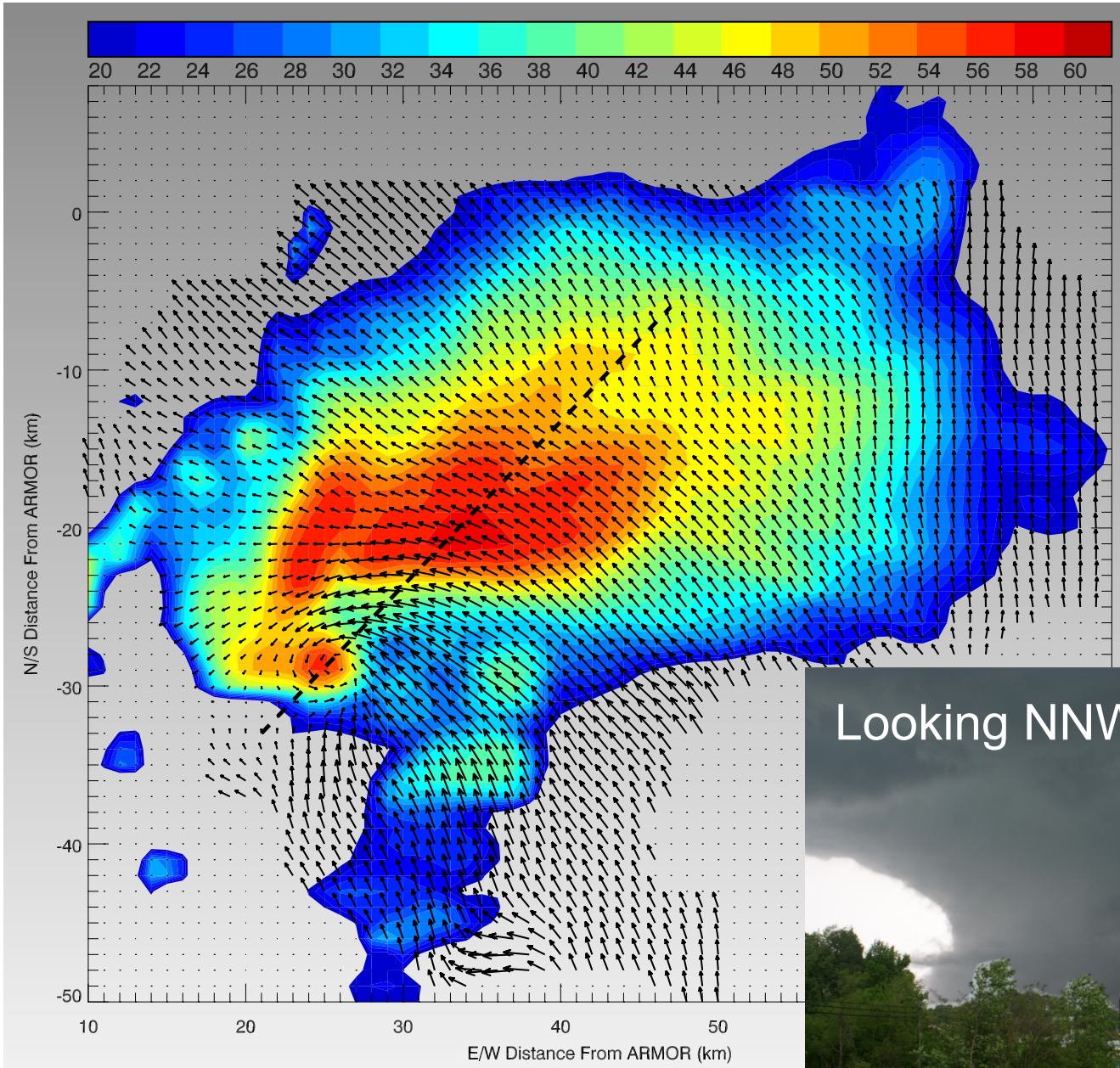
KHTX Reflectivity


a) 0735 UTC
KGWX
MCV
Developing bow
b) 1140 UTC
KHTX
ARMOR
MCV
MCV
Note: place approx location of boundary on this frame
c) 2038 UTC
Smithville EF-5
Hackleburg EF-5
KGWX
Limestone/
Madison Co.
EF-1
Marion/
Winston
Co., AL
EF-3
Cordova EF-4
d) 2219 UTC
Marion/Winston
Co., AL EF-3
Cordova EF-4
KBMX
Tuscaloosa EF-4
Green, Hale and Bibb Co EF-3

The three most prolific supercell storms

Storm ID	Begin Time (UTC)	End Time (UTC)	Storm dura-tion (hr)	Storm path length (km)	Number of torn-adoes	Accum path length (km)	Other notes on significant tornadoes produced
Cullman	1900	0215	7	650	8	250	3 EF-4 tornadoes
Tuscaloosa	1940	0345	8	730	4	380	2 EF-4, 2 EF-3
Cordova	2000	0500	9	850	9	415	EF-4, EF-5, EF-3

In many tornado outbreaks, a few storms generate most of the significant tornadoes.



