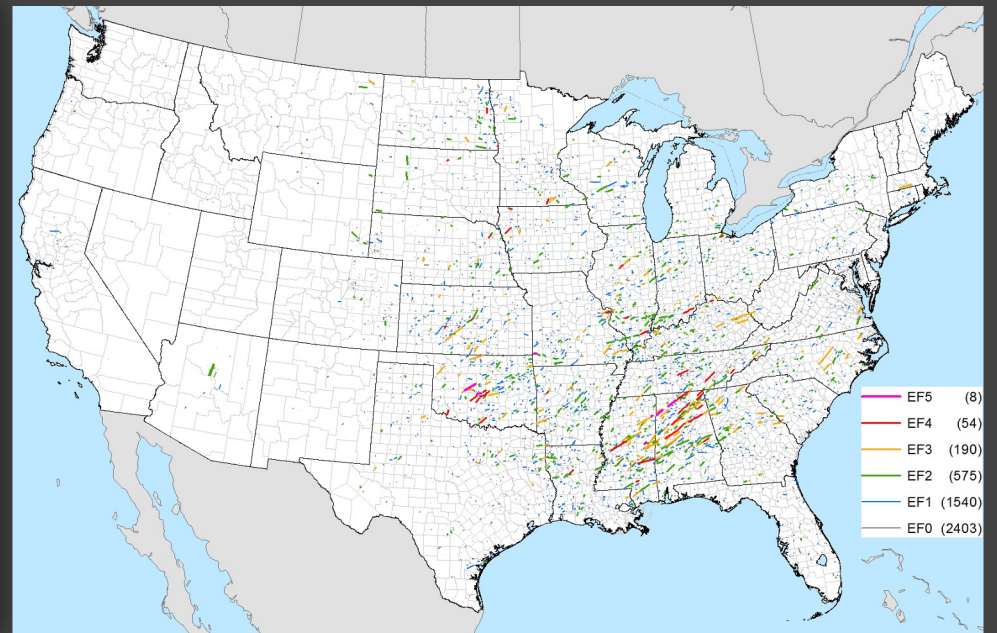
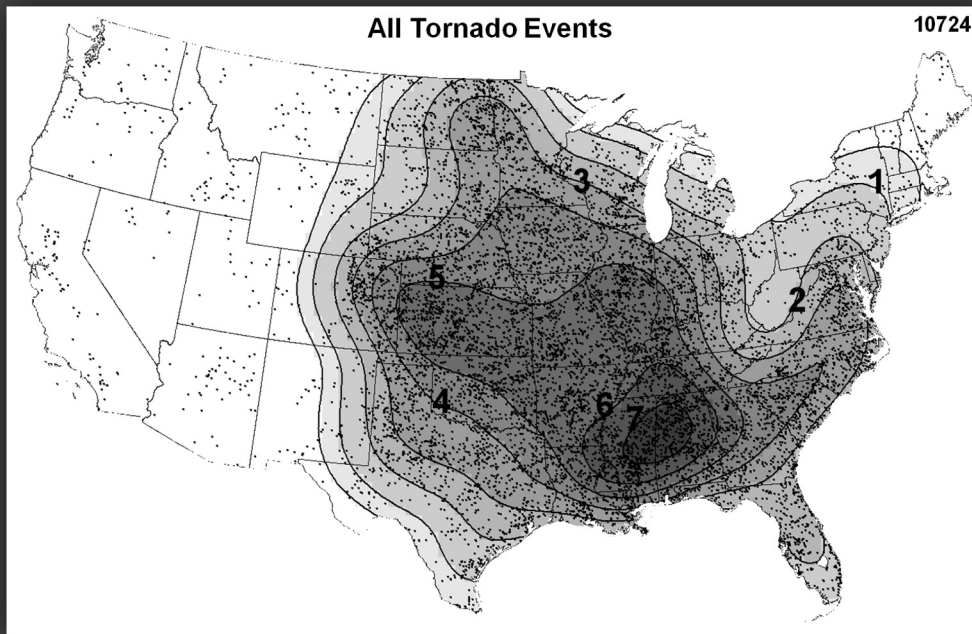


# Tornado Climatology



# Climatology: Why Should We Care?

I'm here to learn about tornadoes!

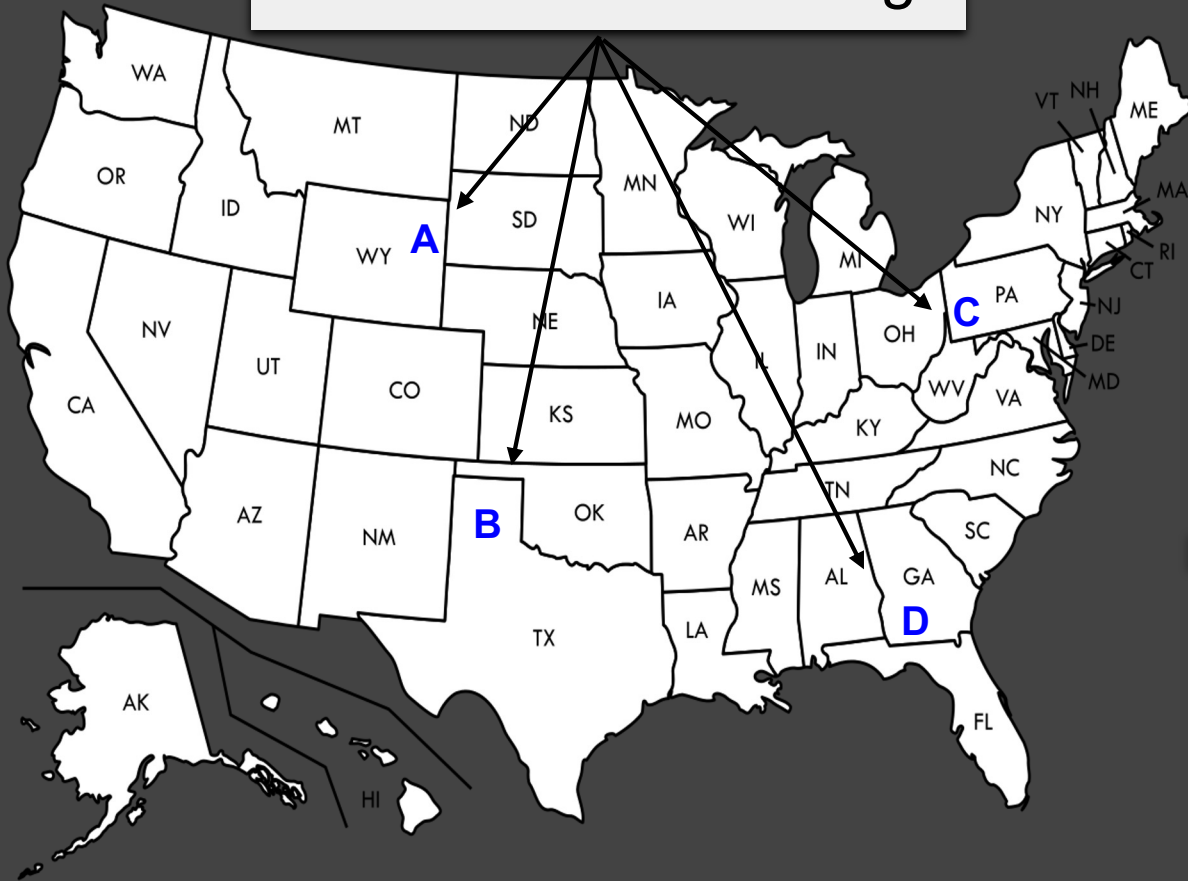
What do I care about climatology?!



Being aware of severe weather climatology helps us establish a baseline of what's "normal".

In turn, this allows us to identify  
anomalous environments  
(whether anomalously low or high).

MLCAPE = 2000 J/kg

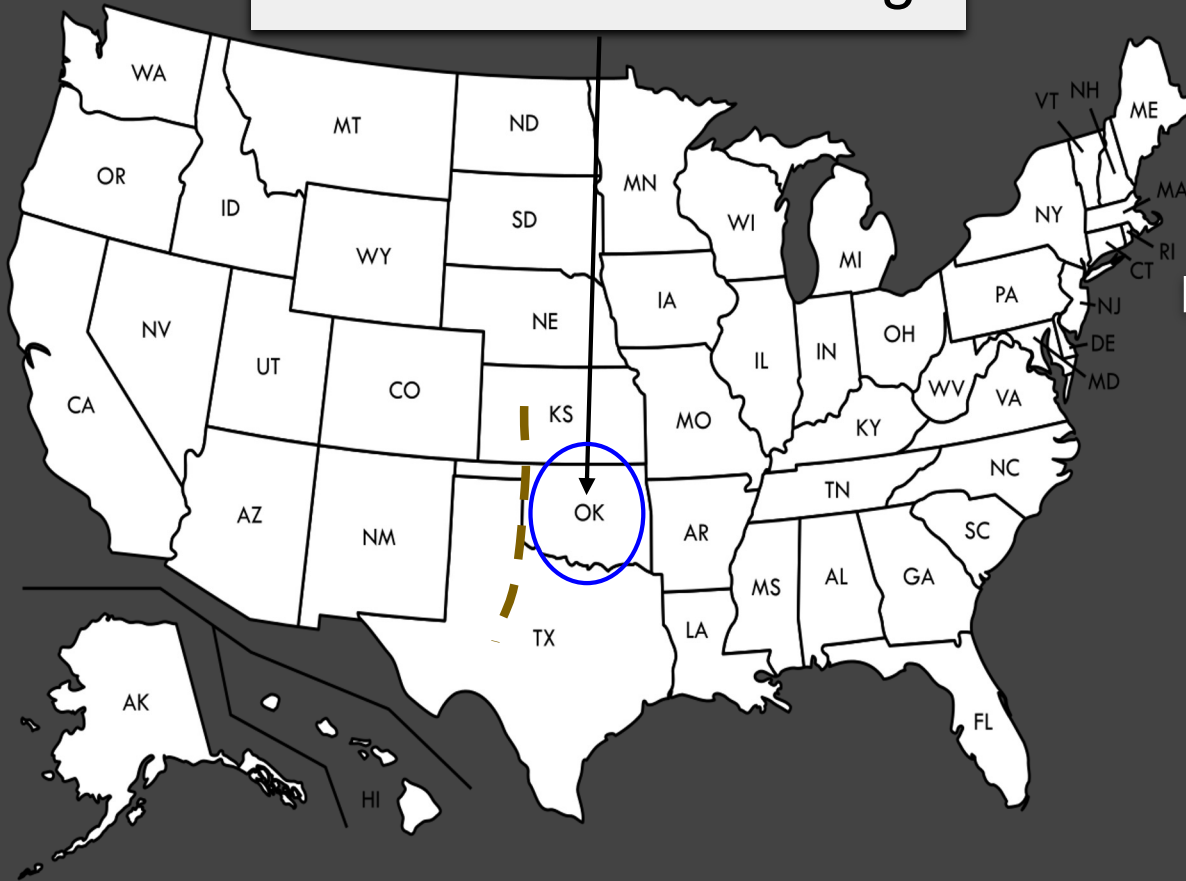


MLCAPE of 2000 J/kg is most common for which location?

Is it common for this time of year?

Is it common for environments associated with tornadoes?

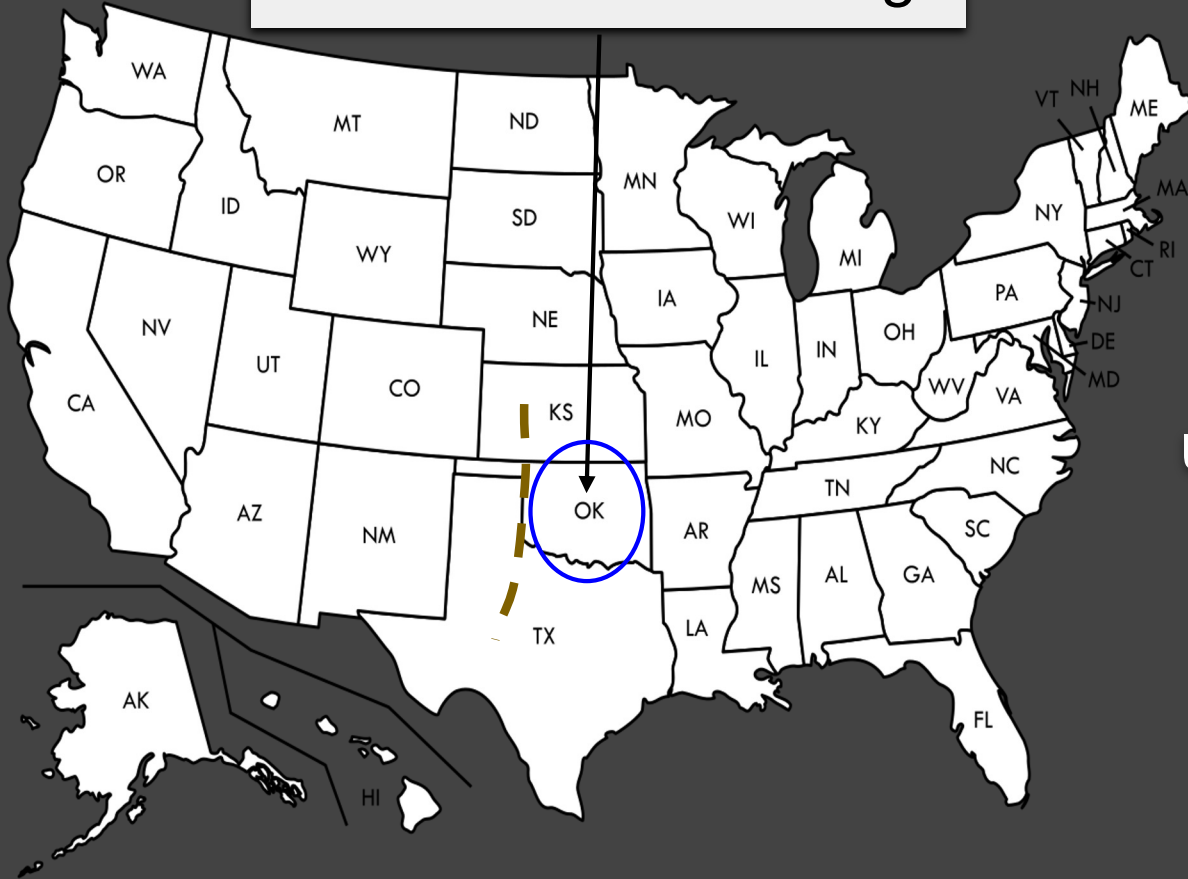
MLCAPE = 3000 J/kg



It's mid-May with an MLCAPE of 3000 J/kg and a dryline across western OK.

Is this a higher than normal risk for severe thunderstorms?

MLCAPE = 3000 J/kg



Understanding climatology can help answer these questions!

# Tornado Climatology

- Work done by SPC forecasters to identify tornado/ingredient climatologies
  - Smith et al. 2012 (Weather and Forecasting)
  - Thompson et al. 2012 (Weather and Forecasting)
  - Grams et al. 2012 (Weather and Forecasting)
- Looked at ~10,000 tornado cases
  - Period: 2003-2011
  - Considered Supercell EF-2+ and QLCS EF-1+
- Assigned storm mode based on WSR-88D data
  - Ex: discrete supercell, QLCS, cluster supercell, etc...
- Collected SPC Mesoanalysis data for each instance at the nearest grid point
- Created plots of tornado events and ingredients based on:
  - Seasonal (spring, summer, fall, winter)
  - Convective mode

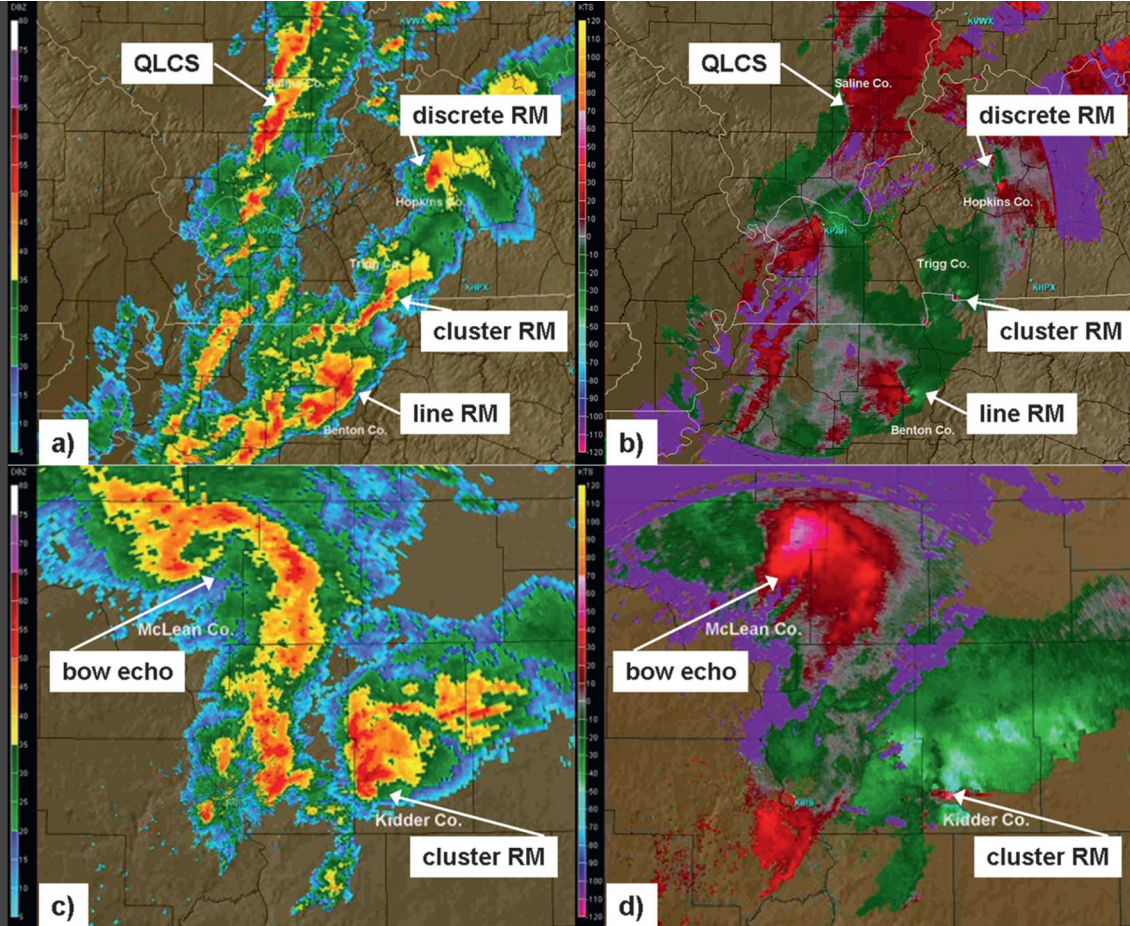
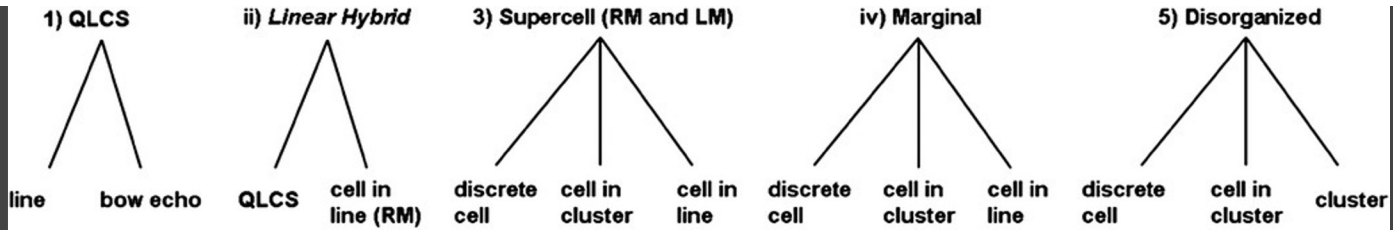