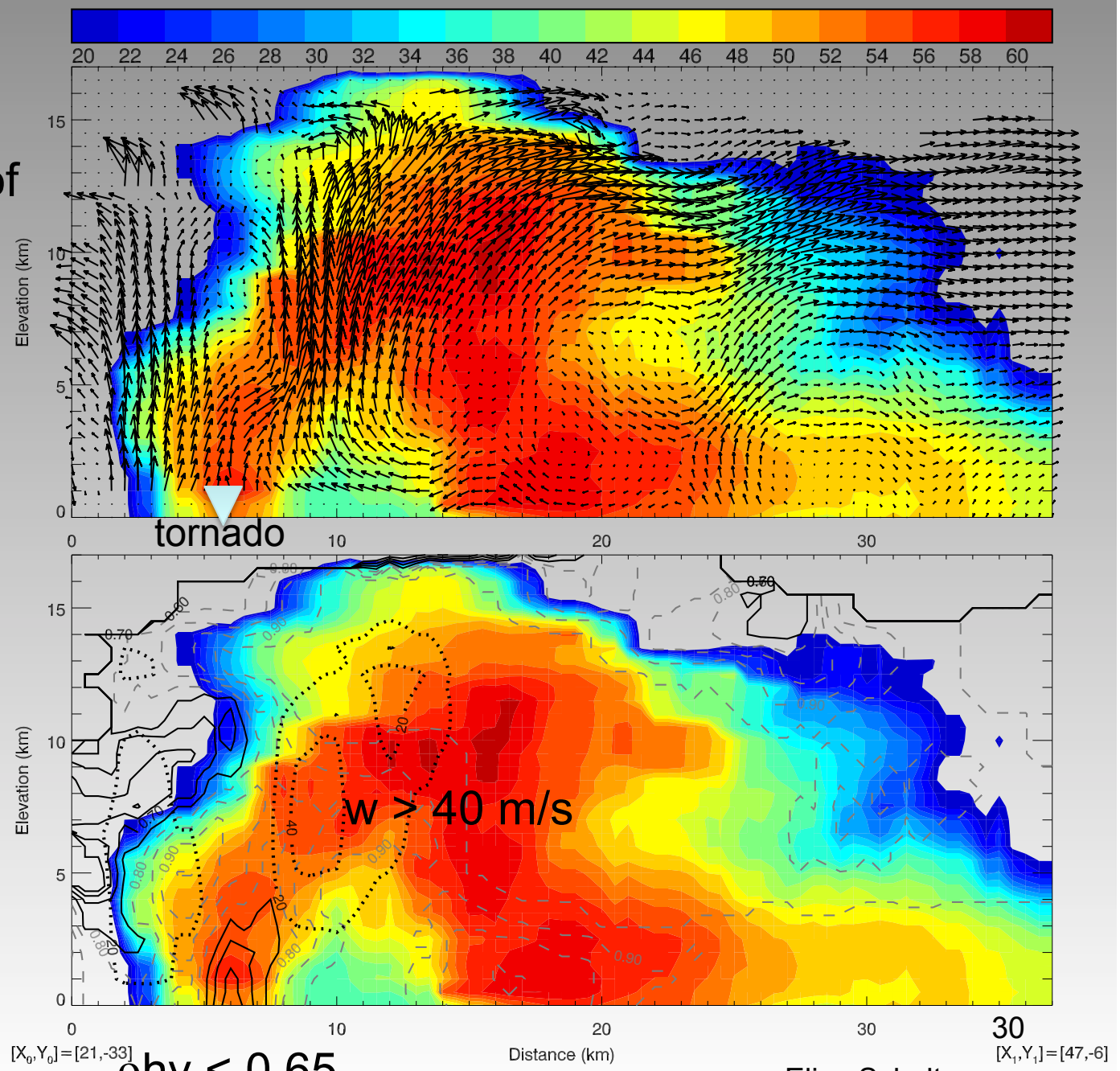
Cullman storm at 2123 UTC

Dual Doppler radar analyses and dual pol debris signature (next slide)

The appearance is typical of most of the violent torandoes 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 super-cells produced a tornado

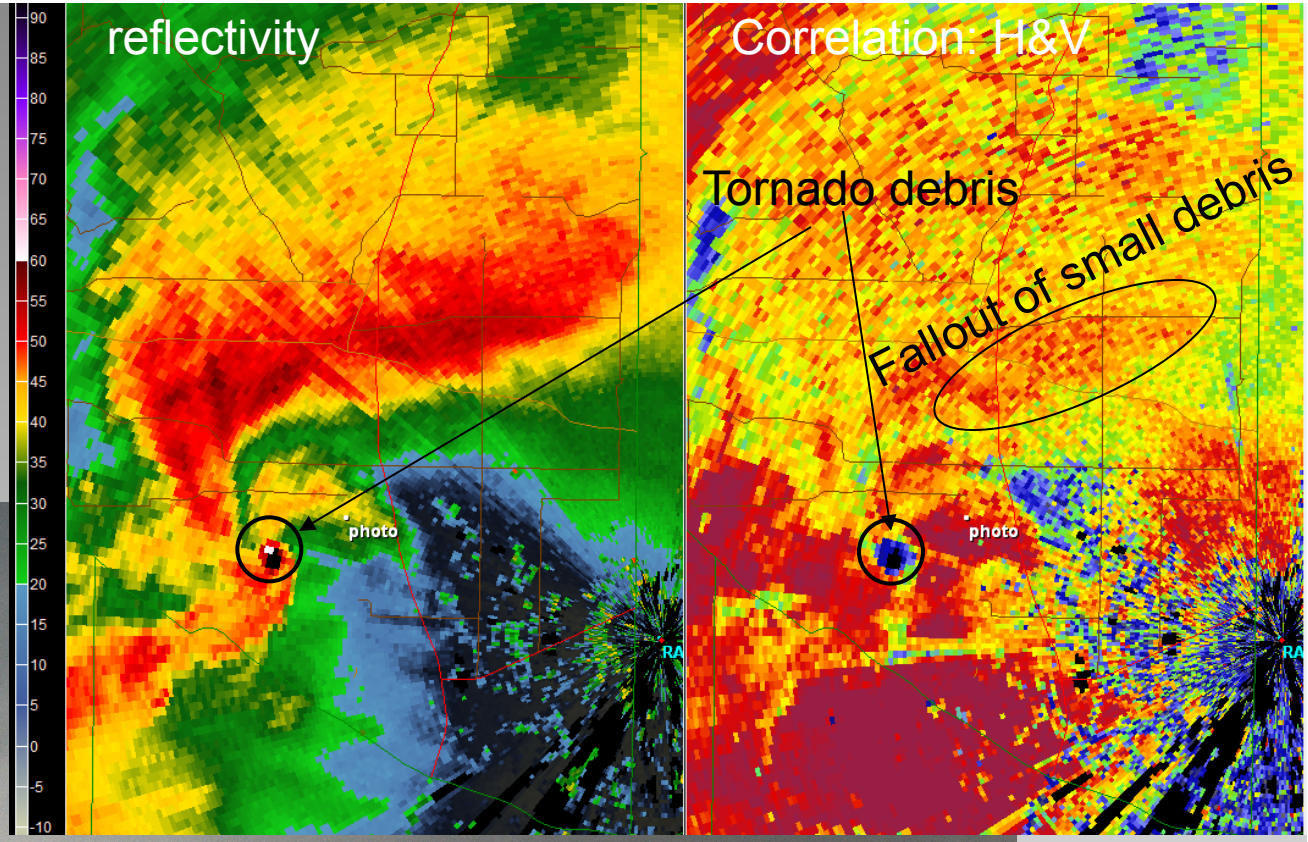


ρhv < 0.65

Elise Schultz

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)



2125 UTC

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

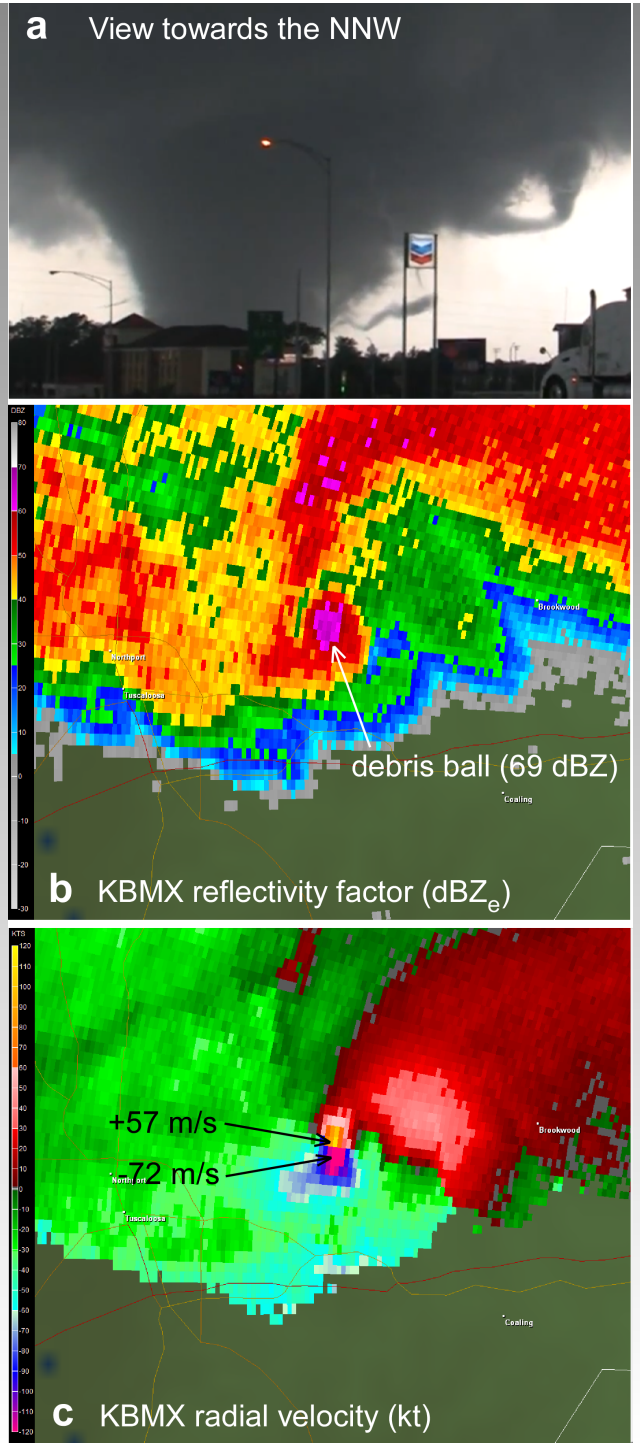
a)Pic of tornado over Tuscaloosa
•Horiz vortices were common in violent tornadoes

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

04/28/2011 16:53

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?

04/28/2011 13:02

Research questions

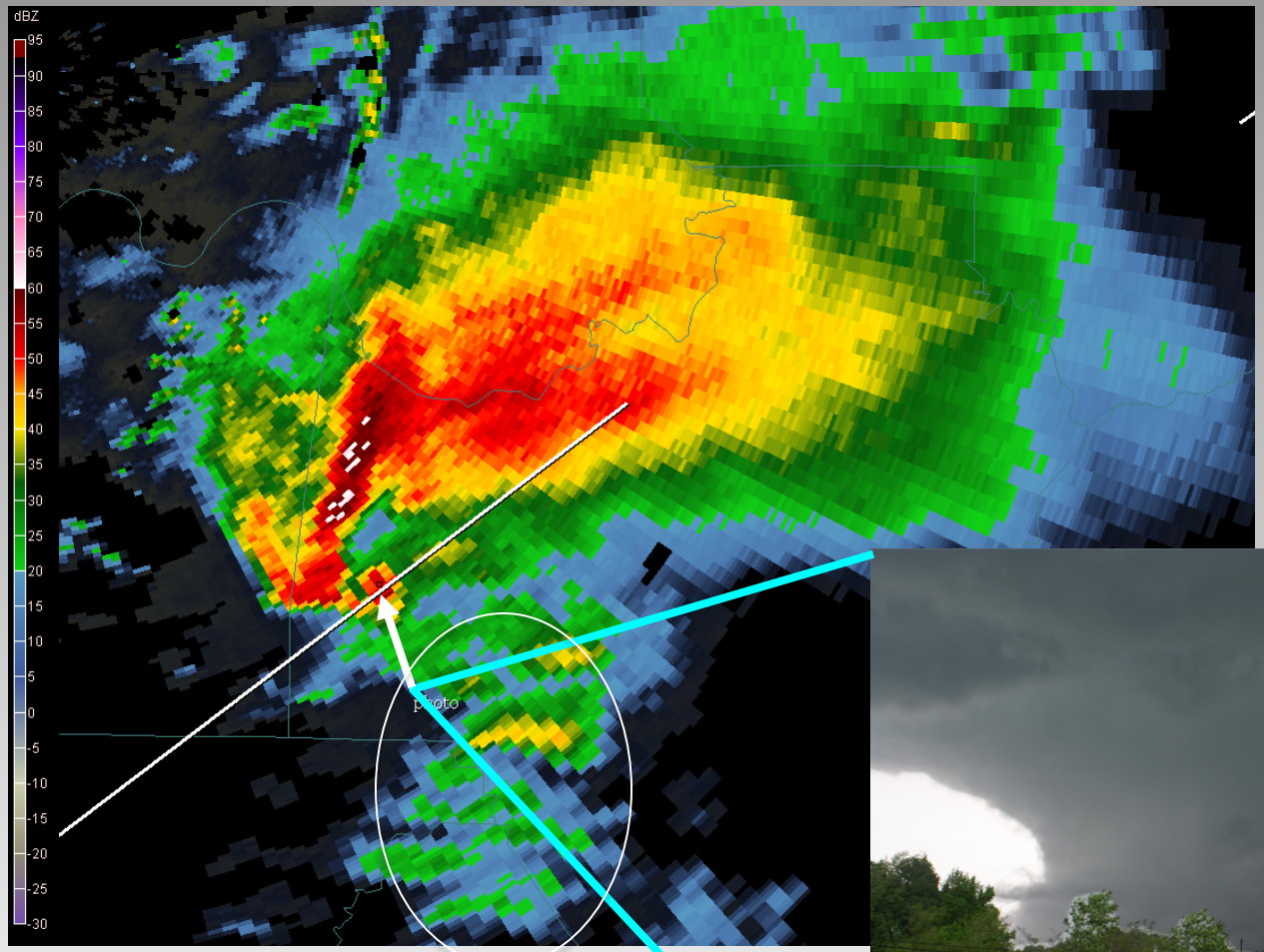
- Why were storms so efficient (90%) in producing tornadoes?
- Why were so many tornadoes long tracked, wide, and intense?
- What mechanisms produced an impressive *mesoscale convective vortex* (MCV) and the flurry of ~16 tornadoes associated with it over Marshall and DeKalb counties?
- Why was debris 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