Fig 2. Smith et al. 2012

Fig 3. Smith et al. 2012

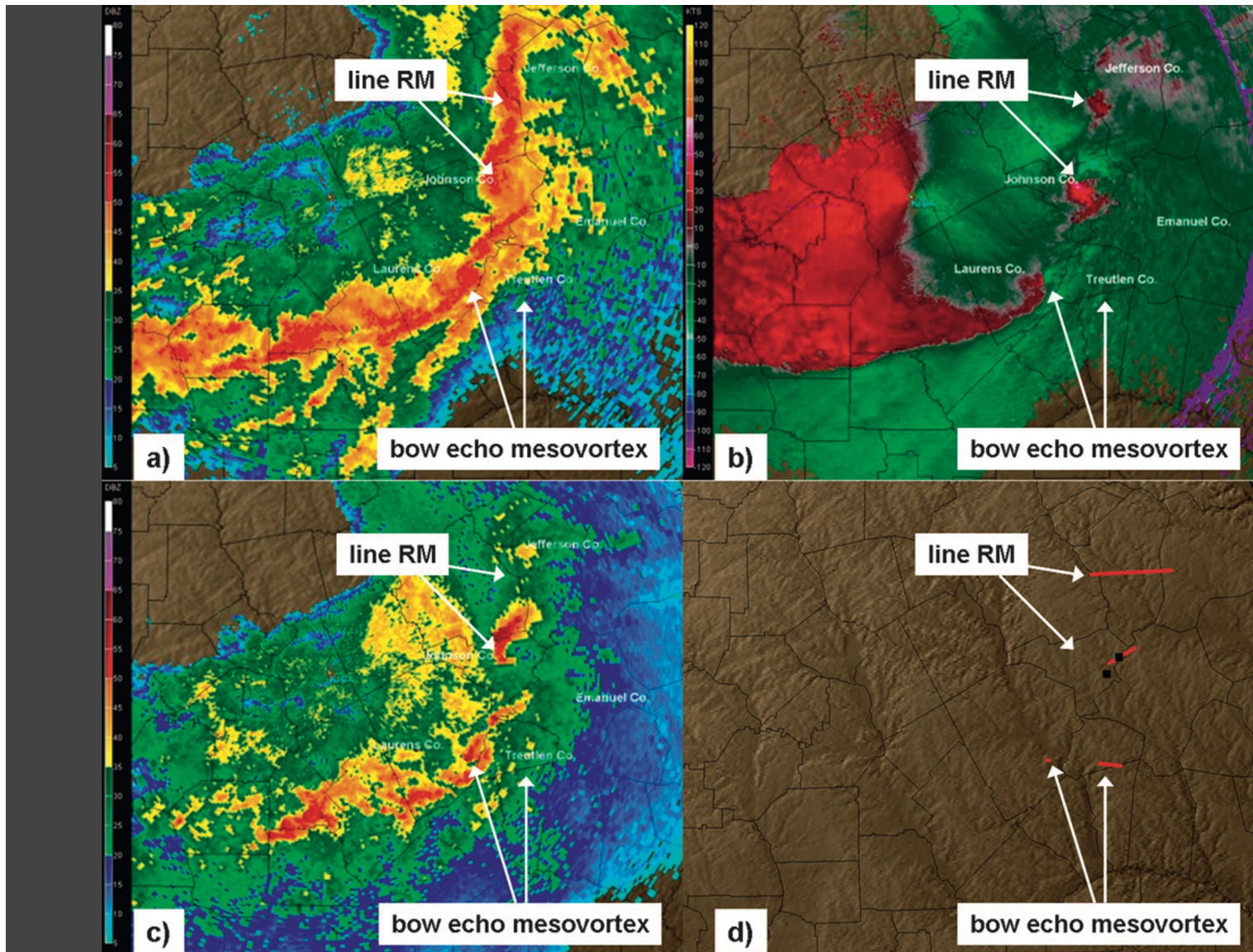
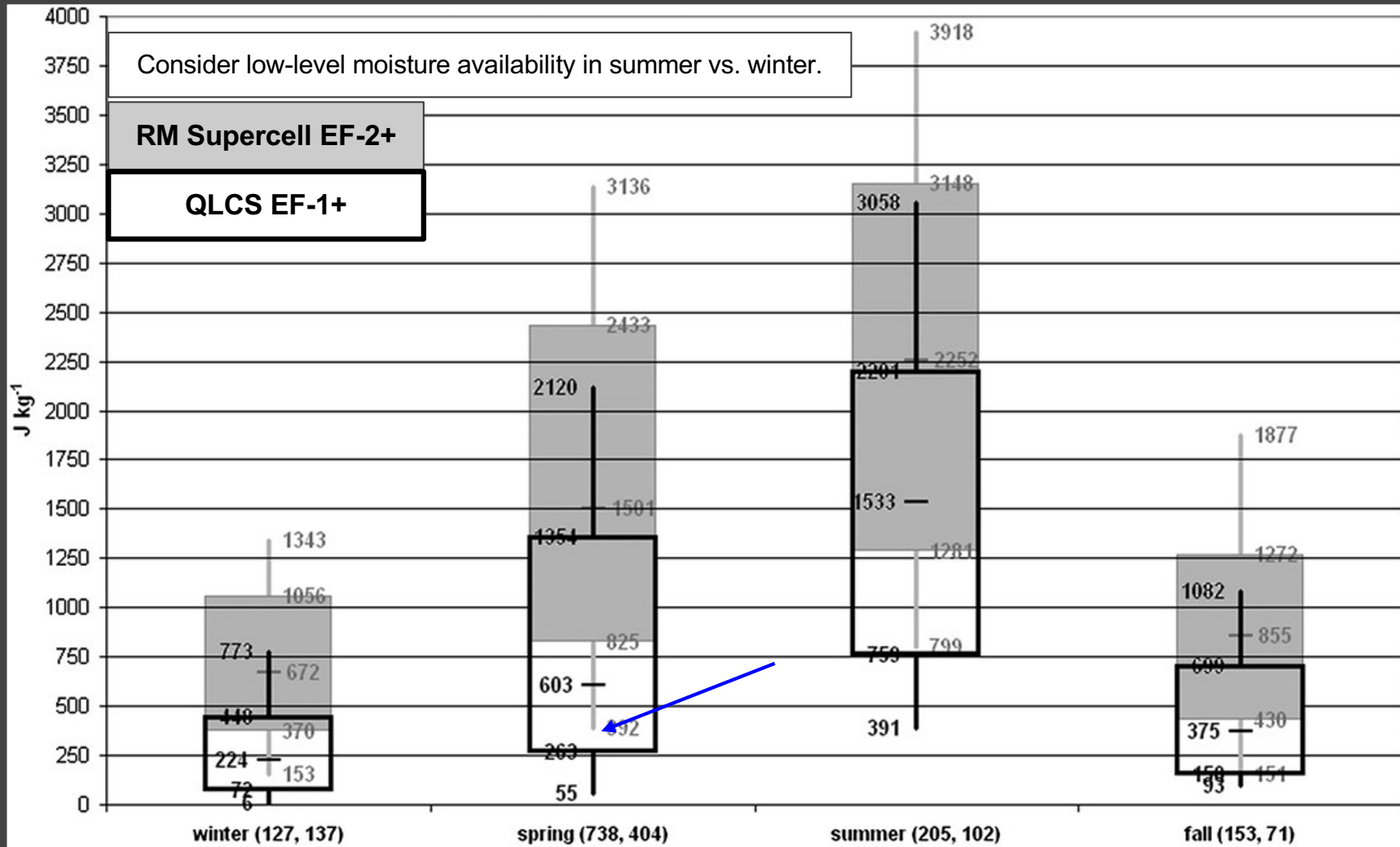


Fig 4. Smith et al. 2012

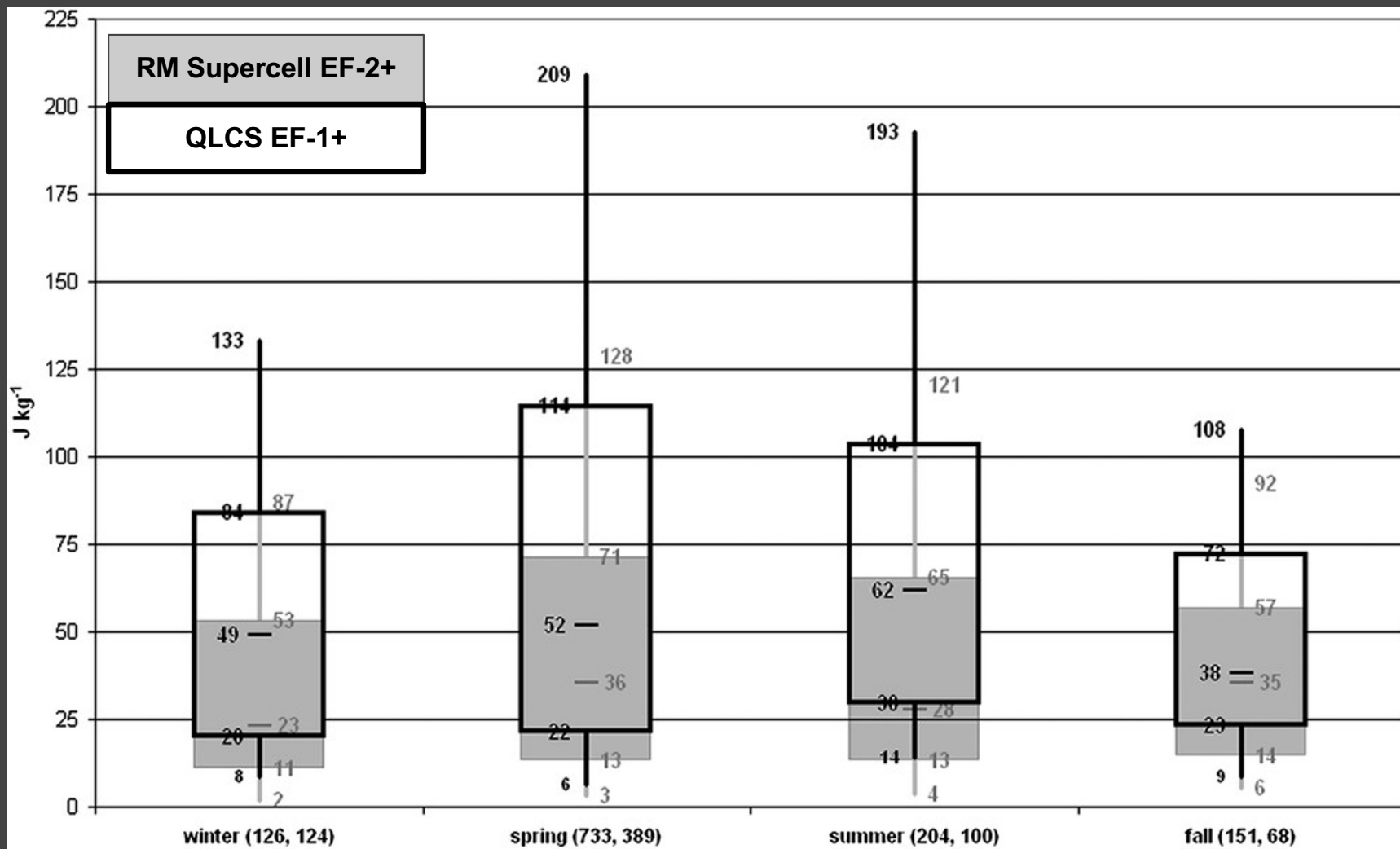
# Ingredient Climatology

- Considered tornado environments for right-moving supercell and QLCS tornado events
- Considered seasonal variations in:
  - MLCAPE
  - MLCIN
  - Effective BWD
  - Effective SRH
  - MLLCL
  - STP