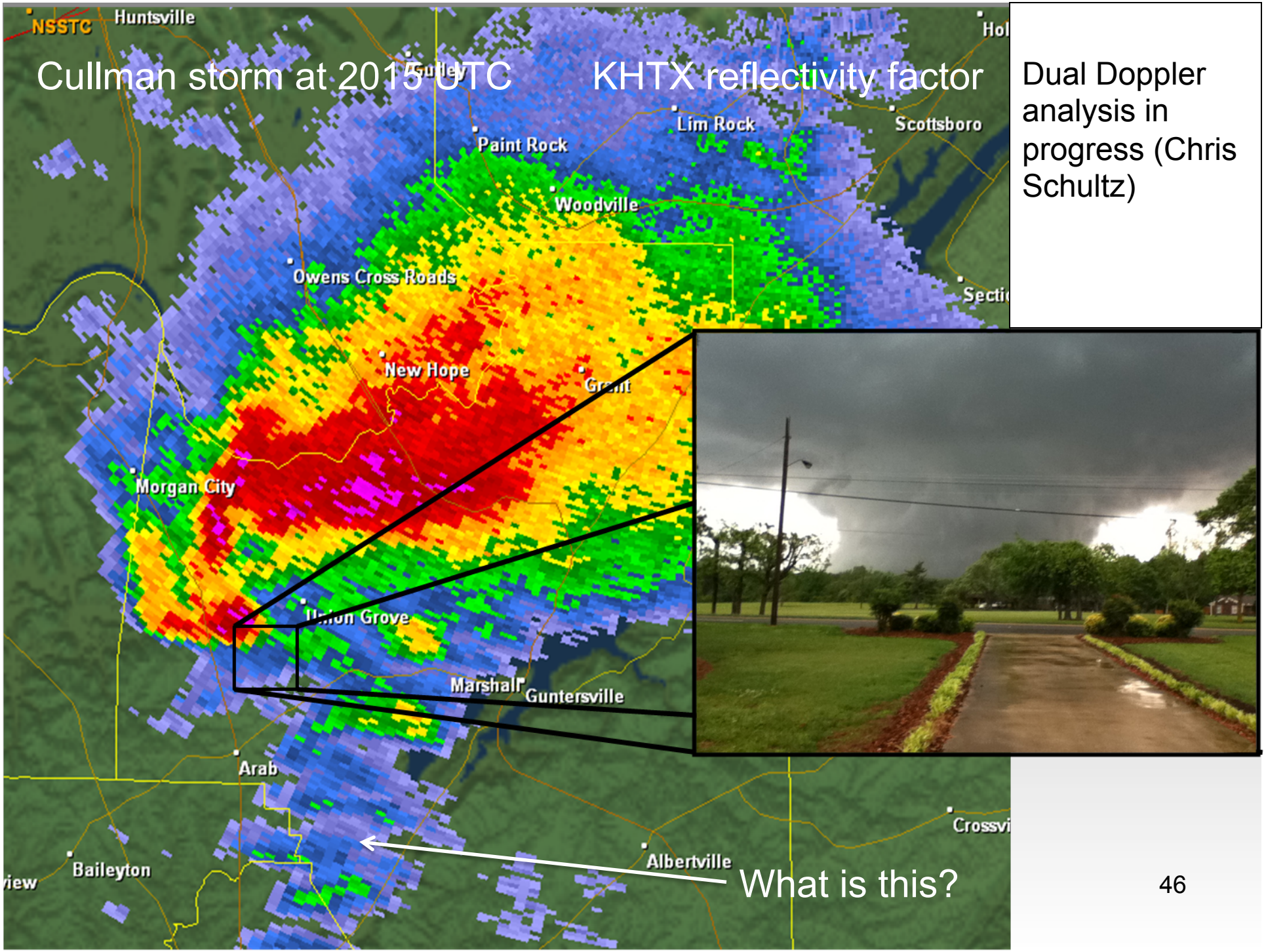
Cullman storm at 2021 UTC



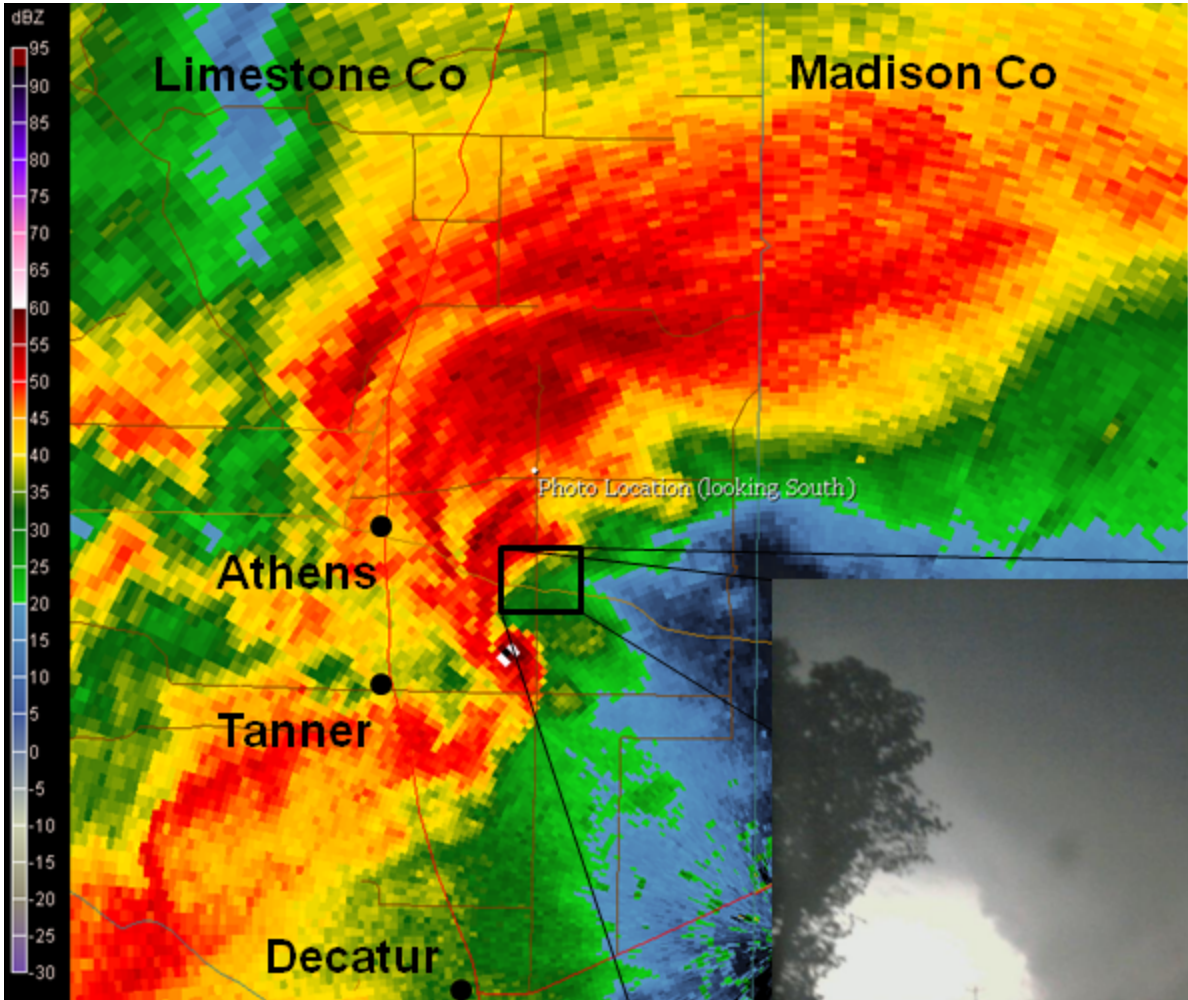
Multiple Doppler (3) radar analyses will be conducted on this storm.

2021 UTC – ARMOR Reflectivity also shows the reflectivity "feed".

Looking NNW



Dual Doppler analysis in progress (Chris Schultz)



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

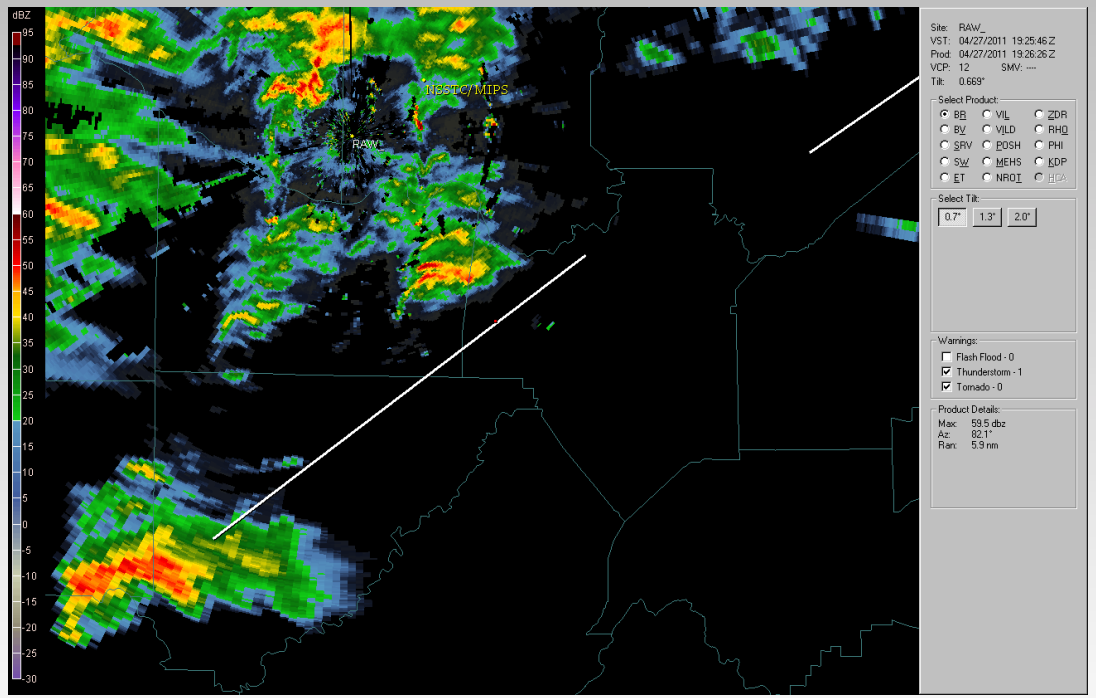
ARMOR Z, 2130 UTC

Debris ball is apparent, also clear ρ_{hv} signature (not shown)