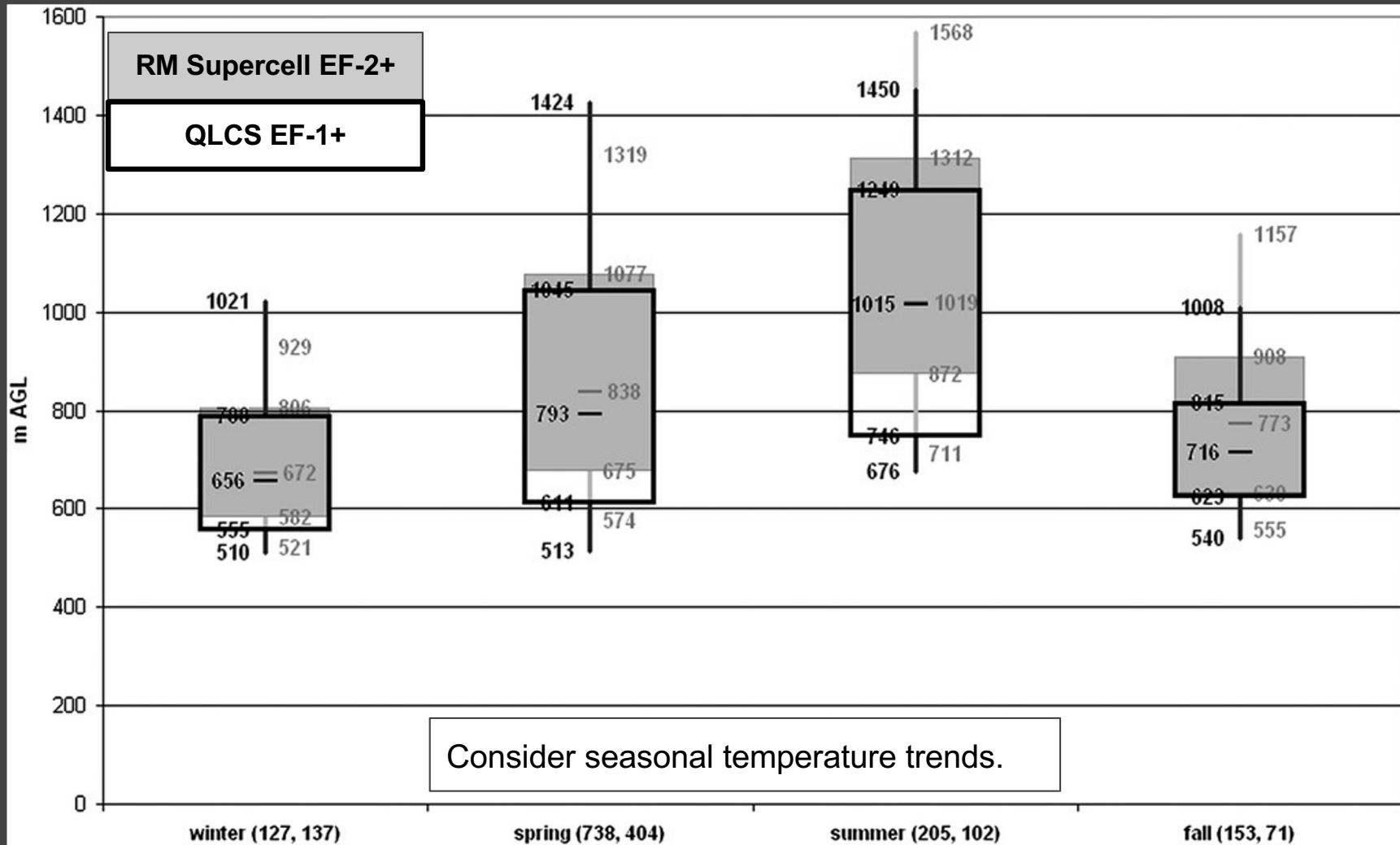
# MLCAPE



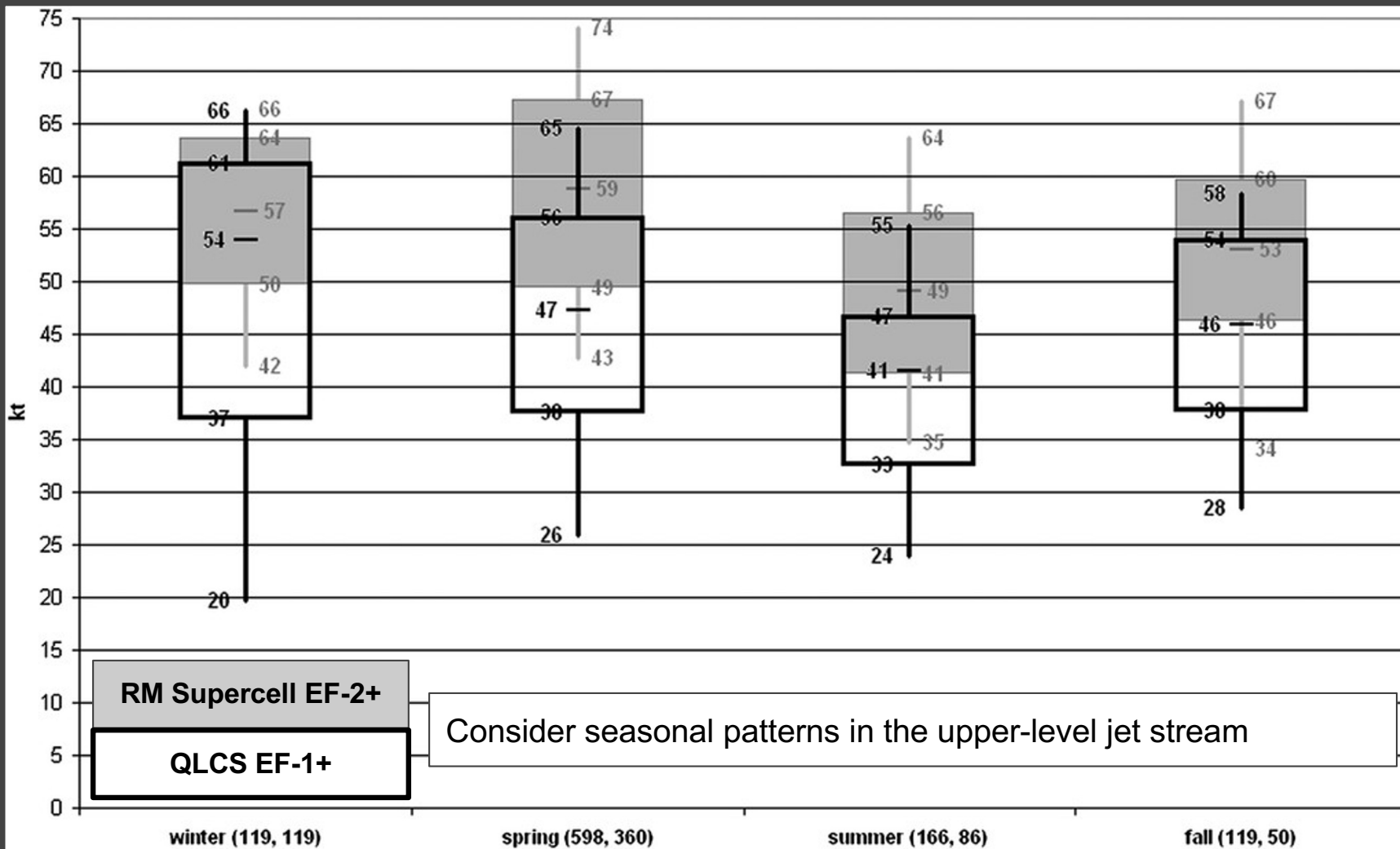
# MLCIN



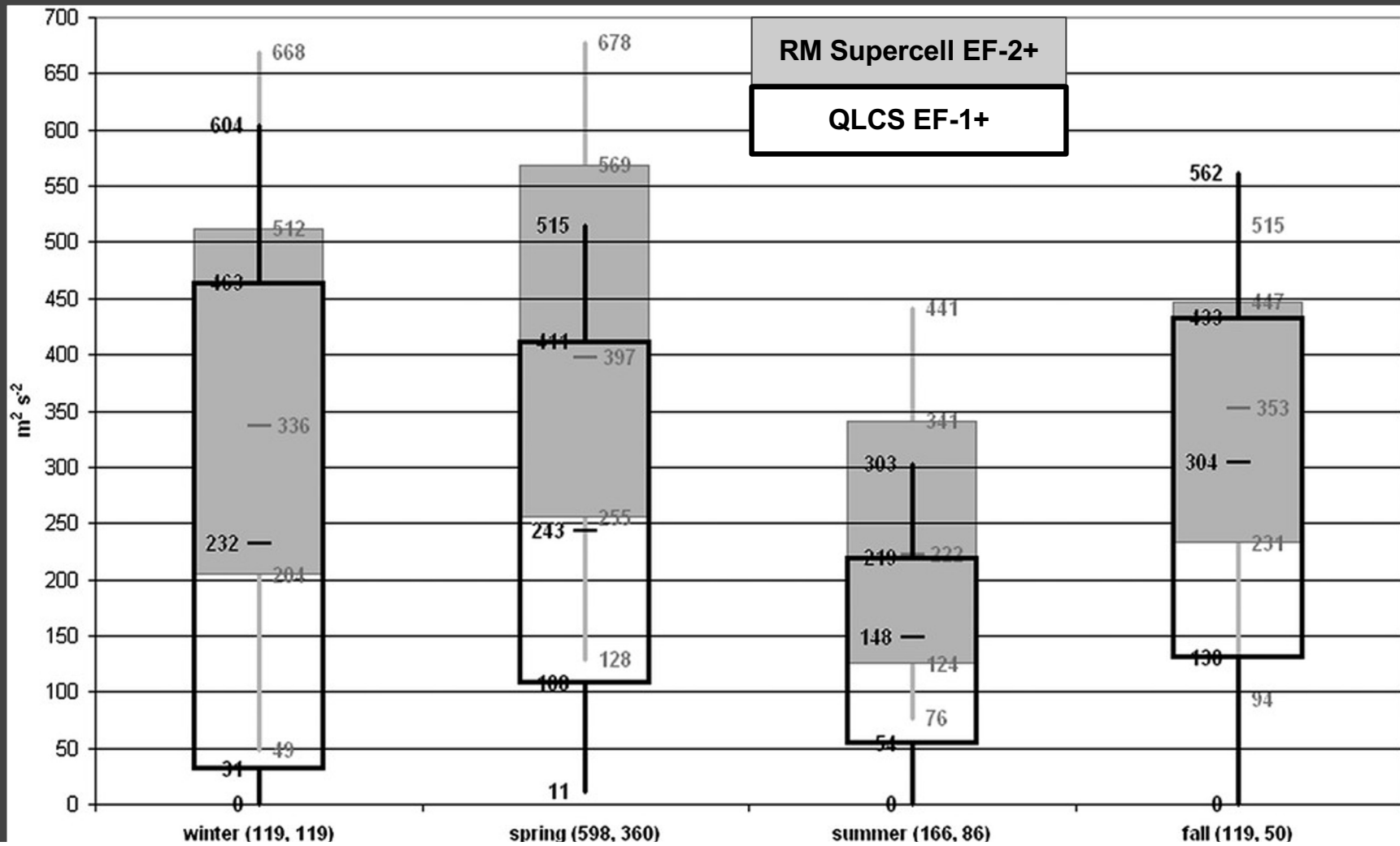
# MLLCL



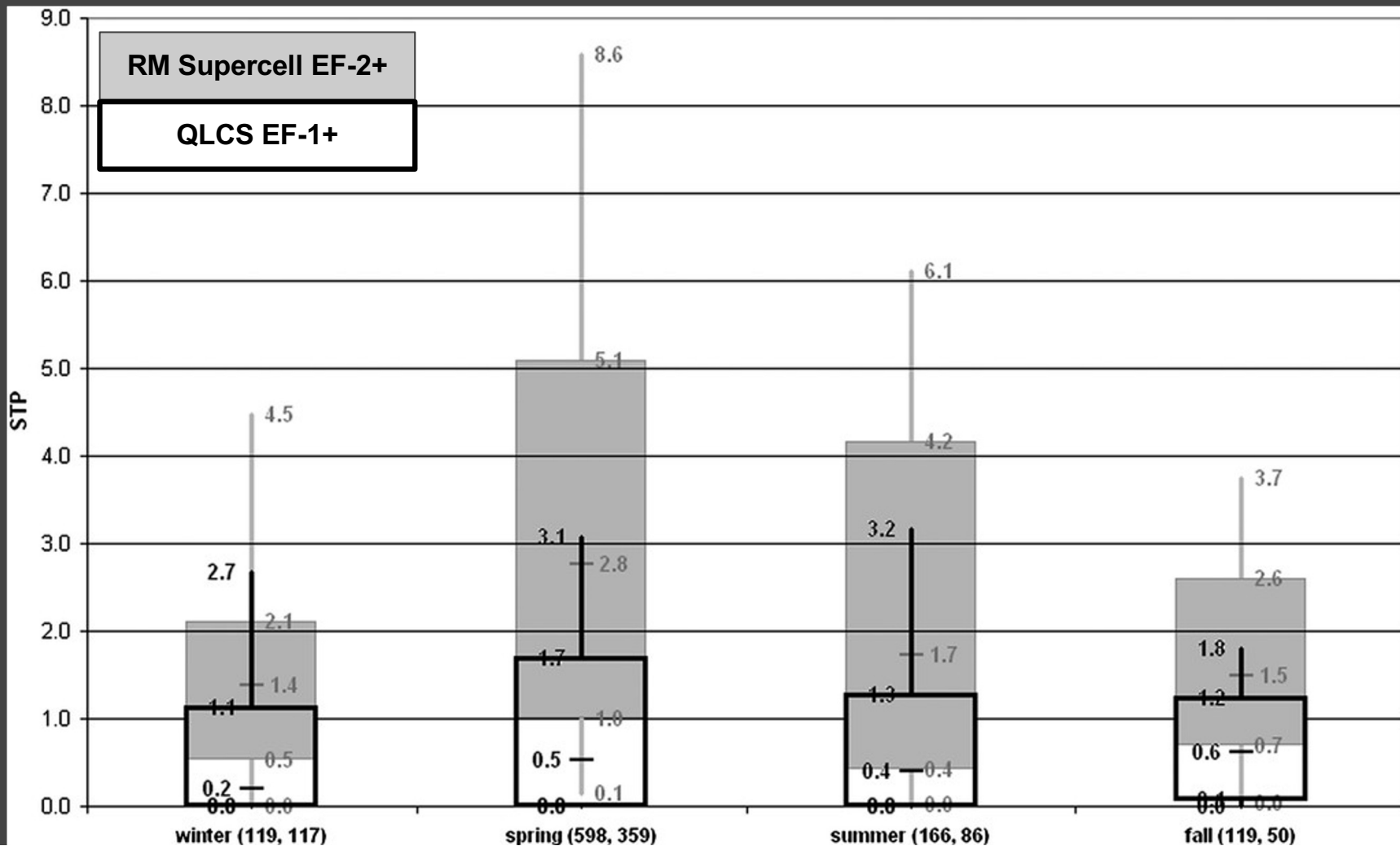
# Eff. Bulk Wind Difference



# Eff. SRH



# Eff. STP



# MLCAPE (J/kg)

QLCS

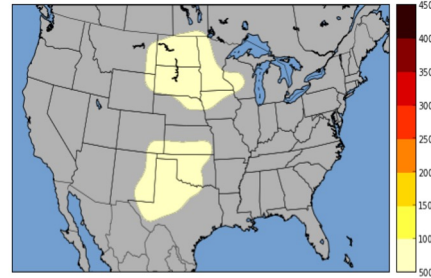
RM Supercell

10th

10% of Environments

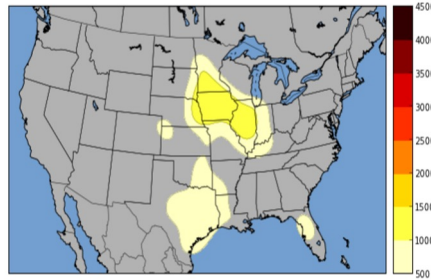


10% of Environments

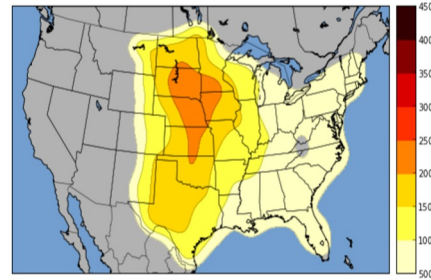


50th

50% of Environments

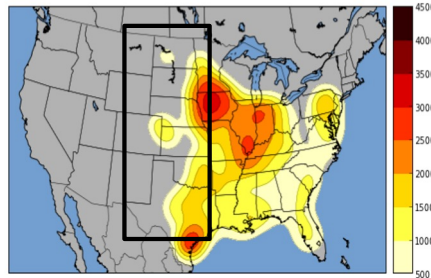


50% of Environments

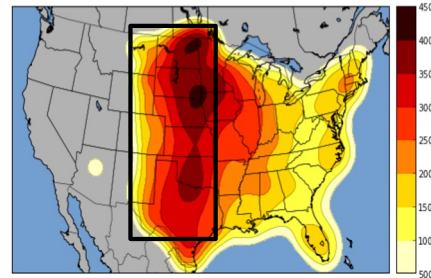


90th

90% of Environments



90% of Environments



\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

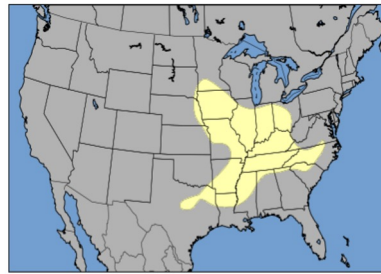
# MLLCL (m)

QLCS

RM Supercell

10th

10% of Environments

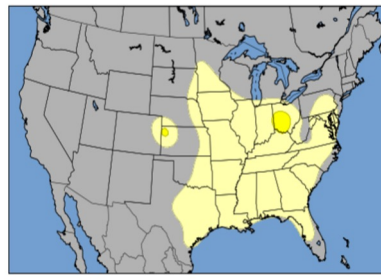


10% of Environments

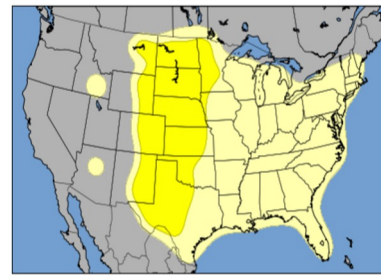


50th

50% of Environments

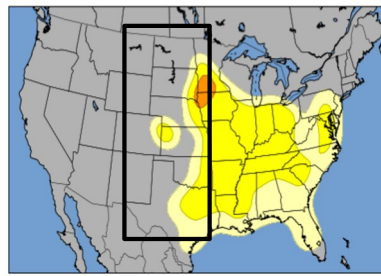


50% of Environments

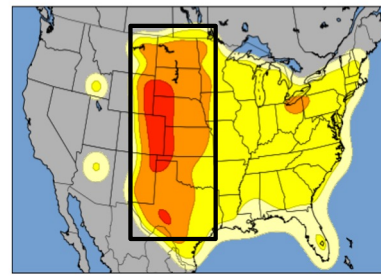


90th

90% of Environments



90% of Environments



\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

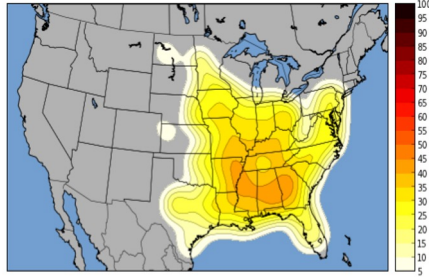
# 0-6 km Bulk Wind Difference (kt)

QLCS

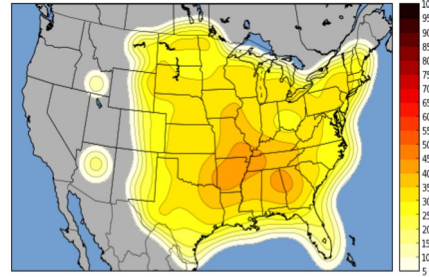
RM Supercell

10th

10% of Environments

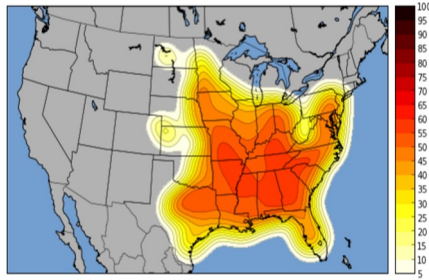


10% of Environments

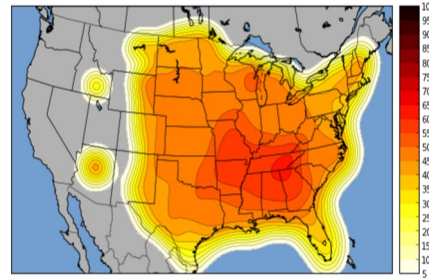


50th

50% of Environments

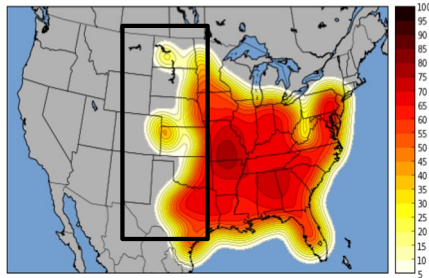


50% of Environments

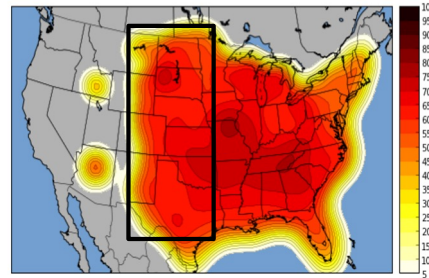


90th

90% of Environments



90% of Environments



\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

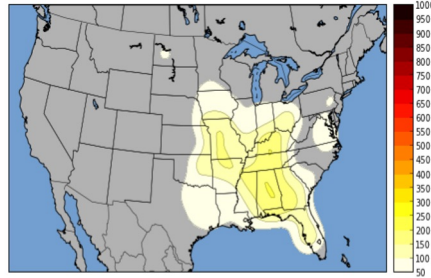
# 0-1 km SRH (m2/s2)

QLCS

RM Supercell

10th

10% of Environments

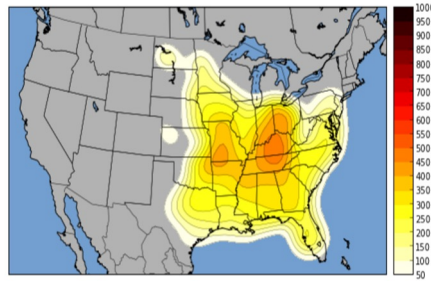


10% of Environments

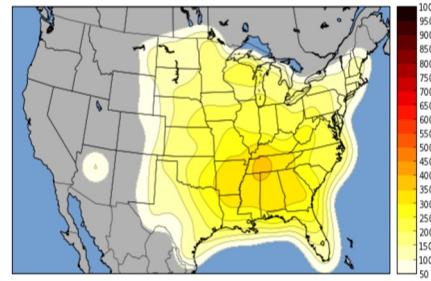


50th

50% of Environments

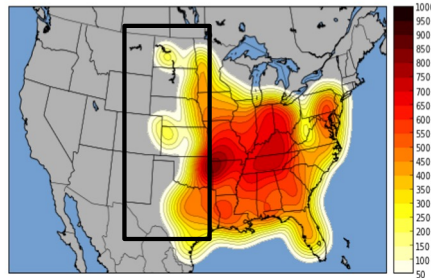


50% of Environments

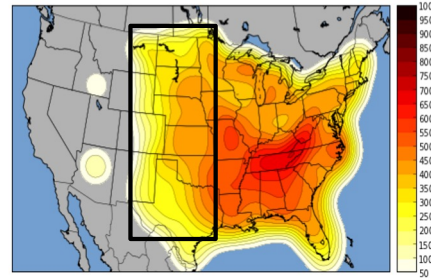


90th

90% of Environments



90% of Environments



\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

# Fixed-Layer STP

QLCS

RM Supercell

10th

10% of Environments

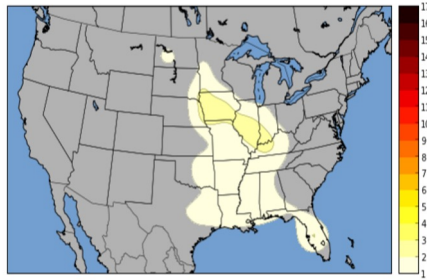


10% of Environments

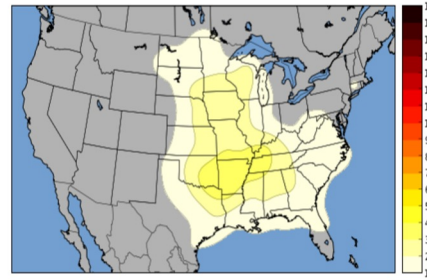


50th

50% of Environments

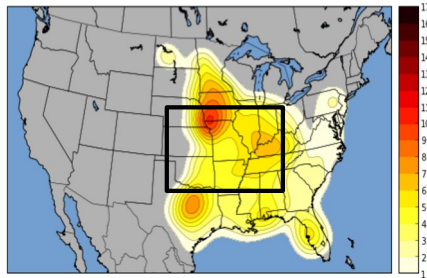


50% of Environments

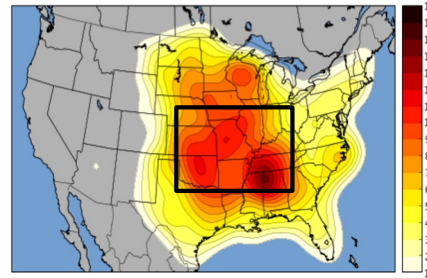


90th

90% of Environments



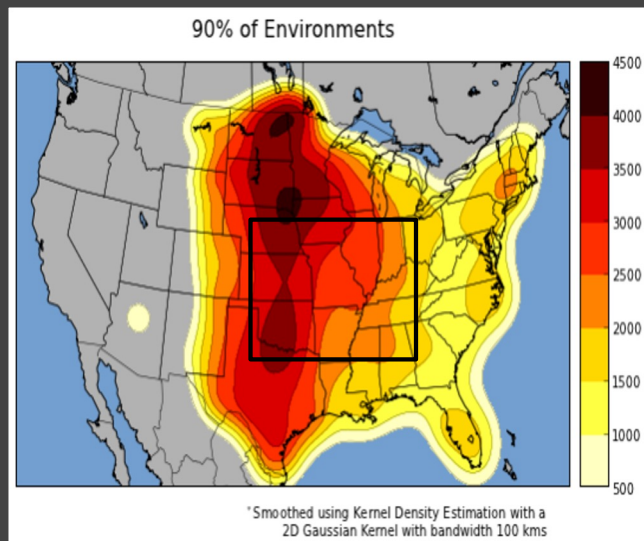
90% of Environments



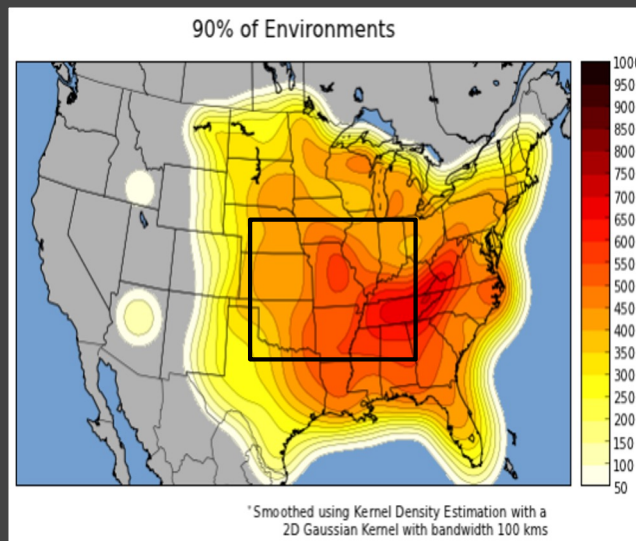
\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

\*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 100 kms

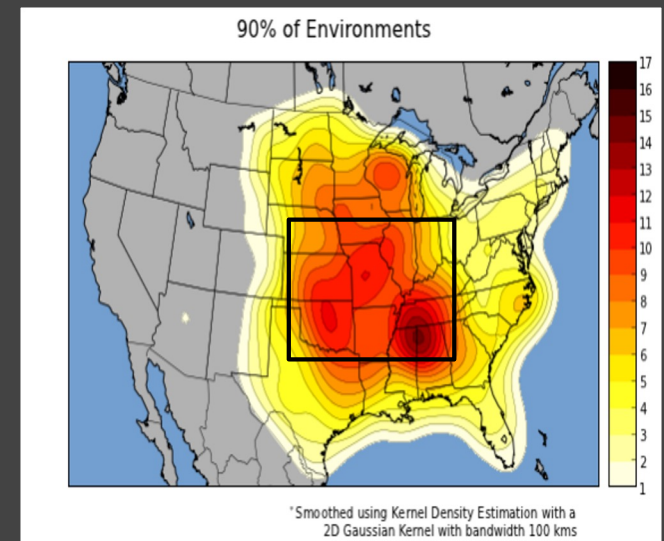
# STP distribution is largely driven by the overlap in MLCAPE and 0-1 km SRH



Supercell MLCAPE

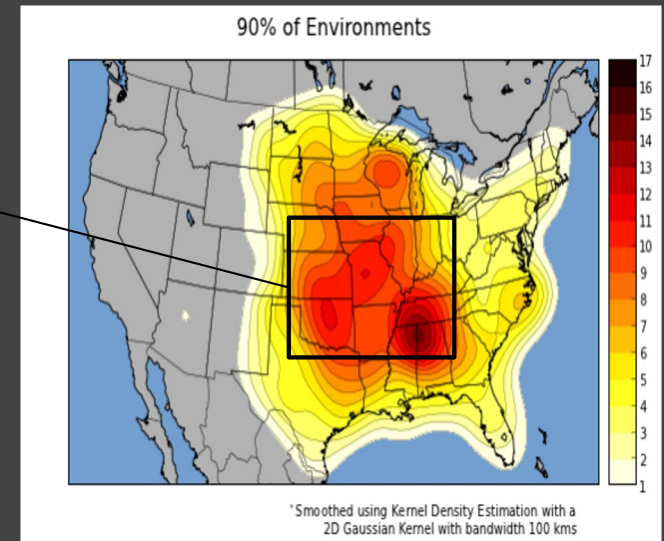
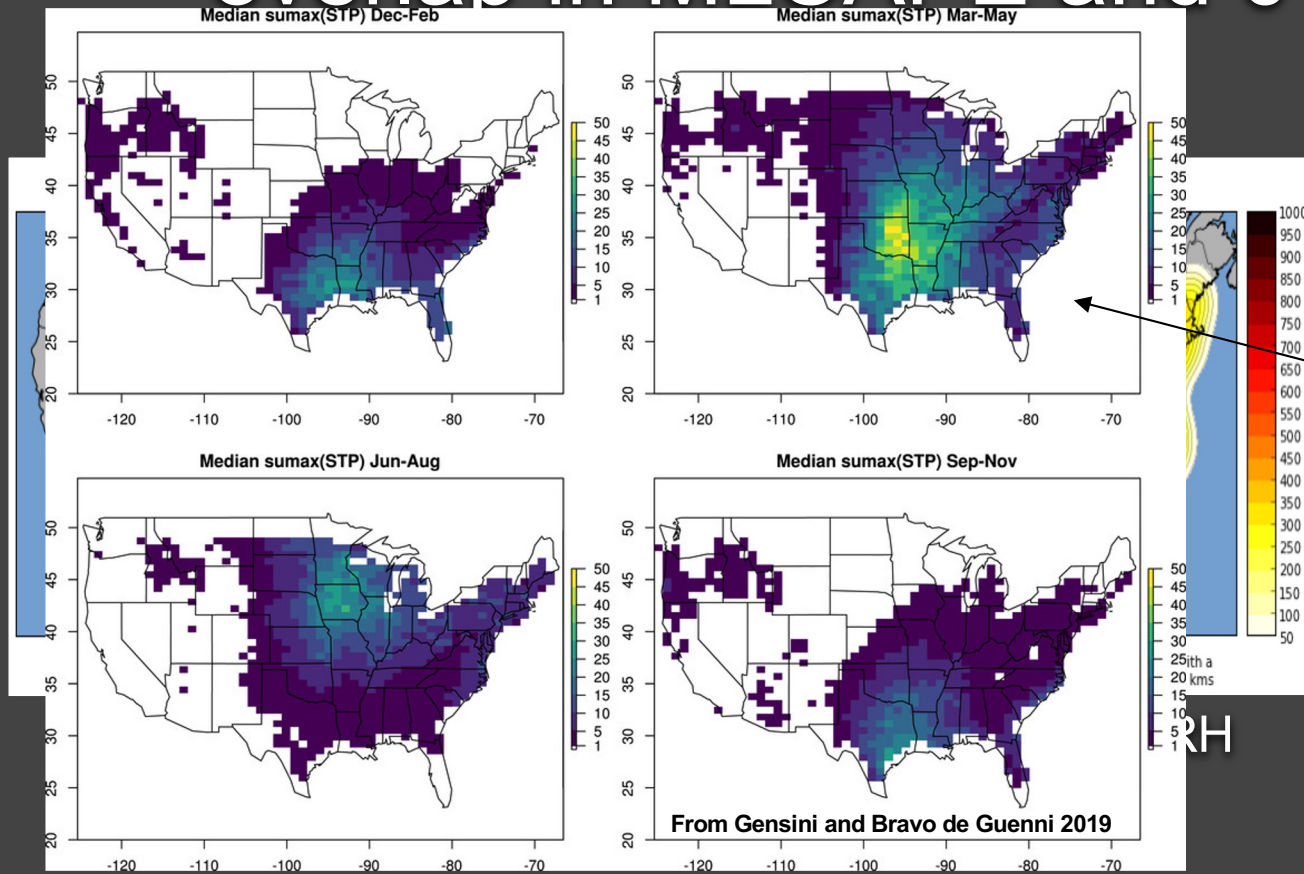


Supercell 0-1 km SRH



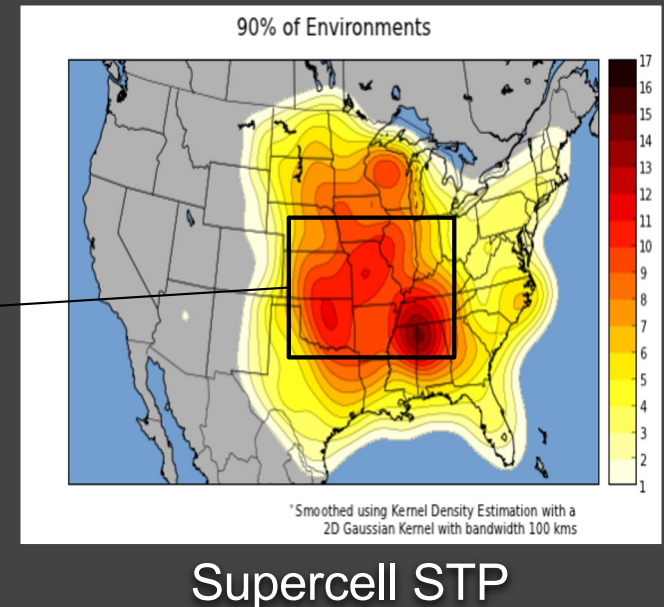
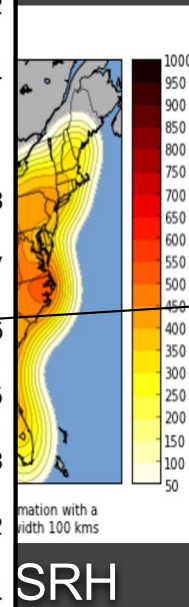
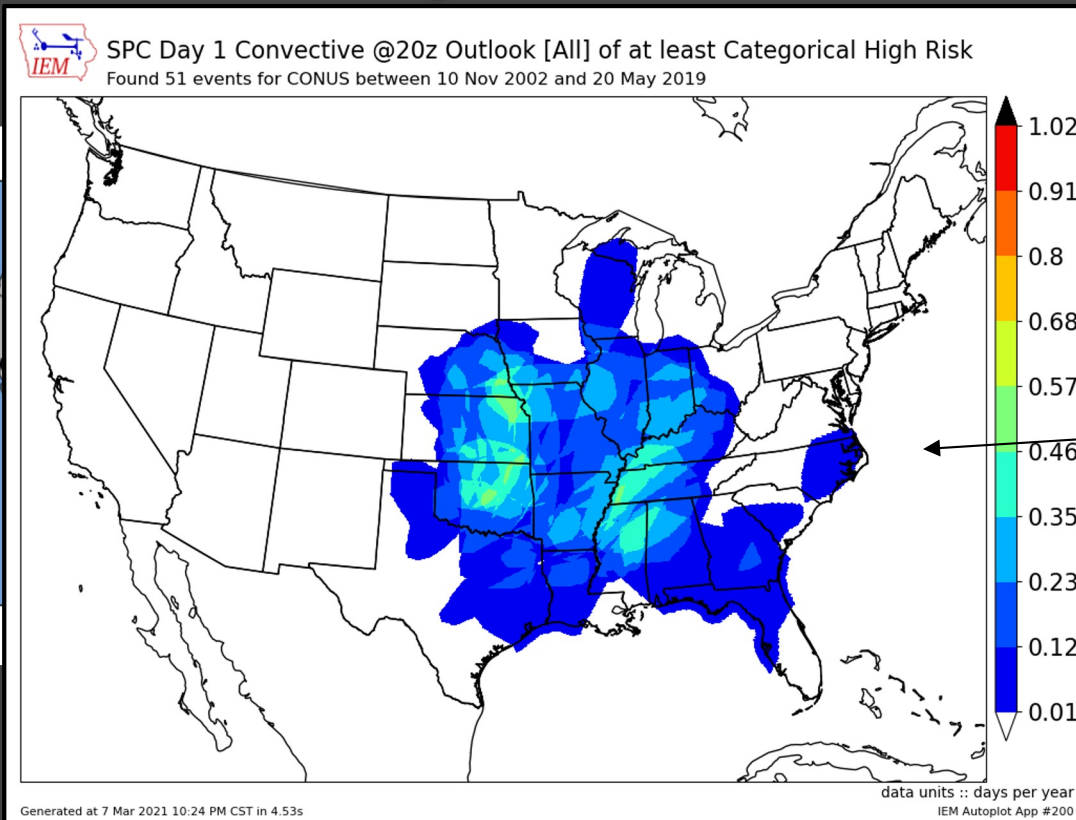
Supercell STP

# STP distribution is largely driven by the overlap in MLCAPE and 0-1 km SRH



Supercell STP

# STP distribution is largely driven by the overlap in MLCAPE and 0-1 km SRH



# Ingredients Summary

- Clear regional and seasonal variations in tornado ingredients
  - Seasonal variations are physically tied to other seasonal trends (ex: temp)
- Regional variations in thermodynamic parameters between Supercell and QLCS
  - Larger CAPE and higher LCL heights for supercells in the Plains
- Vertical shear is similar spatially for Supercell and QLCS tornadoes
  - Slightly greater wind shear in MS/TN Valleys

Overall Frequency:  
Tornadoes/year

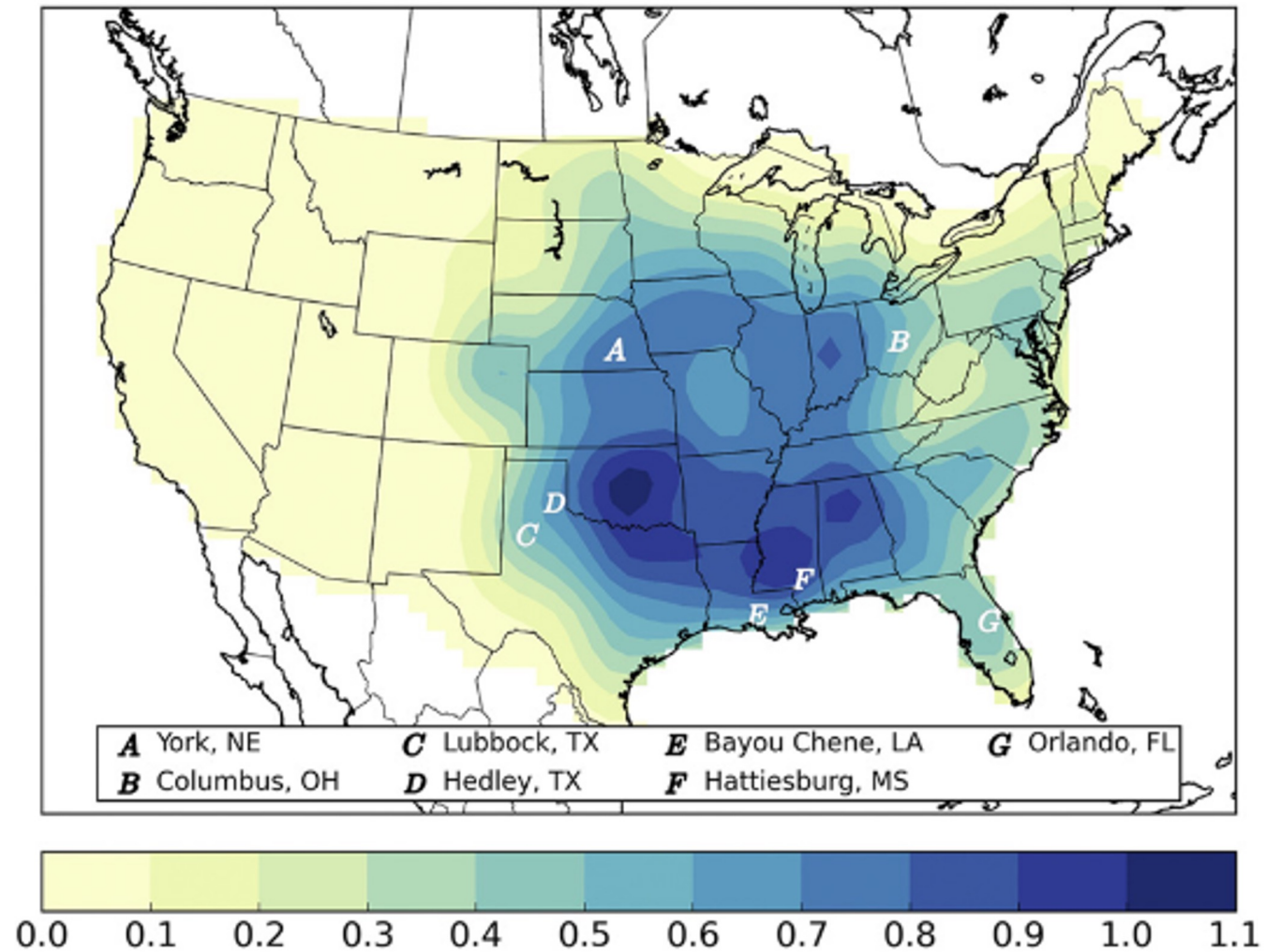


FIG. 3. The total number of tornadoes per year for every grid point across the United States.

## Diurnal Trend

Start time of the 4-hour period that captures the highest fraction of tornado reports.

(Requires  $N > 40$ )

See also:  
Krocak and Brooks  
2020 (WAF)

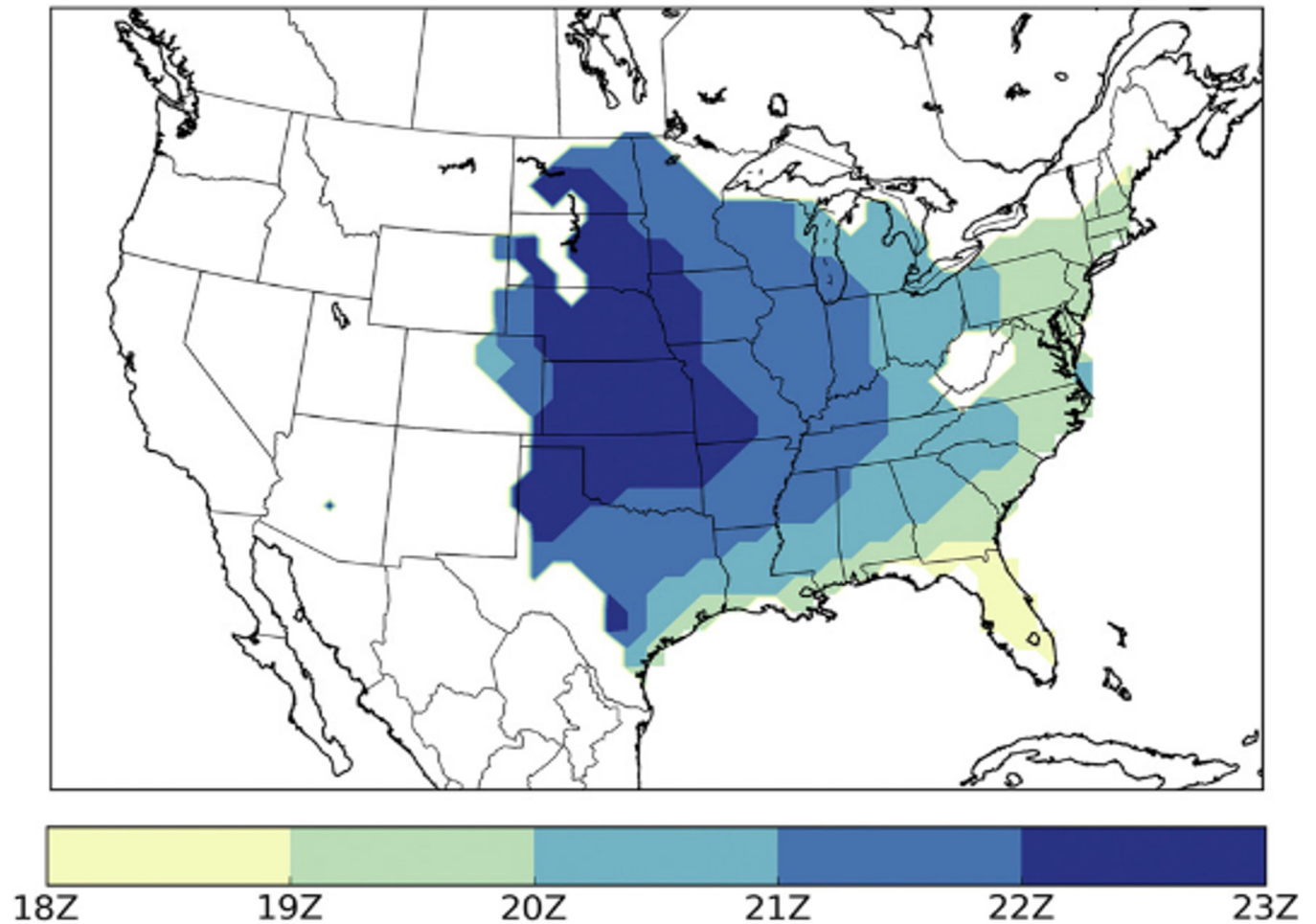
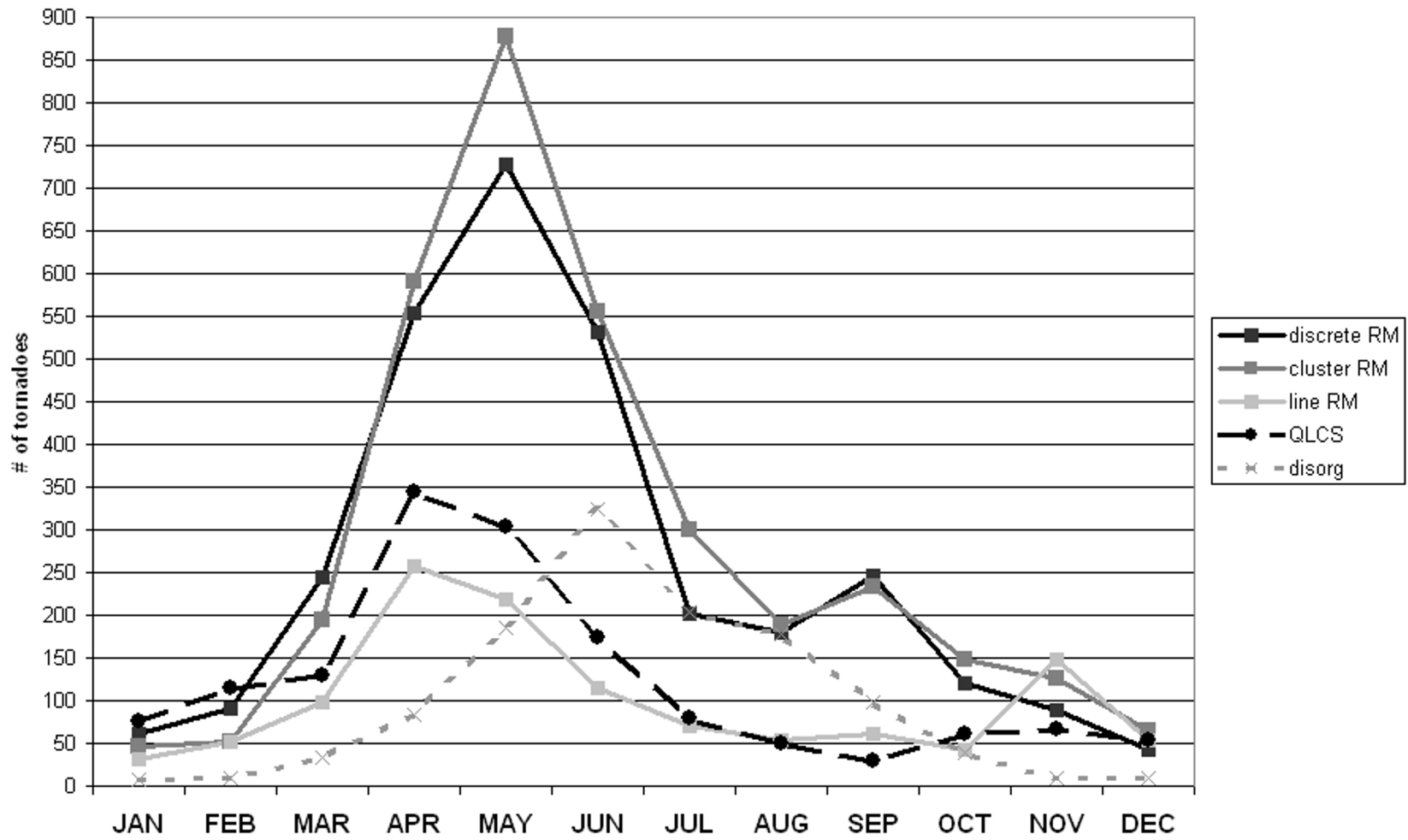
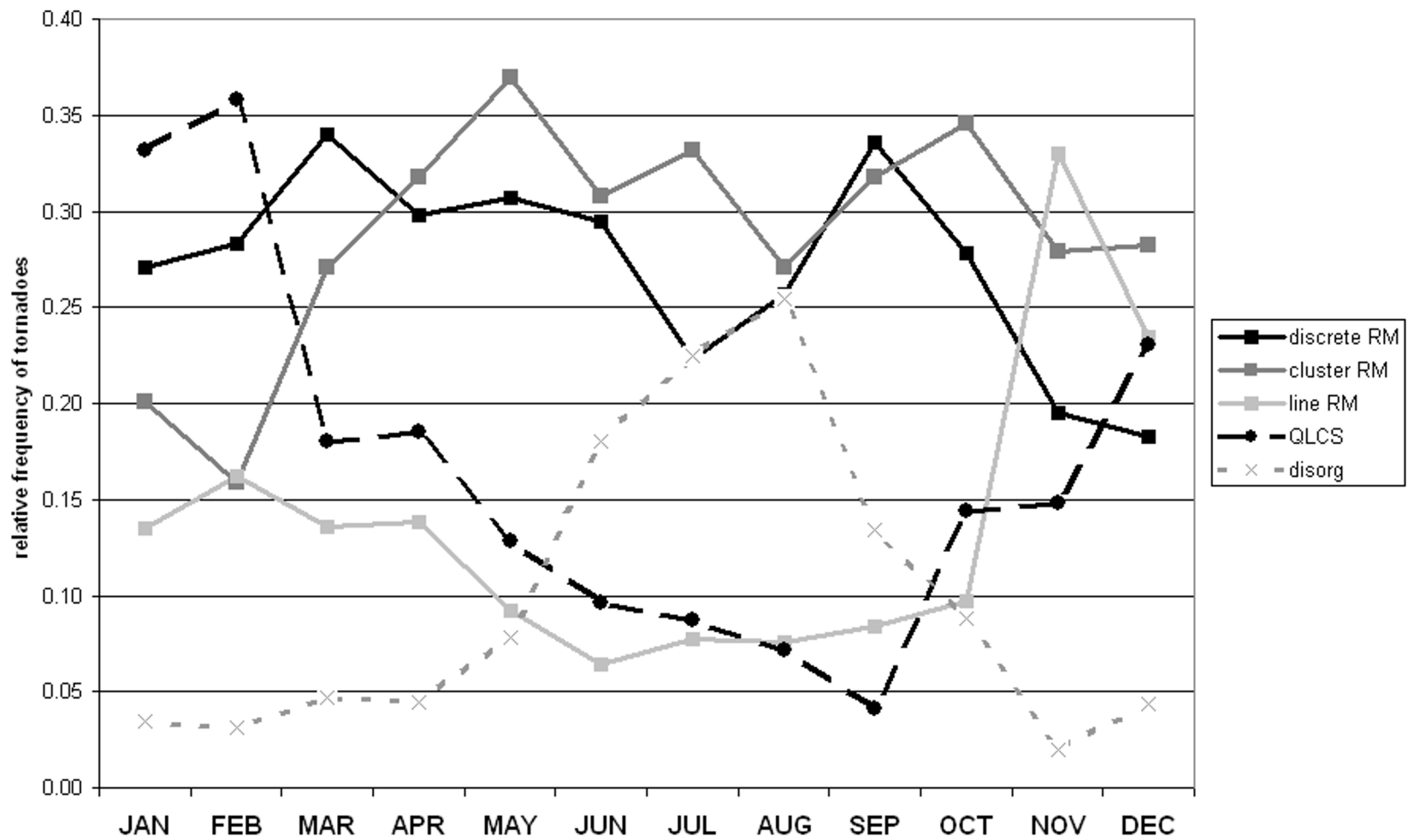