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

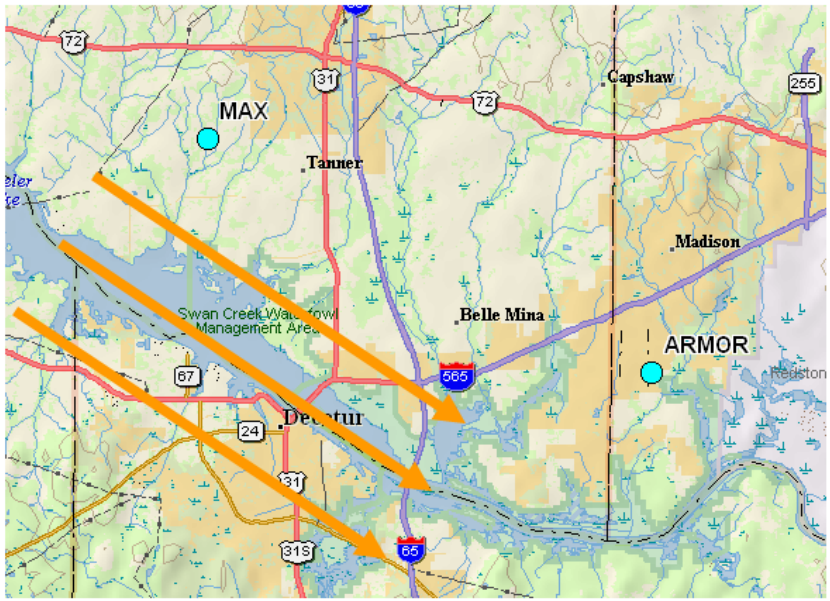


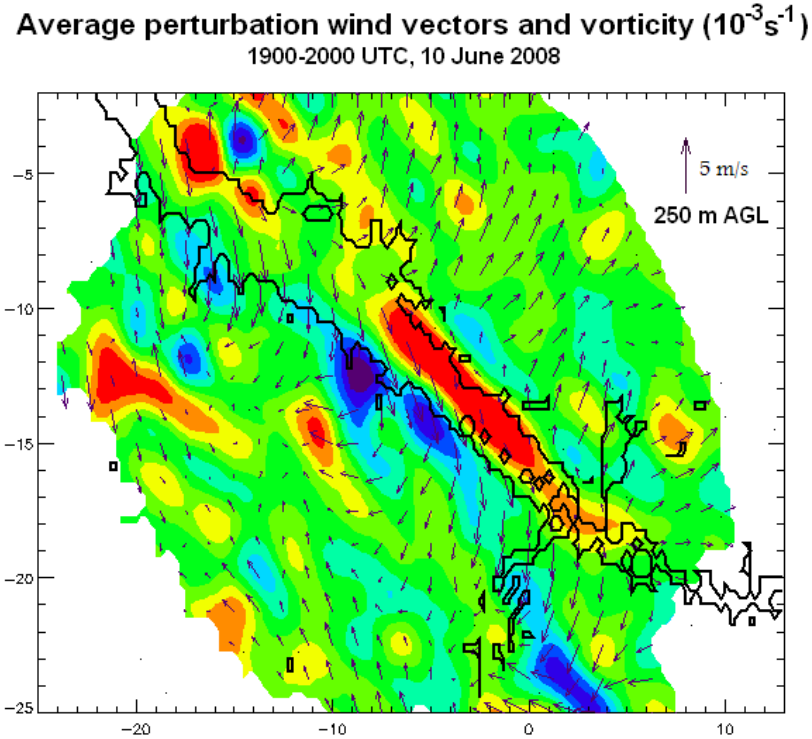
1925 - 2037 UTC – ARMOR Reflectivity

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

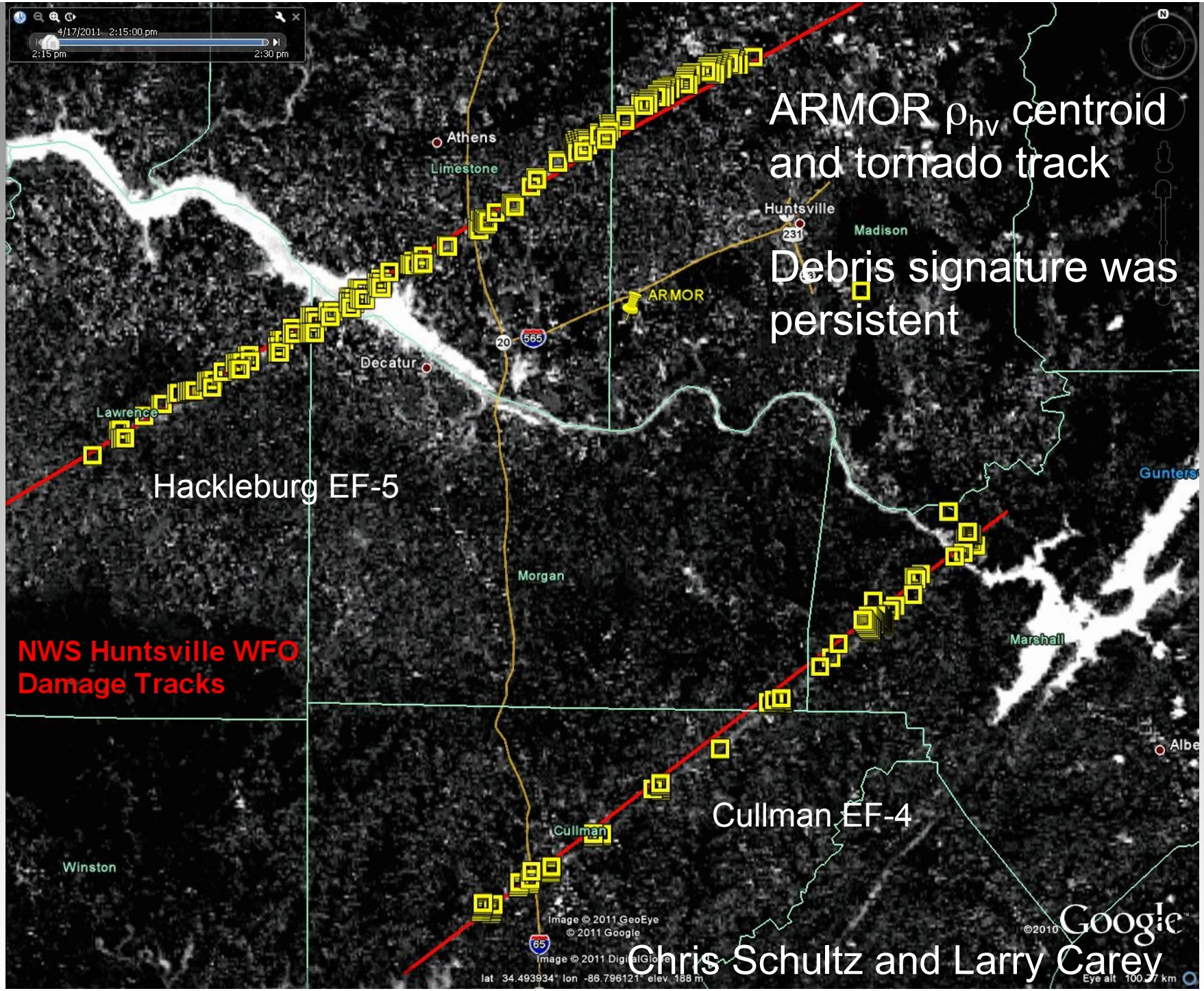




External influences on tornadogenesis:

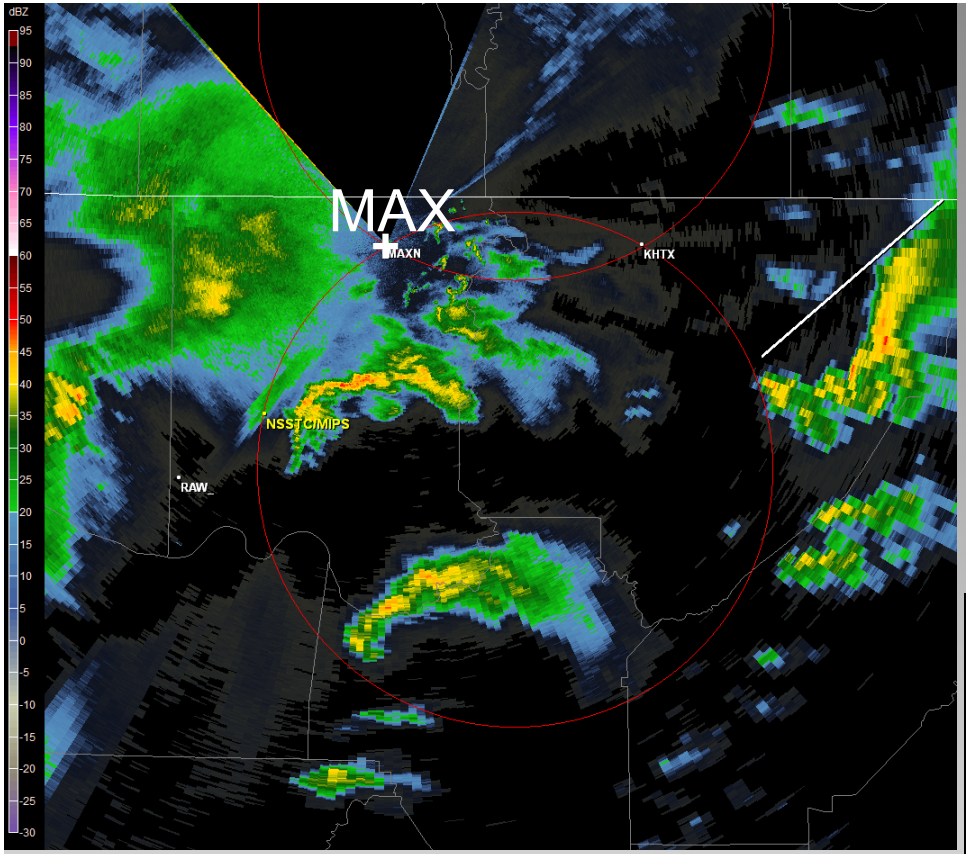
1. Topography was apparently influential in one of the mid-day QLCS tornadoes. More later?
2. Gravity wave interactions may have been prevalent:
   a) Feeder flow into the first Cullman storm tornado. Gravity wave interactions involved in the genesis of the second EF-4 tornado?
   b) Gravity wave interactions 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!