FIG. 7. Start time of the 4-h period that captures the highest fraction of tornado reports for every location across the country. Note the calculation was only done for points with greater than 40 reports over the 1954–2015 period.

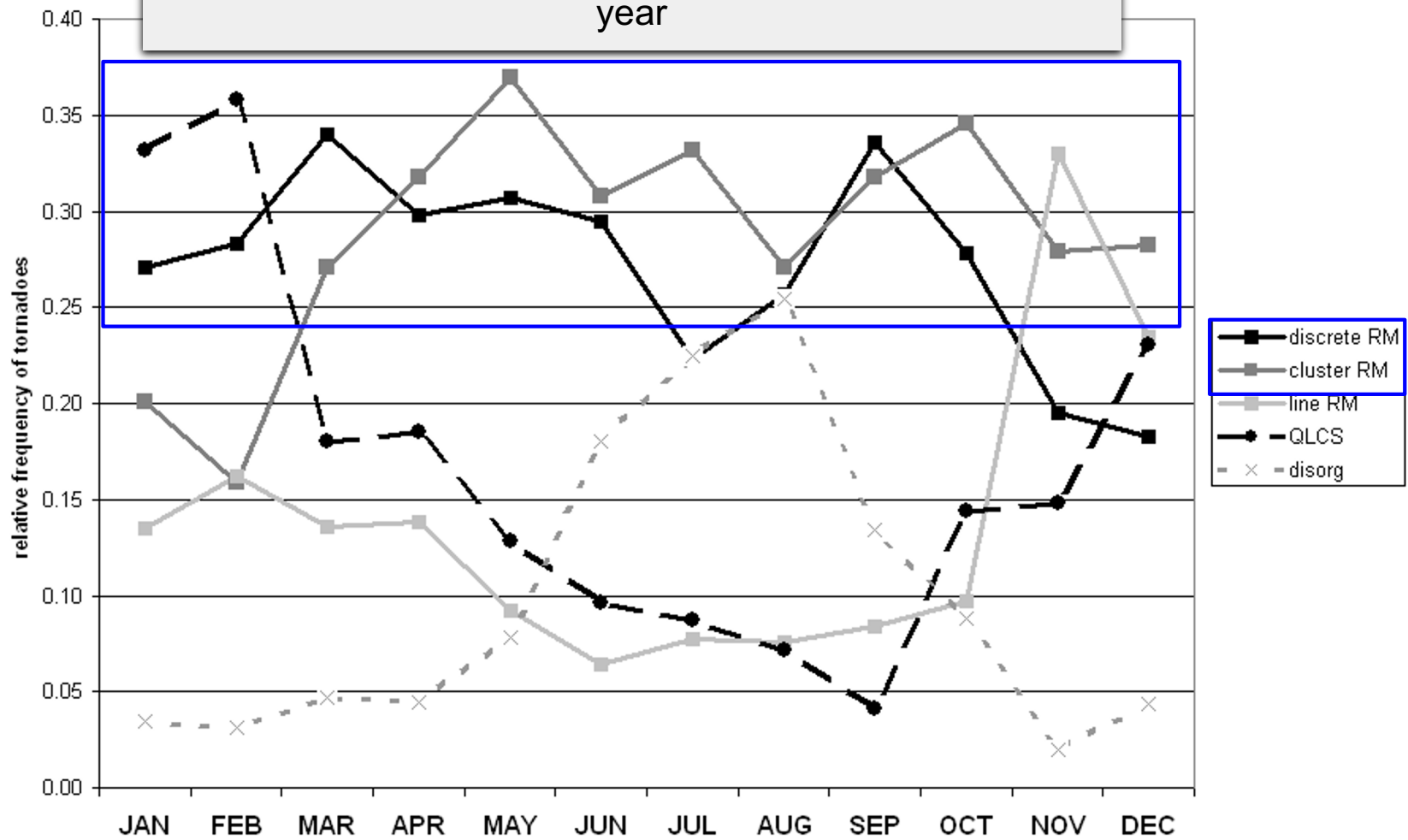
### Tornadoes: convective mode by month



Tornadoes: relative frequency by mode and month

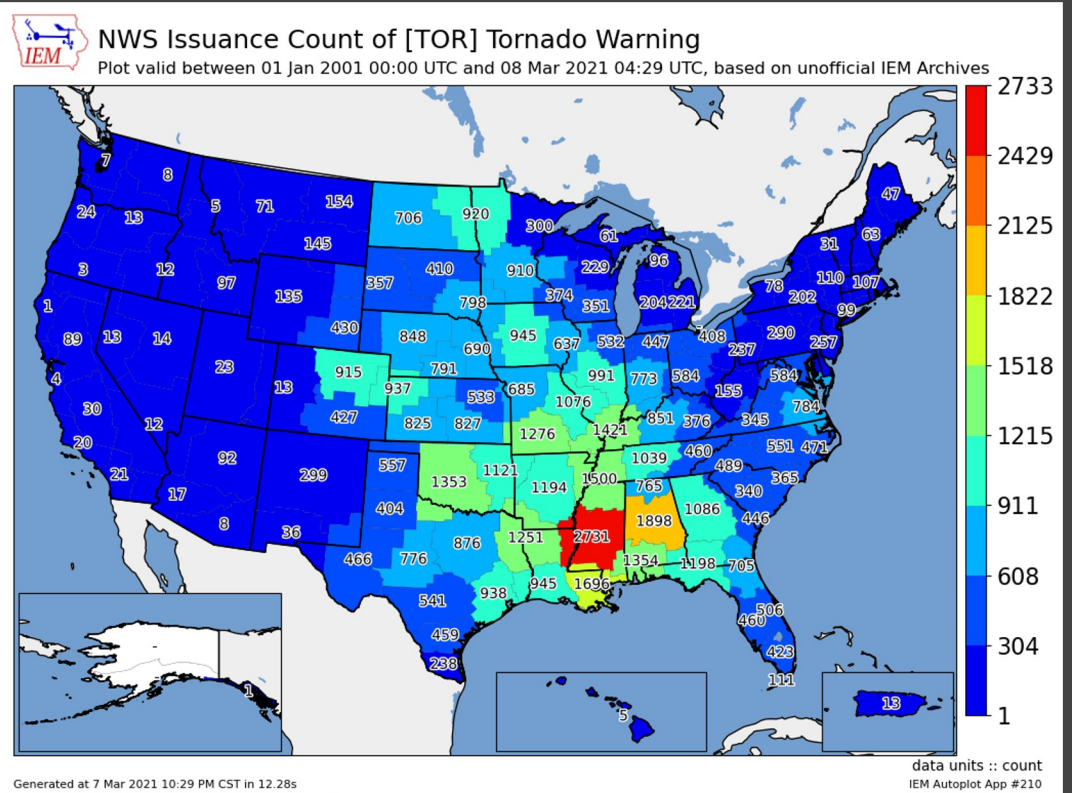
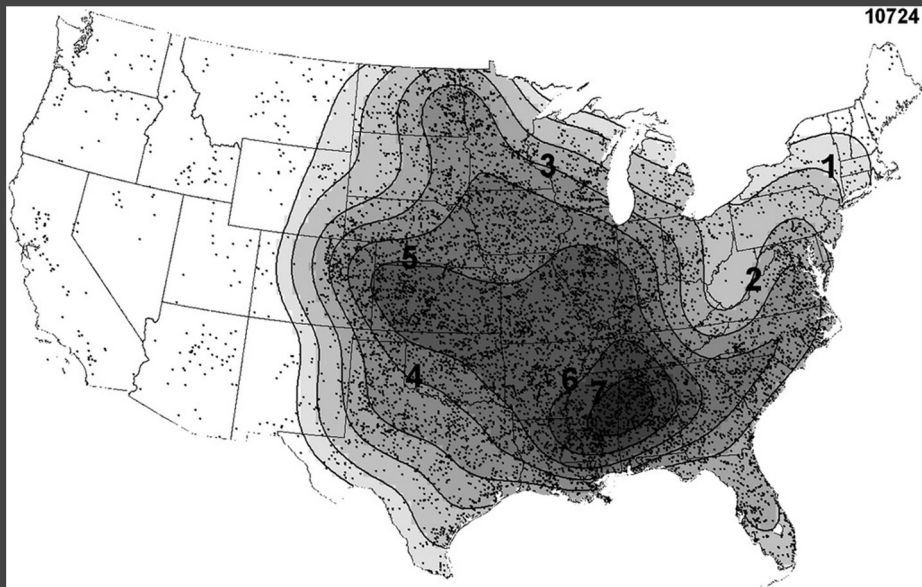


**Tornadoes: relative frequency by mode and month**  
Supercell Tornadoes tend to dominate throughout the year

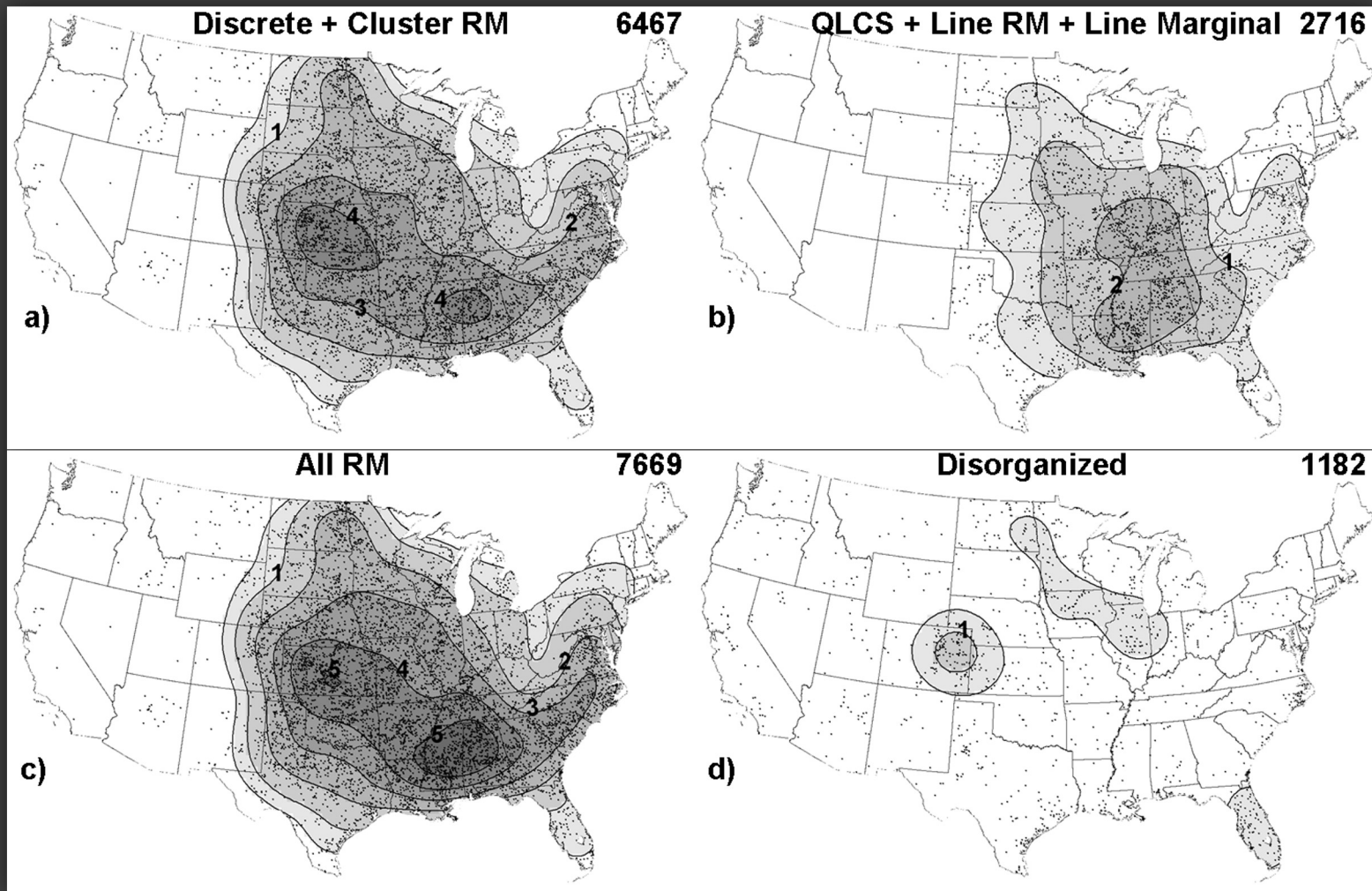


# Tornado Events per Decade

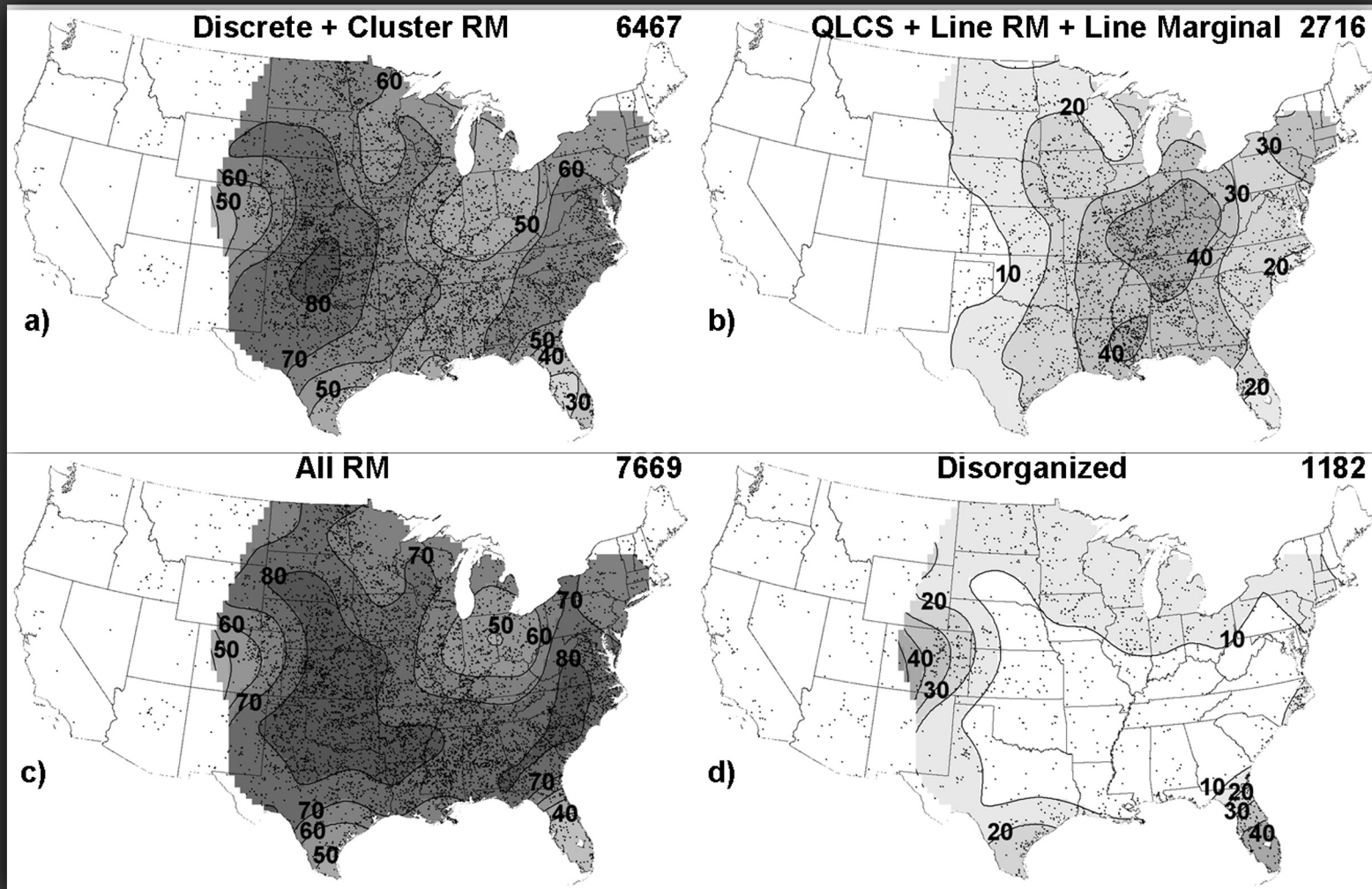
This result is supported well by the number of tornado warnings issued over the past 20 years  
(Though these datasets are not entirely independent...)



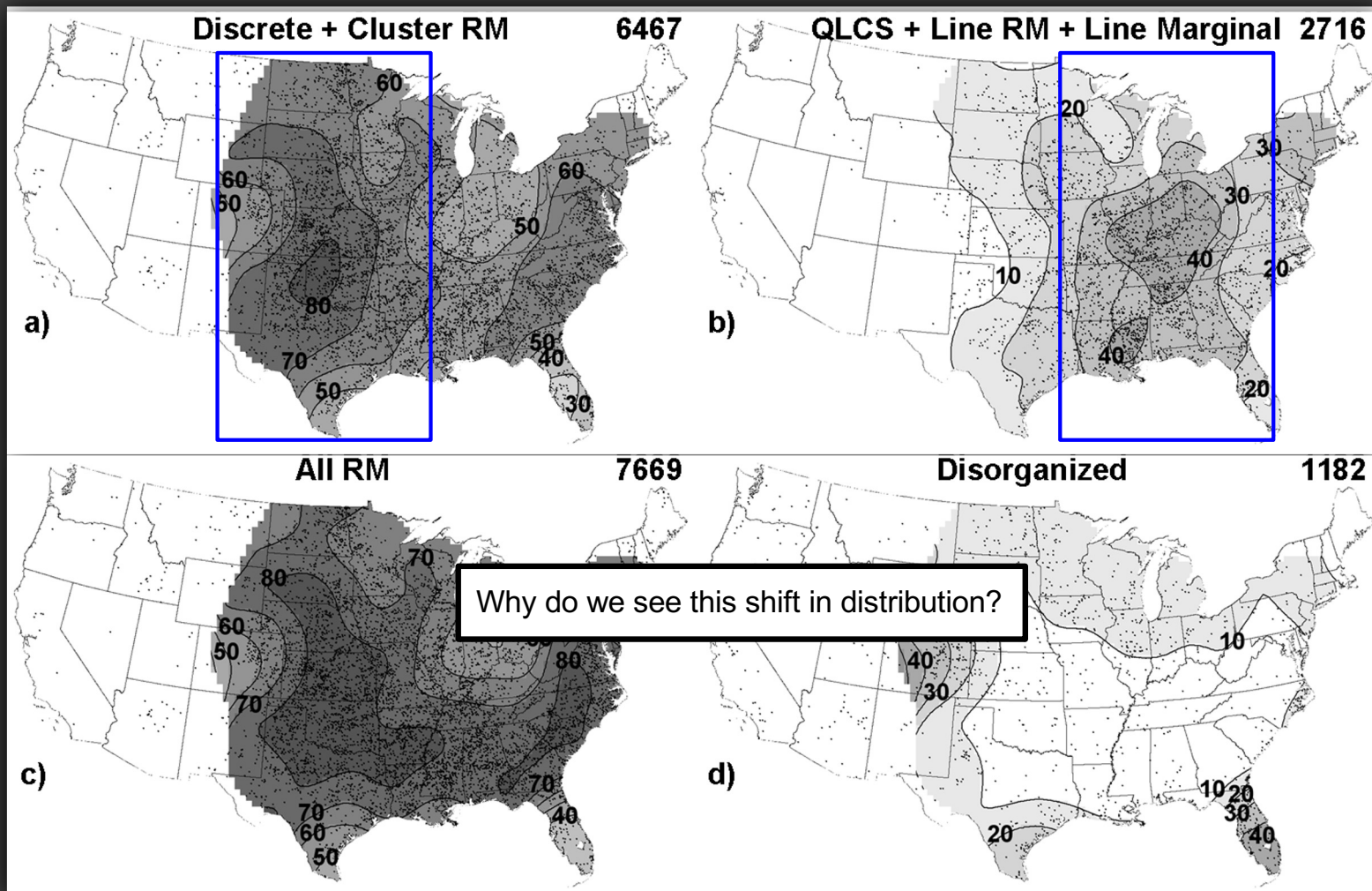
# Tornado Events per Decade



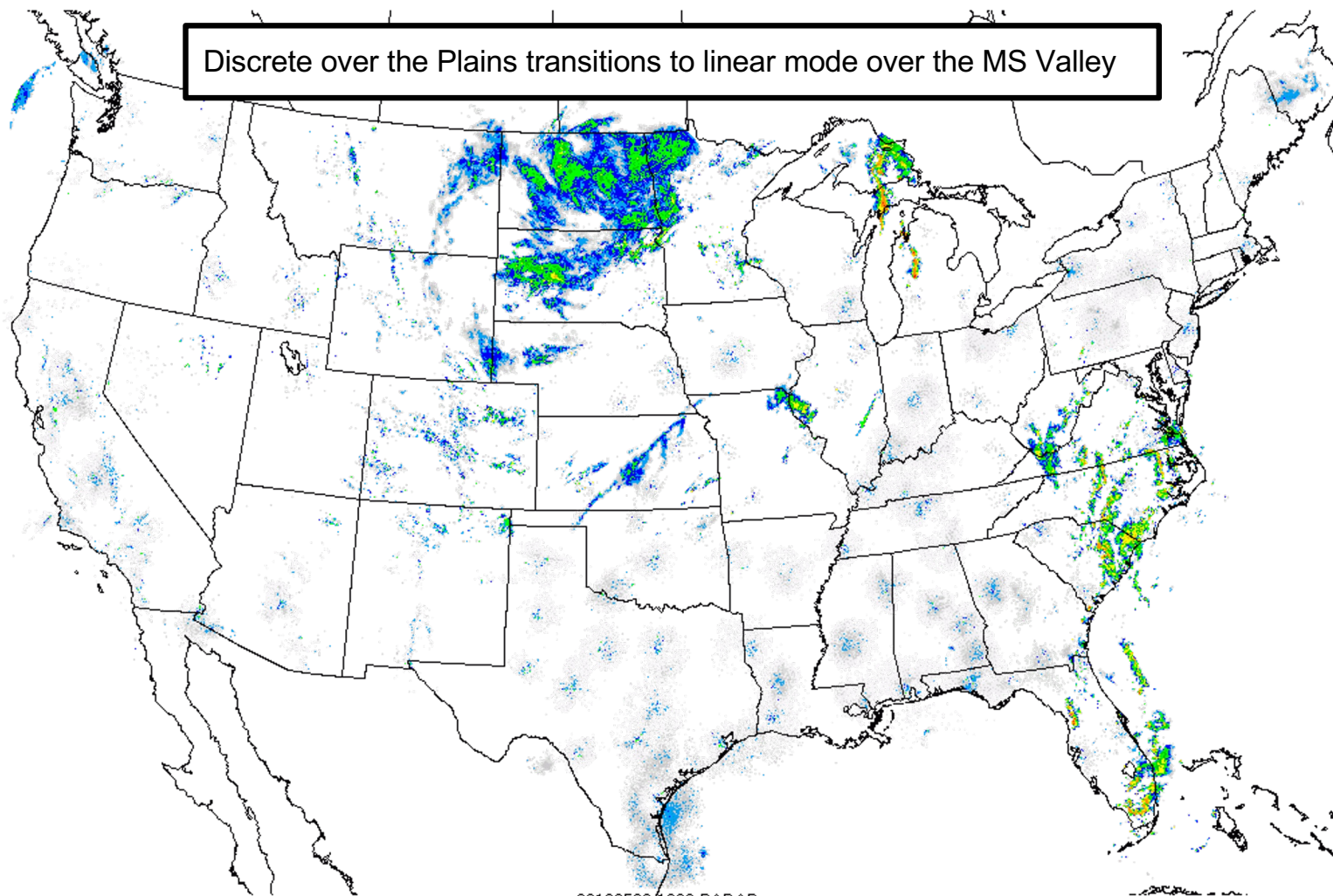
# Tornado Relative Frequency



# Tornado Relative Frequency

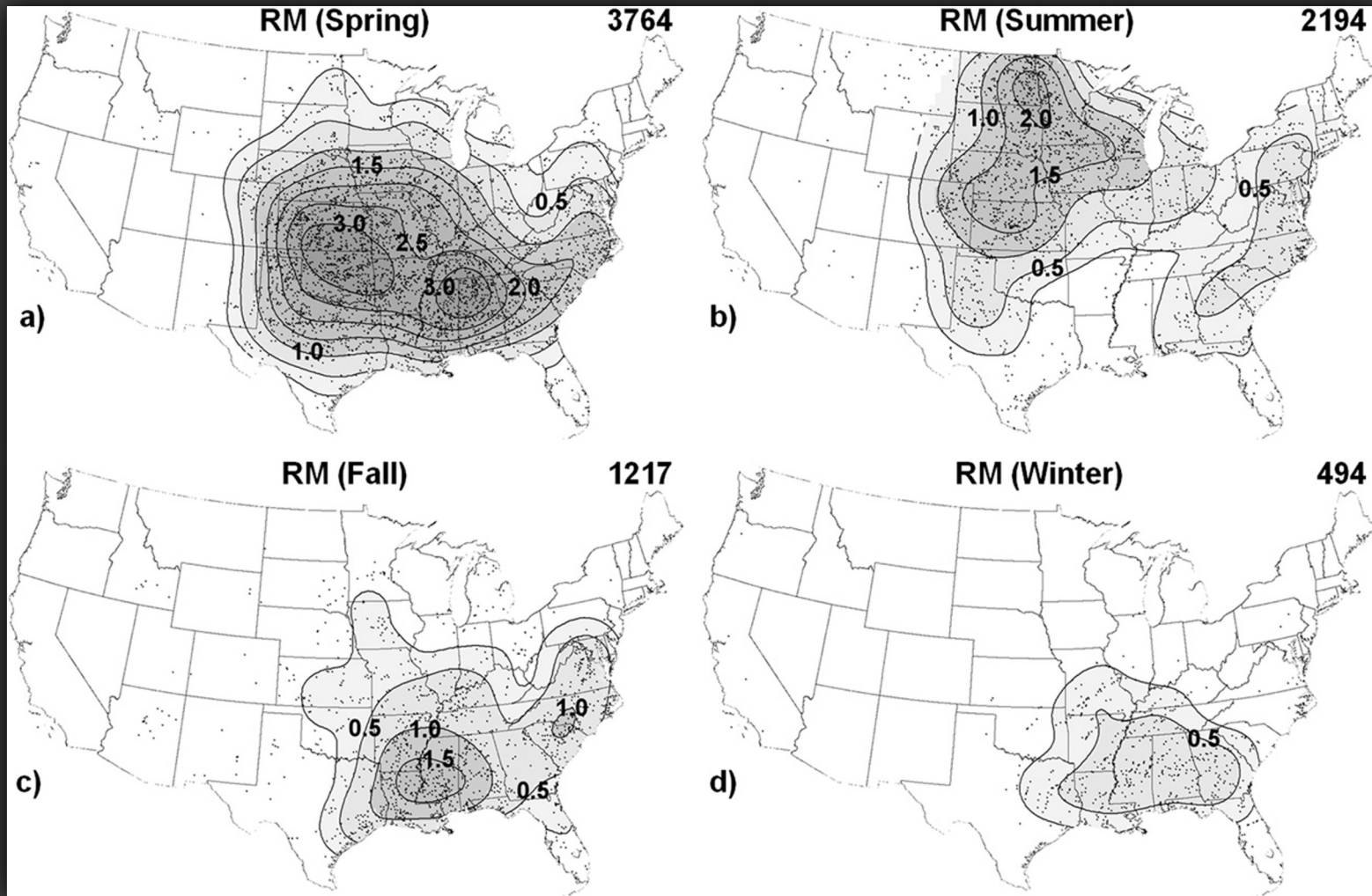


Discrete over the Plains transitions to linear mode over the MS Valley

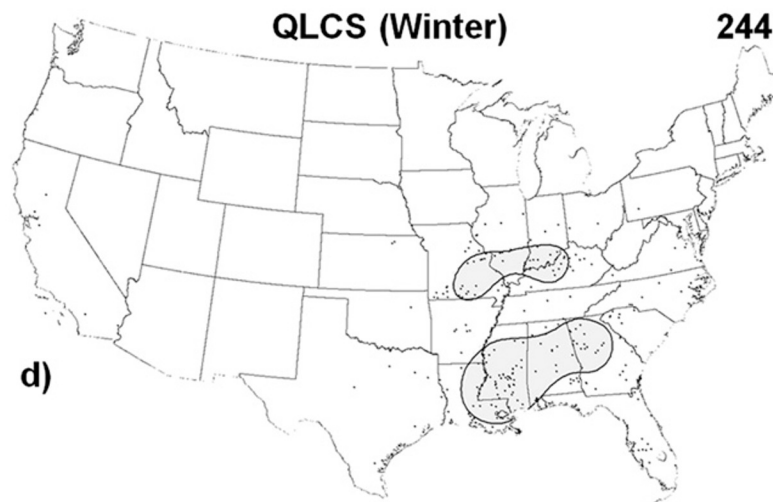
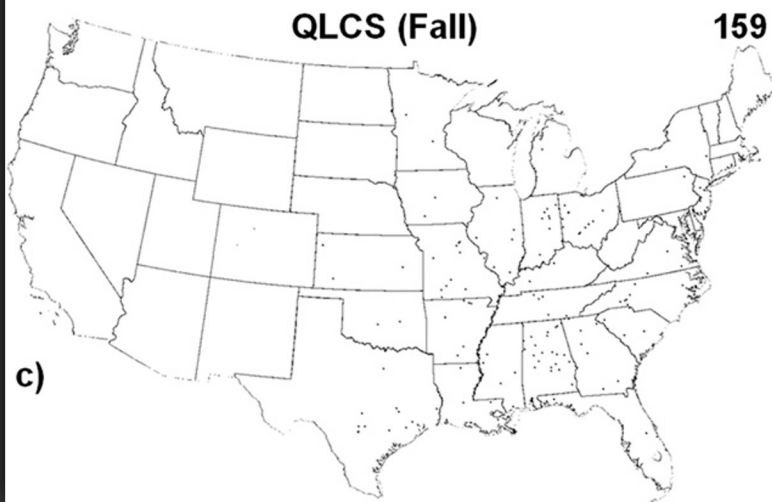
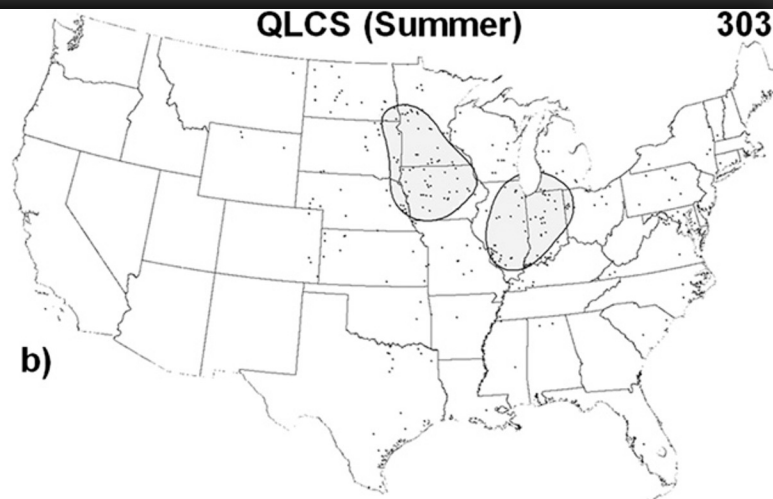
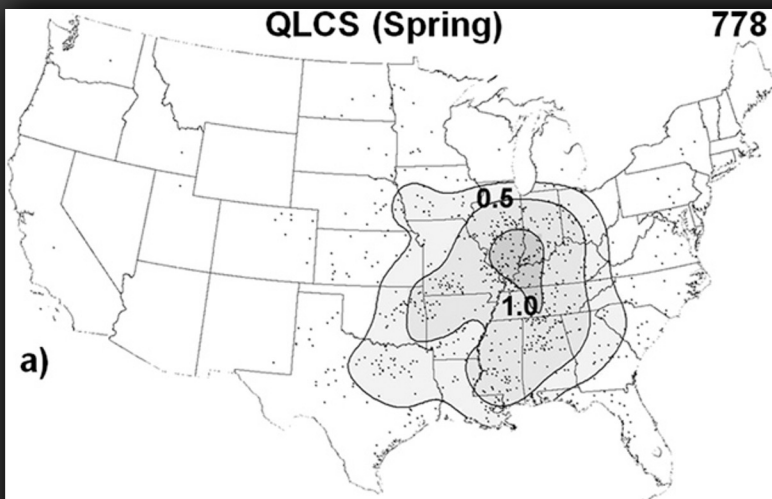


20130520/1800 RADAR

# RM Supercell Tornadoes by Season



# QLCS Tornadoes by Season



# Tornado Climatology Summary

- Tornadoes tend to occur more frequently across the southern Plains and northern Gulf states
  - Typically occur mid/late afternoon over the central CONUS, but can occur at any time of day.
  - Associated STP values tend to be higher in this region - suggesting a favorable tor environment
  
- Supercell tornadoes tend to dominate the distribution
  - Can occur over a wider range of the eastern 2/3rds of the CONUS compared to QLCS tornadoes
  - Favored over the Plains in the spring, but can occur throughout the year across the CONUS.
    - Spring maxima is due to favorable overlap of quality CAPE/Shear.
    - Western maxima may be related to initiation mechanisms favoring discrete modes vs. upscale growth further east
  
- QLCS tornadoes are also most common in the spring with a minimum in the fall.
  - However, these can also occur throughout the year.
  - Tornado maxima over the OH/MS River Valleys may be related to upscale growth from the west

# Tornado Climatology: Application

So tornadoes happen in the Spring in the center U.S.  
- big deal!  
How is this helpful?!



We can use tornado ingredient climatologies to help characterize how favorable an environment is for tornadoes.

# Conditional Intensity Forecasts

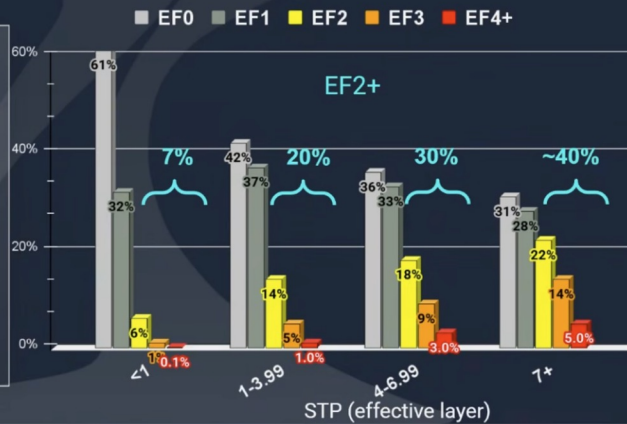
## Conditional Intensity Groups (CIG)

### Tornado

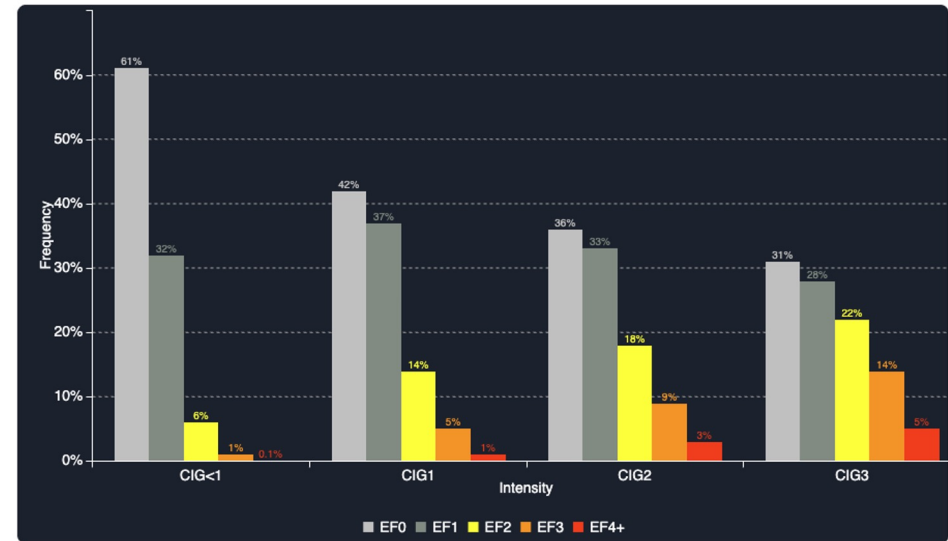
20 years of tornado intensities by environment

Define conditional intensity groups (CIG) based on expected tornado distribution

- STP <1 : 7% EF2+
- STP 1-4 : 20% EF2+ (CIG1)
- STP 4-7 : 30% EF2+ (CIG2)
- STP 7+ : 40% EF2+ (CIG3)