4/17/2011 2:15:00 pm
2:15 pm
2:30 pm
ARMOR ρ_{hv} centroid and tornado track
Debris signature was persistent
Athens
Limestone
Huntsville
Madison
ARMOR
Decatur
Lawrence
Hackleburg EF-5
Morgan
NWS Huntsville WFO Damage Tracks
Marshall
Cullman EF-4
Cullman
Winston
Image © 2011 GeoEye
© 2011 Google
Image © 2011 DigitalGlobe
lat 34.493934° lon -86.796121° elev 188 m
©2010 Google
Chris Schultz and Larry Carey

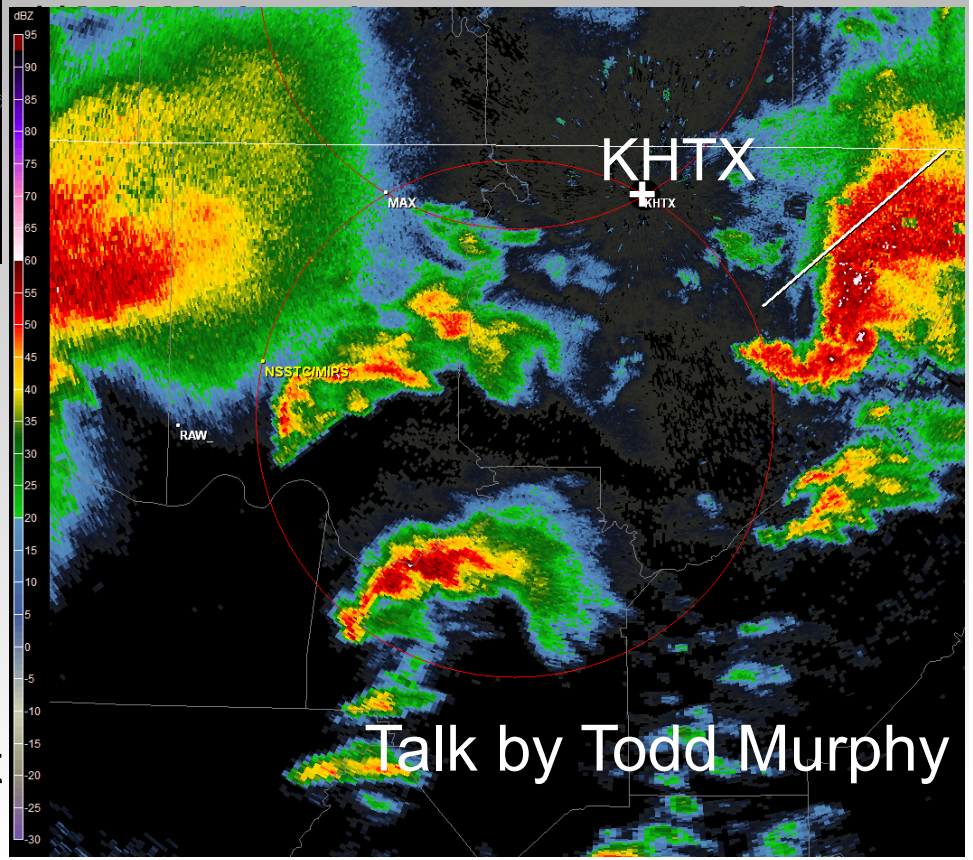
Gravity Wave Interactions?

← 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 signficant tree-covered topography. High-quality aerial images will be valuable in documenting terrain impacts.
  - Terrrain 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.)

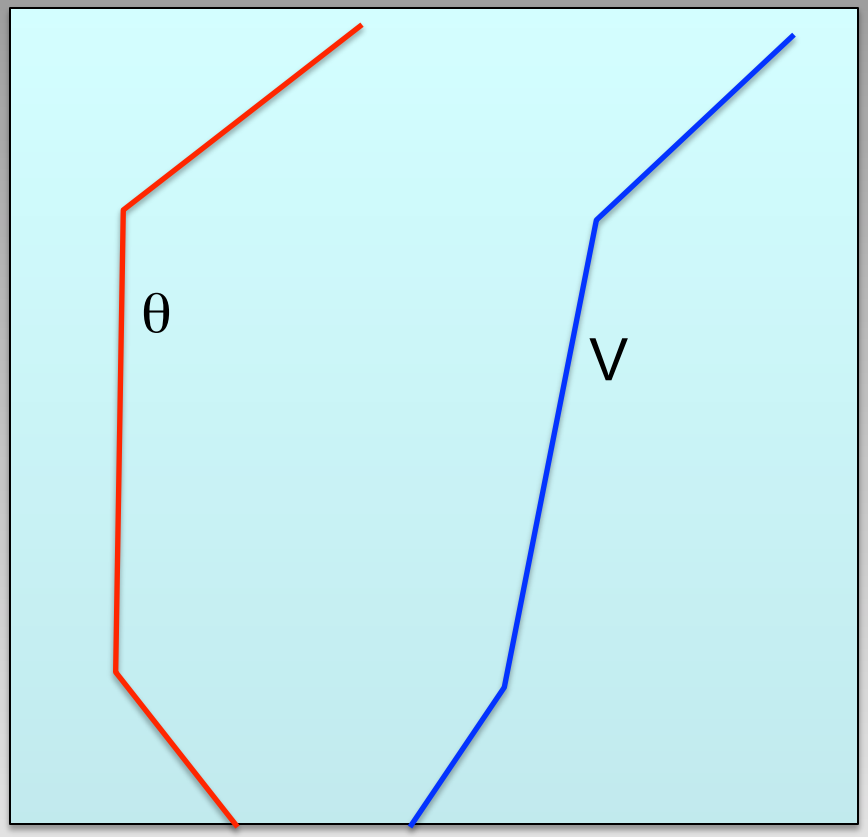
- Dual-polarization and Z debris signatures
  - Abundant opportunity to relate ρ_{hv} to debris type by comparing with aerial images
  - Papers already submitted
- *Detailed analysis of a large MCV and its influence in tornadogenesis*
  - High quality dual Doppler analysis of a large MCV with banded structures