## Tornado Intensity Distribution by Conditional Intensity Group



Storm Prediction Center

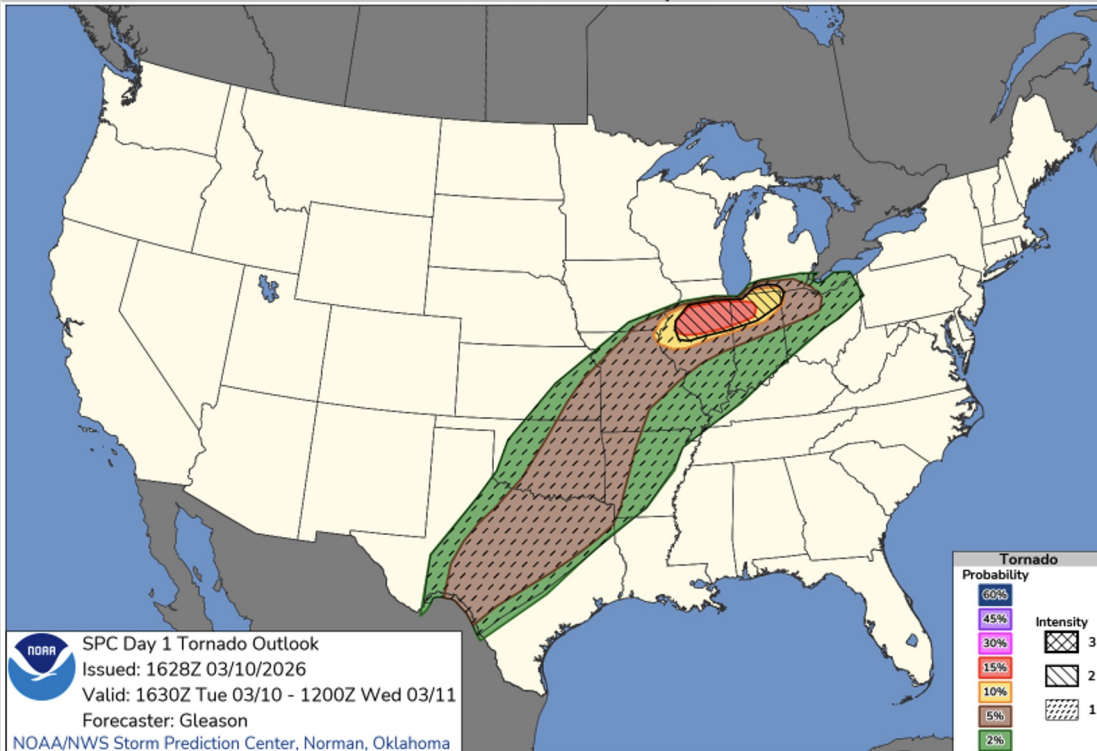
11

Norman, OK

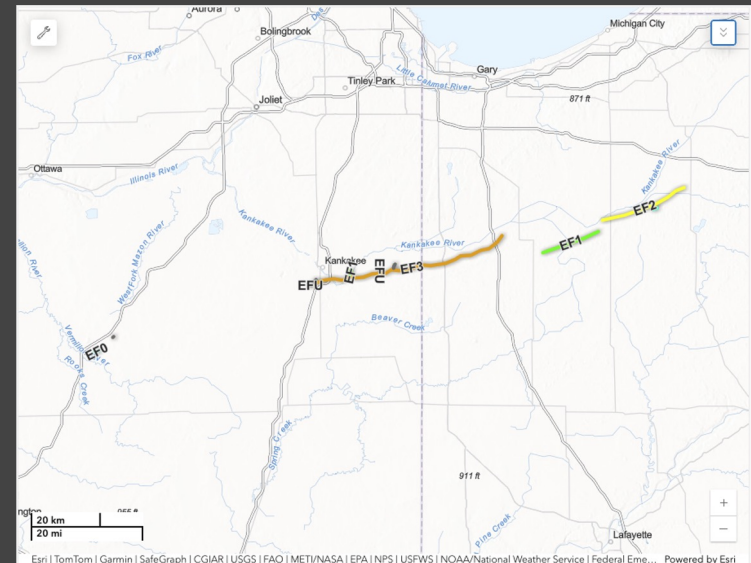
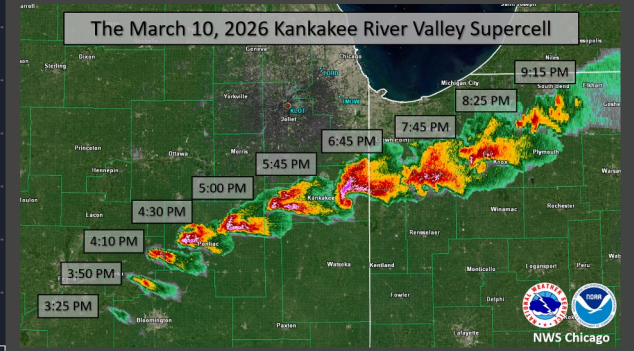
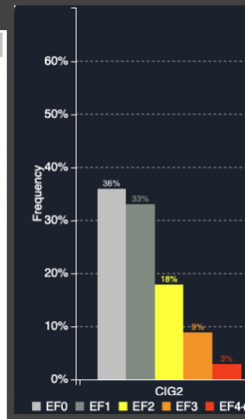


# Conditional Intensity Forecast Example: 10 March 2026

Probabilistic Tornado Graphic

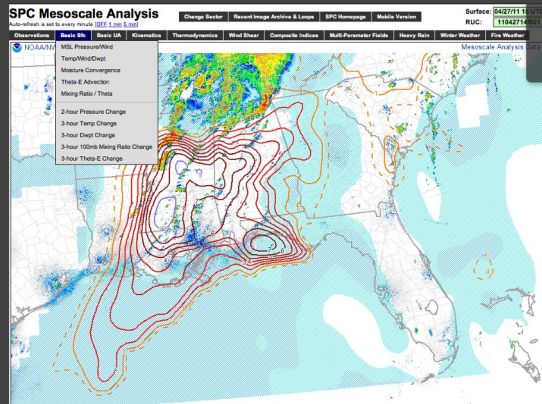
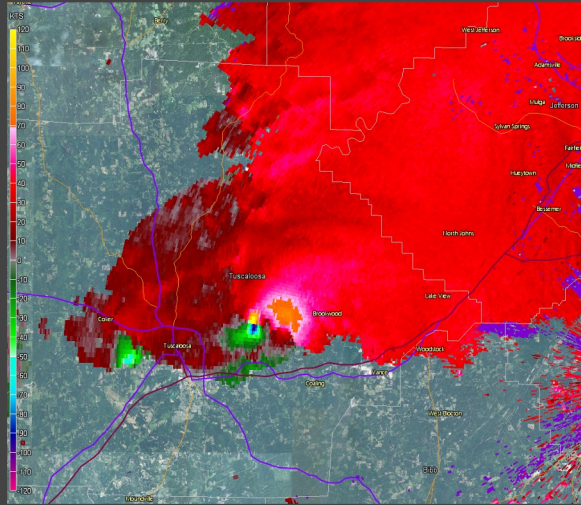


Day 1 Tornado Risk	Area (sq. mi.)	Area Pop.	Some Larger Population Centers in Risk Area
CIG2	25,371	4,331,947	Fort Wayne, IN...Joliet, IL...Peoria, IL...South Bend, IN...Gary, IN...
CIG1	423,695	47,995,001	Dallas, TX...Indianapolis, IN...Columbus, OH...Austin, TX...Fort Worth, TX...
15 %	14,743	2,033,213	Joliet, IL...Peoria, IL...Bloomington, IL...Normal, IL...Pekin, IL...
10 %	19,169	2,873,659	Fort Wayne, IN...South Bend, IN...Gary, IN...Hammond, IN...Lafayette, IN...
5 %	239,833	24,056,760	Dallas, TX...Fort Worth, TX...Oklahoma City, OK...Kansas City, MO...Tulsa, OK...
2 %	180,793	24,794,686	San Antonio, TX...Indianapolis, IN...Columbus, OH...Austin, TX...Cleveland, OH...



Eri | TomTom | Garmin | SafeGraph | CGIAR | USGS | FAO | MET/NASA | EPA | NPS | USFWS | NOAA/National Weather Service | Federal Elec... Powered by Eri

# Questions?



Bonus material

# SPC Mesoscale Analysis

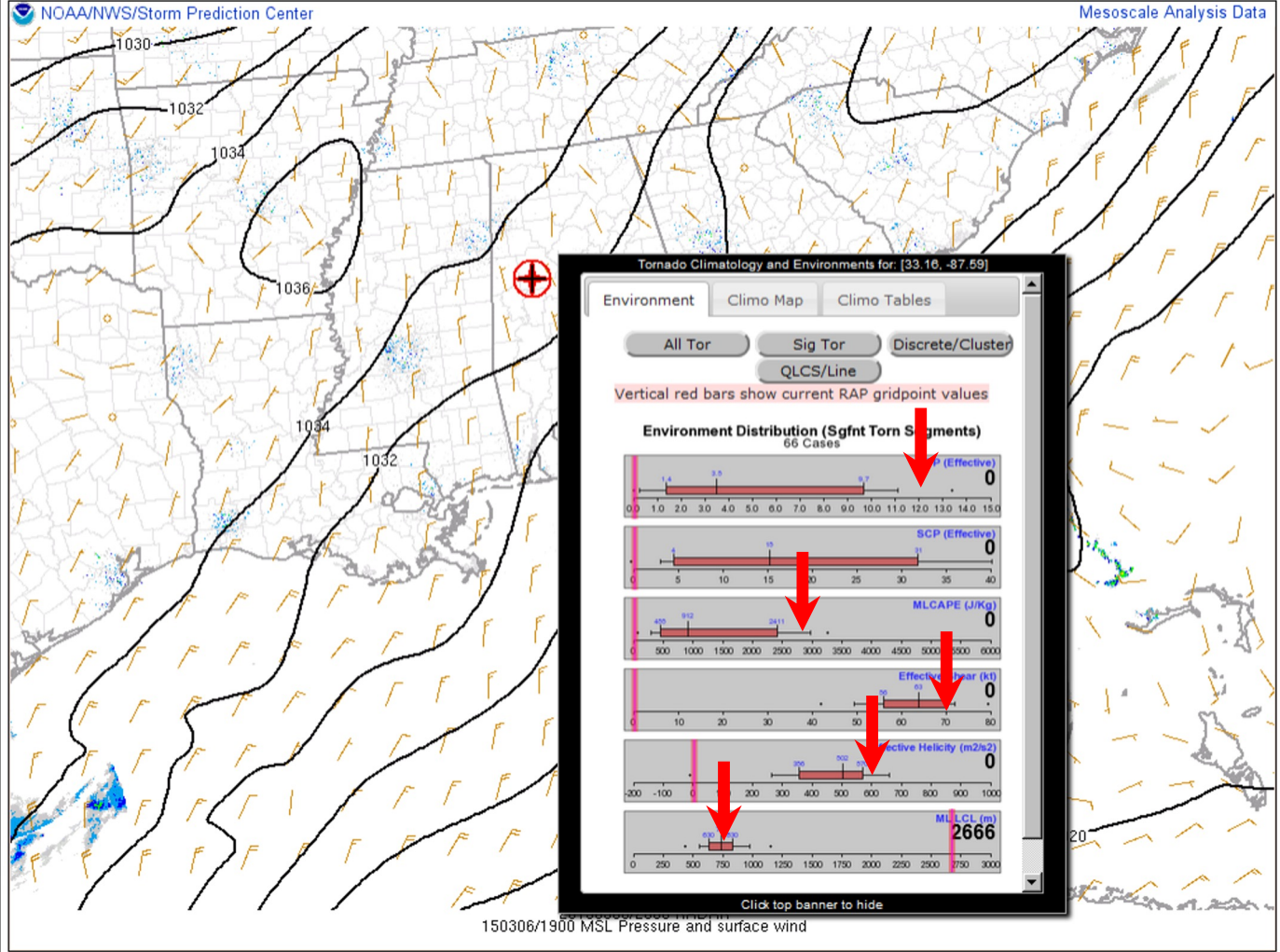
[Change Sector](#) [Image Archive & Loops](#) [SPC Homepage](#) [Mobile Version](#)

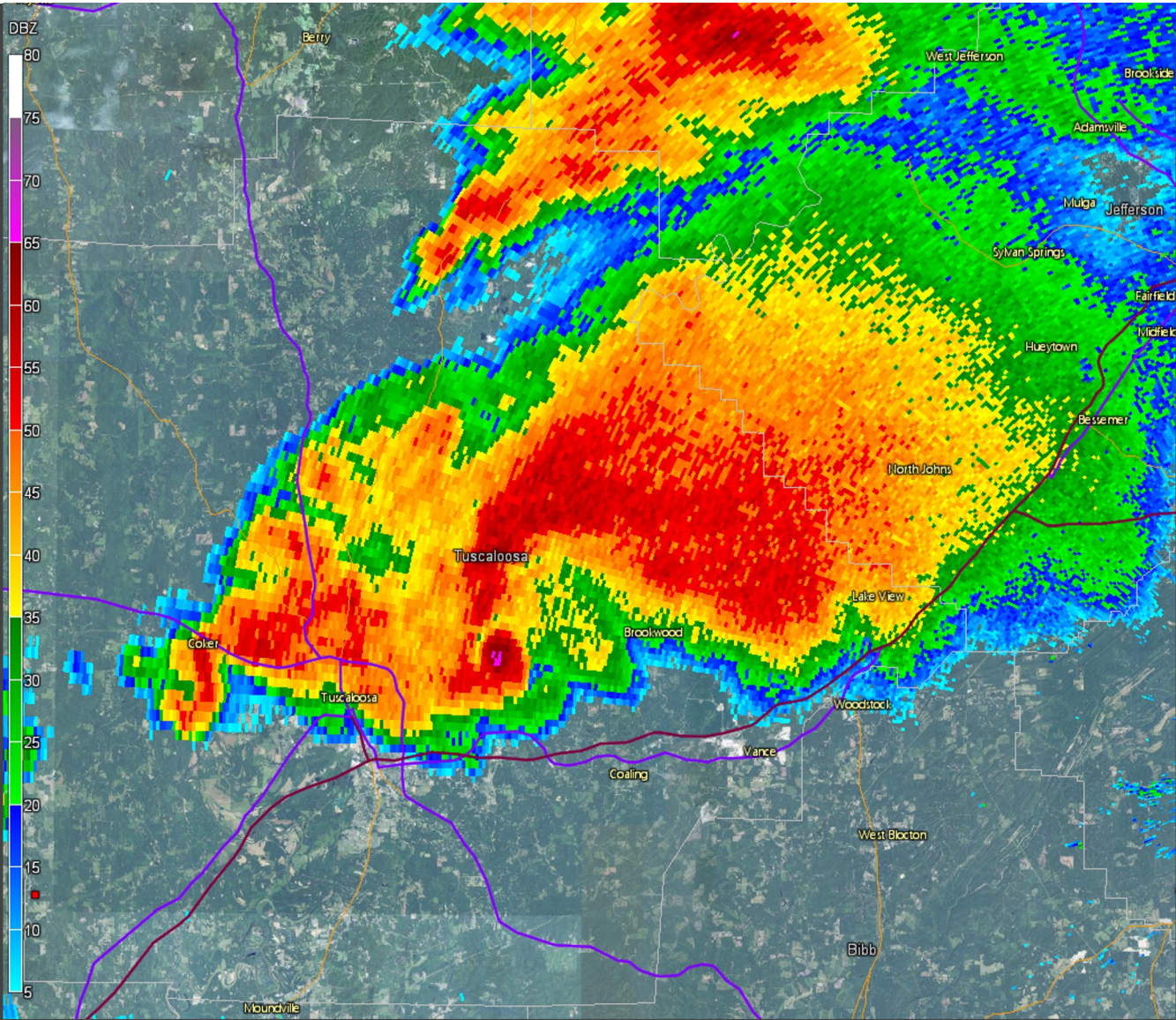
**NEW: Double-click map for tornado climatology and environmental breakdowns.**

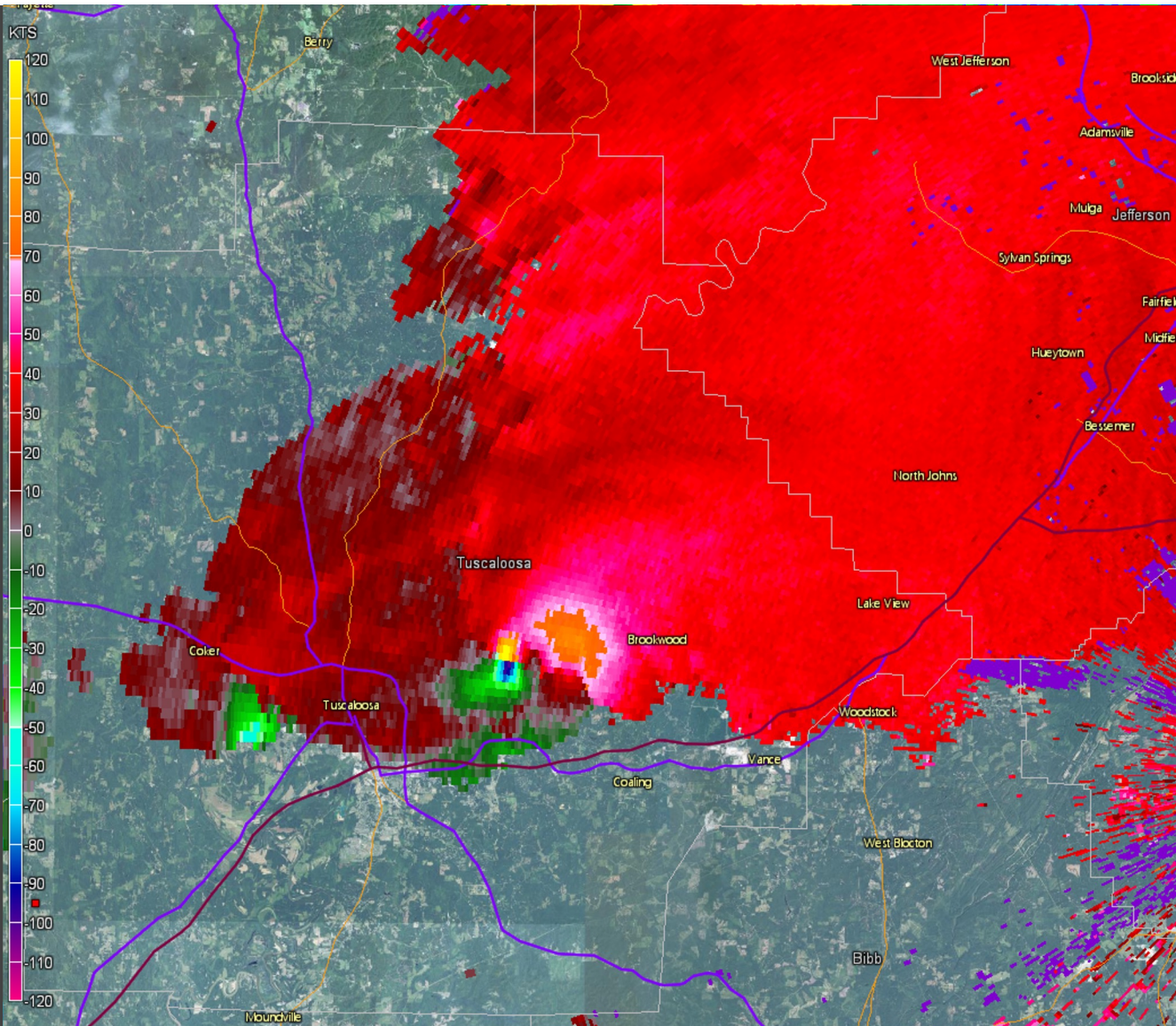
Auto-refresh is set to every minute [OFF 1 min 5 min]

## Operational EMC RAP

[Observations](#) [Basic Sfc](#) [Basic UA](#) [Kinematics](#) [Thermodynamics](#) [Wind Shear](#) [Composite Indices](#) [Multi-Parameter Fields](#) [Heavy Rain](#) [Winter Weather](#) [Fire Weather](#)







April 27, 2011 Tuscaloosa, AL EF-4



# SPC Mesoscale Analysis

Change Sector

Image Archive & Loops

SPC Homepage

Mobile Version

**NEW: Double-click map for tornado climatology and environmental breakdowns.**

Auto-refresh is set to every 10 seconds

Operational EMC RAP

Observations

Bas

Site Indices

Multi-Parameter Fields

Heavy Rain

Winter Weather

Fire Weather



Tornado Climatology and Environments for: [35.31, -111.89]

Environment Climo Map Climo Tables

All Tor Sig Tor Discrete/Cluster  
QLCS/Line

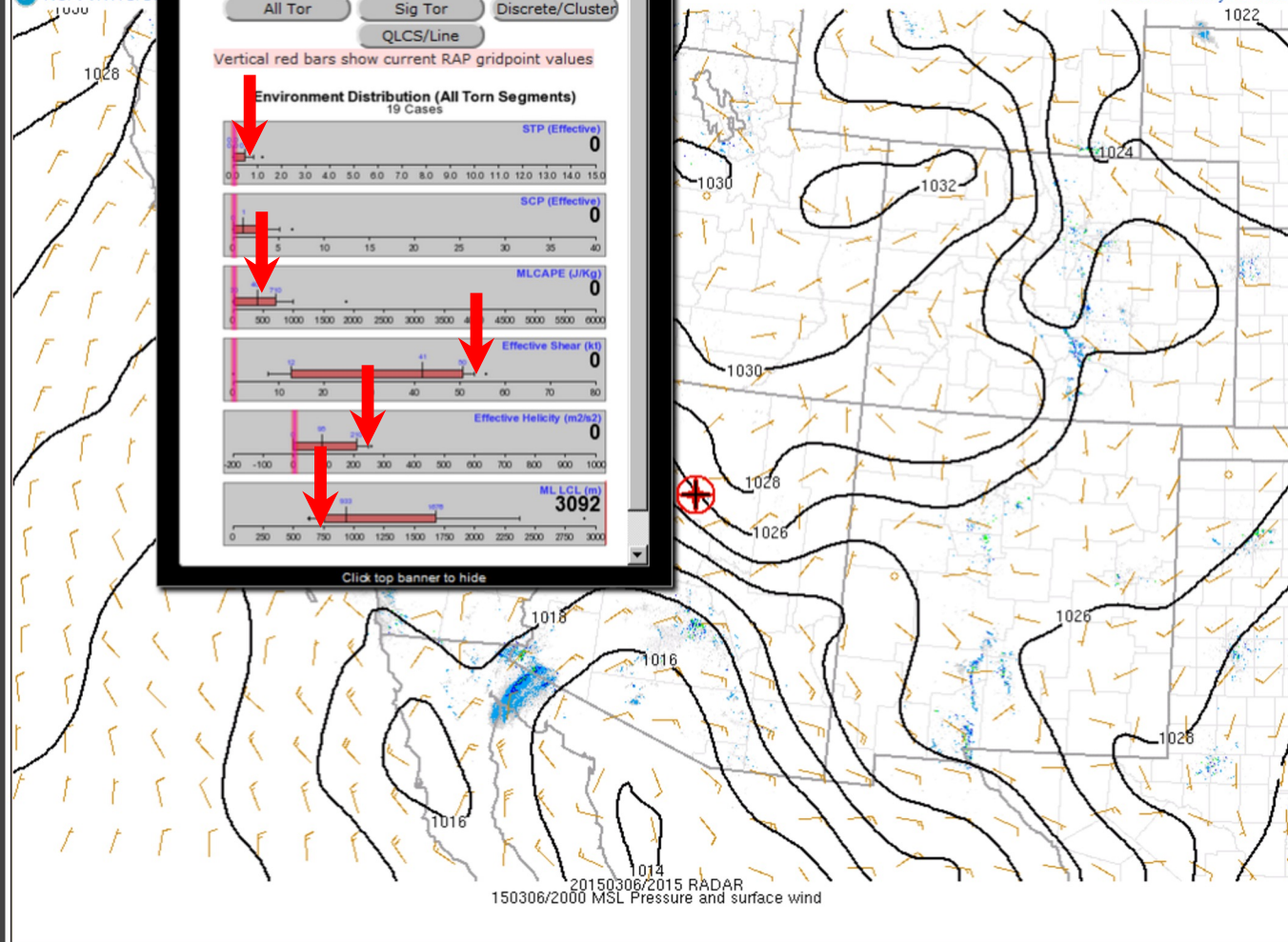
Vertical red bars show current RAP gridpoint values