Acknowledgement: This research is supported by the National Science Foundation under the RAPID program

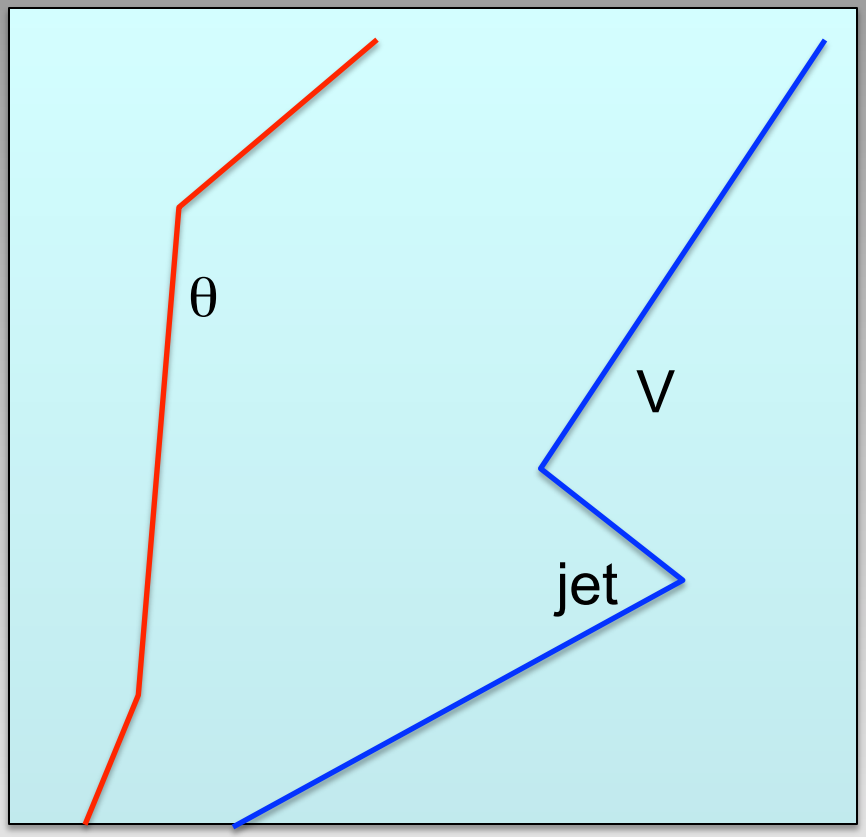
- **Boundary layer** influences on tornadoes

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:

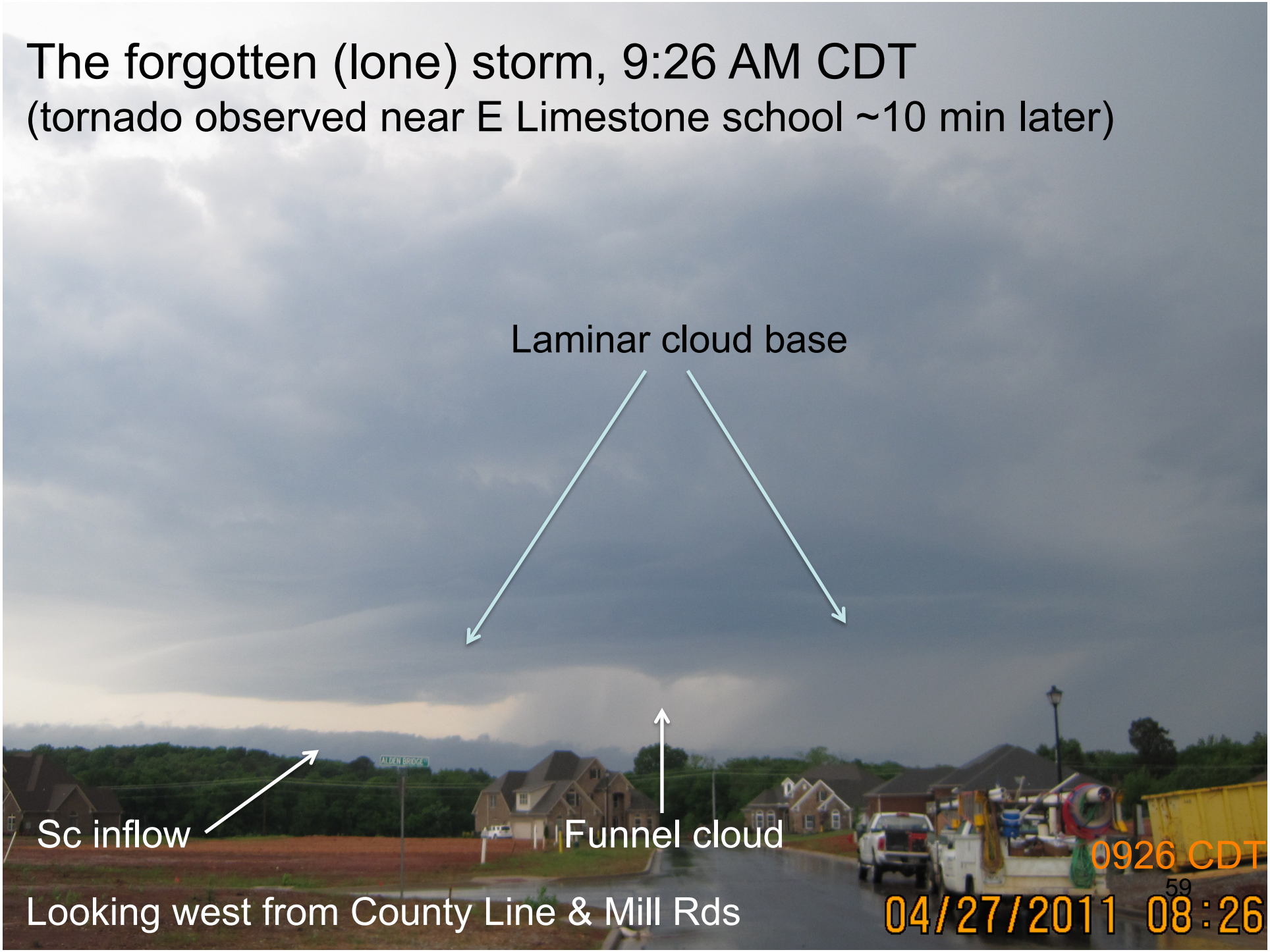
http://www.facebook.com/UAHsevereweather

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