**Environment Distribution (All Torn Segments)**  
19 Cases

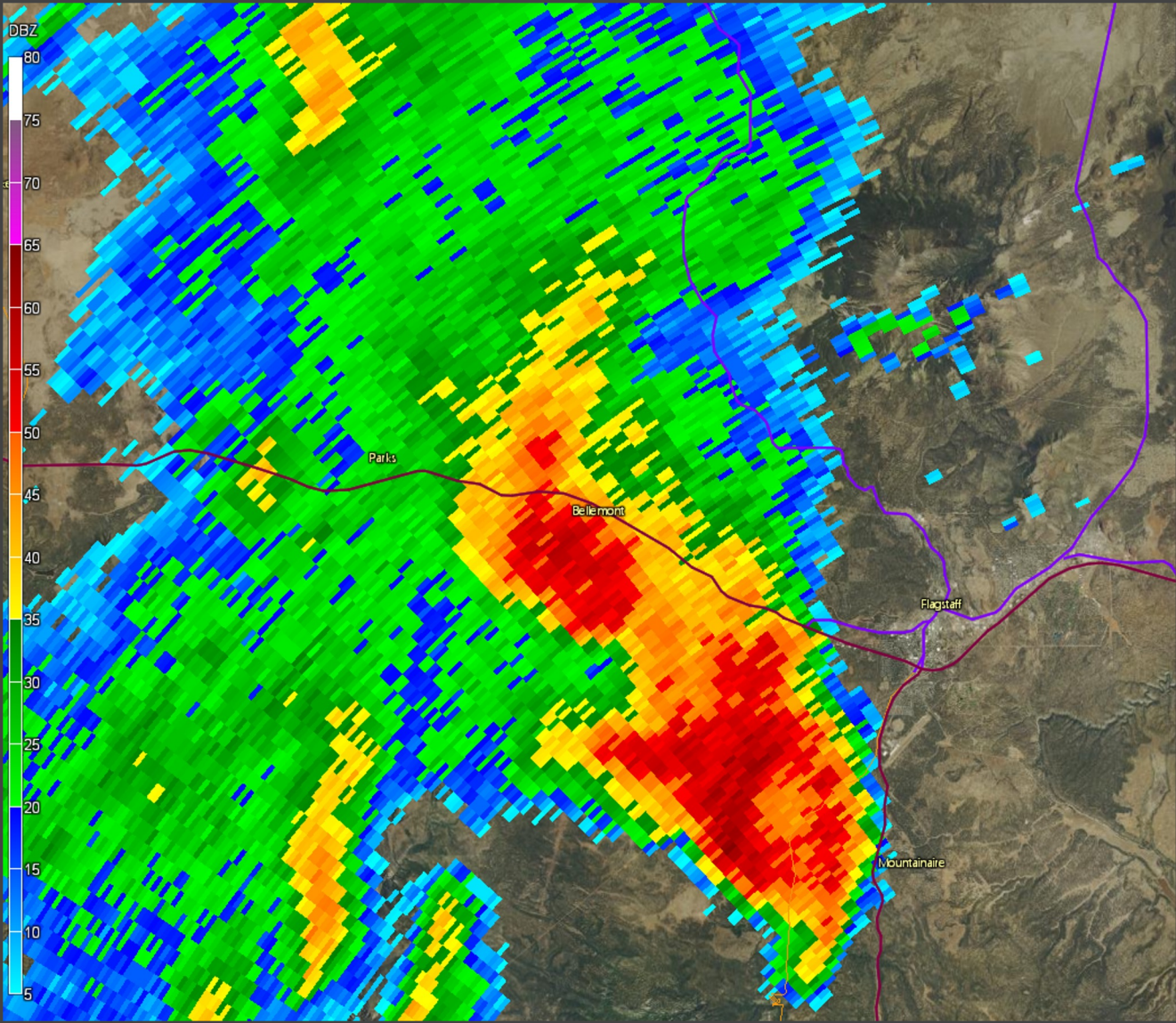
STP (Effective)	0
SCP (Effective)	0
MLCAPE (J/Kg)	0
Effective Shear (kt)	0
Effective Helicity (m2h2)	0
ML LCL (m)	3092

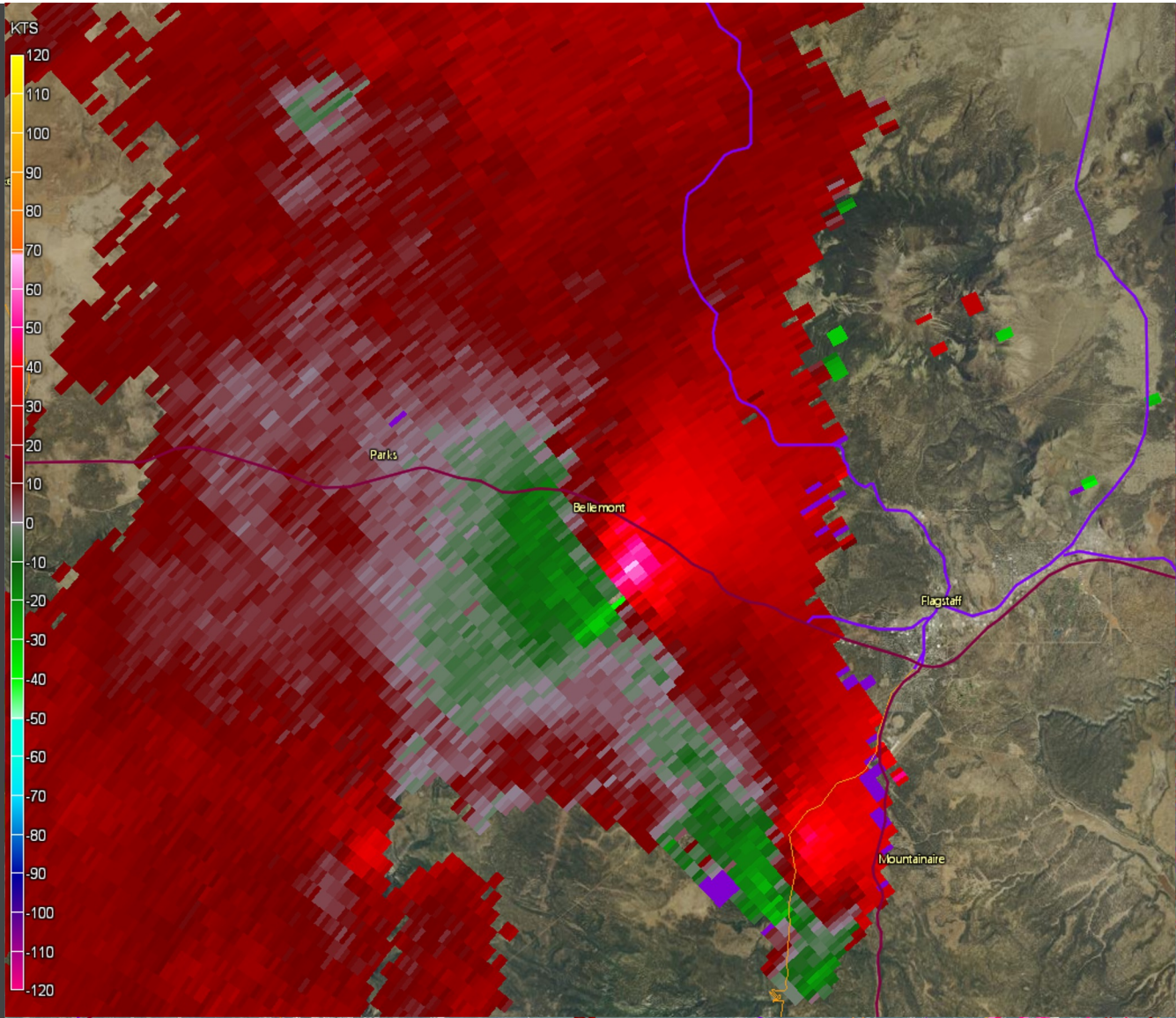
Click top banner to hide

Mesoscale Analysis Data

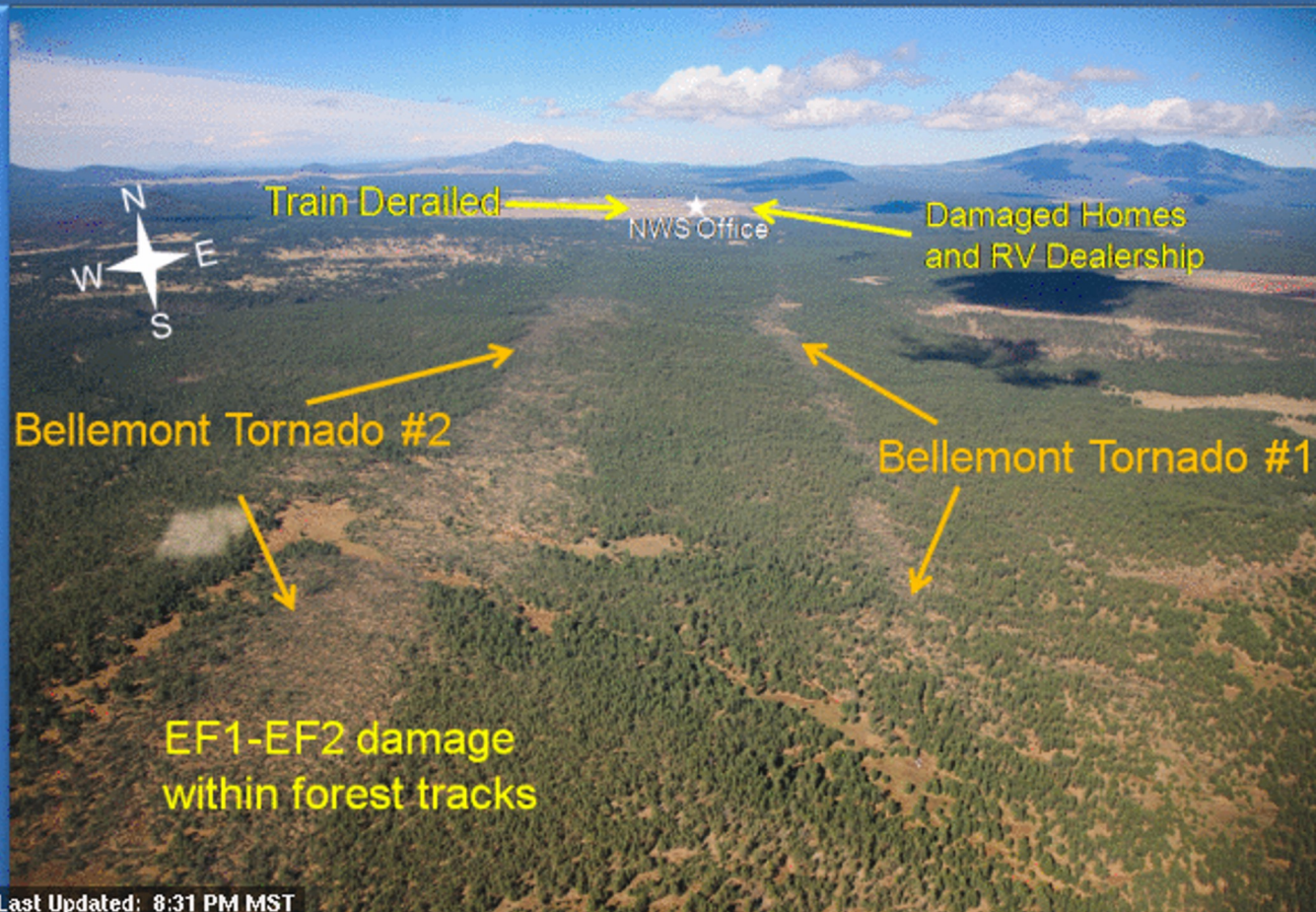


20150306/2015 RADAR  
150306/2000 MSL Pressure and surface wind





## Tornado Tracks near Bellemont, AZ October 6, 2010



Issued Saturday, October 9, 2010

National Weather Service - Flagstaff, AZ

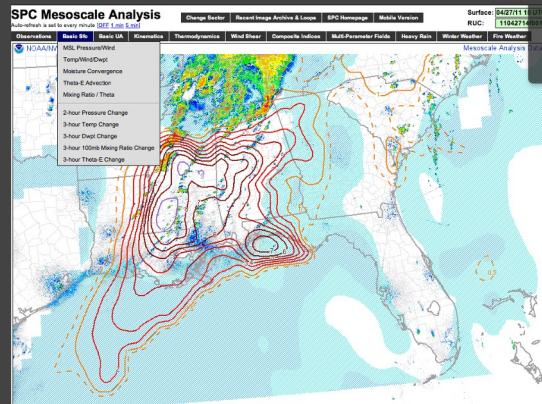
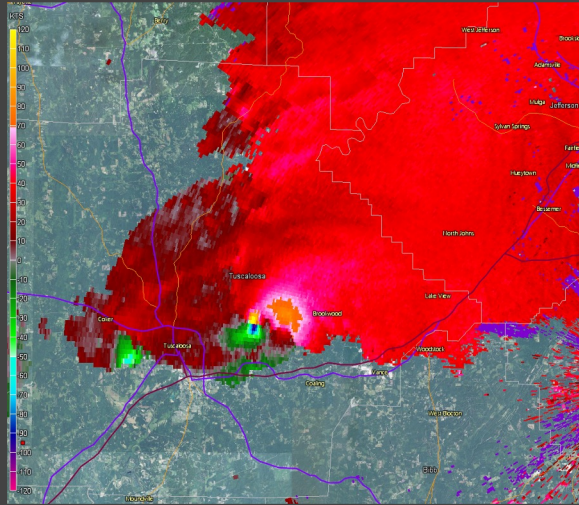


Bellemont, AZ  
EF-2

Doesn't just apply to  
high-end Plains/SE  
Environments!

Convective  
parameter  
magnitudes are  
relative to  
location/season.

# Estimating Tornado Probability & Intensity in Real Time



# Estimating Tornado Probability & Intensity in Real Time

- Recent studies have shown that observed WSR-88D and environmental trends can yield reasonable probabilities of tornado occurrence and intensity in real time.
  - Smith et al. 2015 (WAF)
  - Thompson et al. 2017 (WAF)
  - Cohen et al. 2018 (WAF)
  - Smith et al. 2020 (parts 1 & 2) (WAF)
- Recent studies by SPC featured:
  - ~4700 tornadoes from 2009-2013
  - ~10500 severe events & tornadoes from 2014
    - Tornado events required credible report or TDS
    - Environmental data, such as STP, also collected
- Used 2009-2014 tornadoes to create **conditional probabilities** by EF scale
- Used 2014-2015 tornadoes and severe events to create **unconditional probabilities** by EF scale.

# Tornado Detection Via WSR-88D

- Combined radar attributes (same place and time)
  - Storm-relative velocity ( $V_{\text{rot}} > \sim 40$  kt)
    - Stronger and deeper □ higher EF2+ probability
  - Correlation coefficient  $< 0.8$ 
    - More obvious and deeper □ higher EF2+ probability
  - Reflectivity  $> 20$  dbZ (can include “debris ball”)
  - Low ZDR
- Radar signatures combined with expectation based on storm environment

Harper

# Vrot Example

0.5° peak  $V_{rot}$  91.8 kt

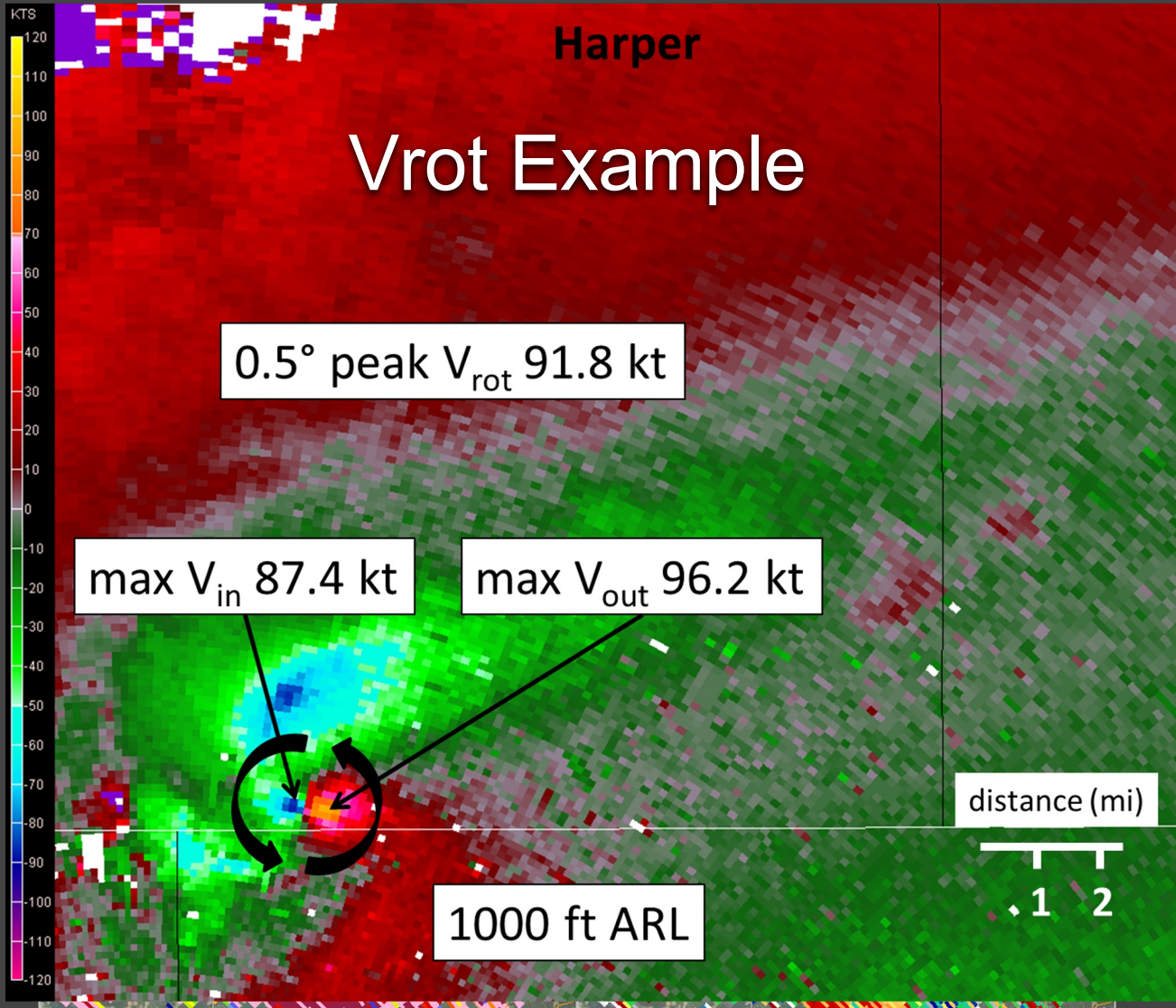
max  $V_{in}$  87.4 kt

max  $V_{out}$  96.2 kt

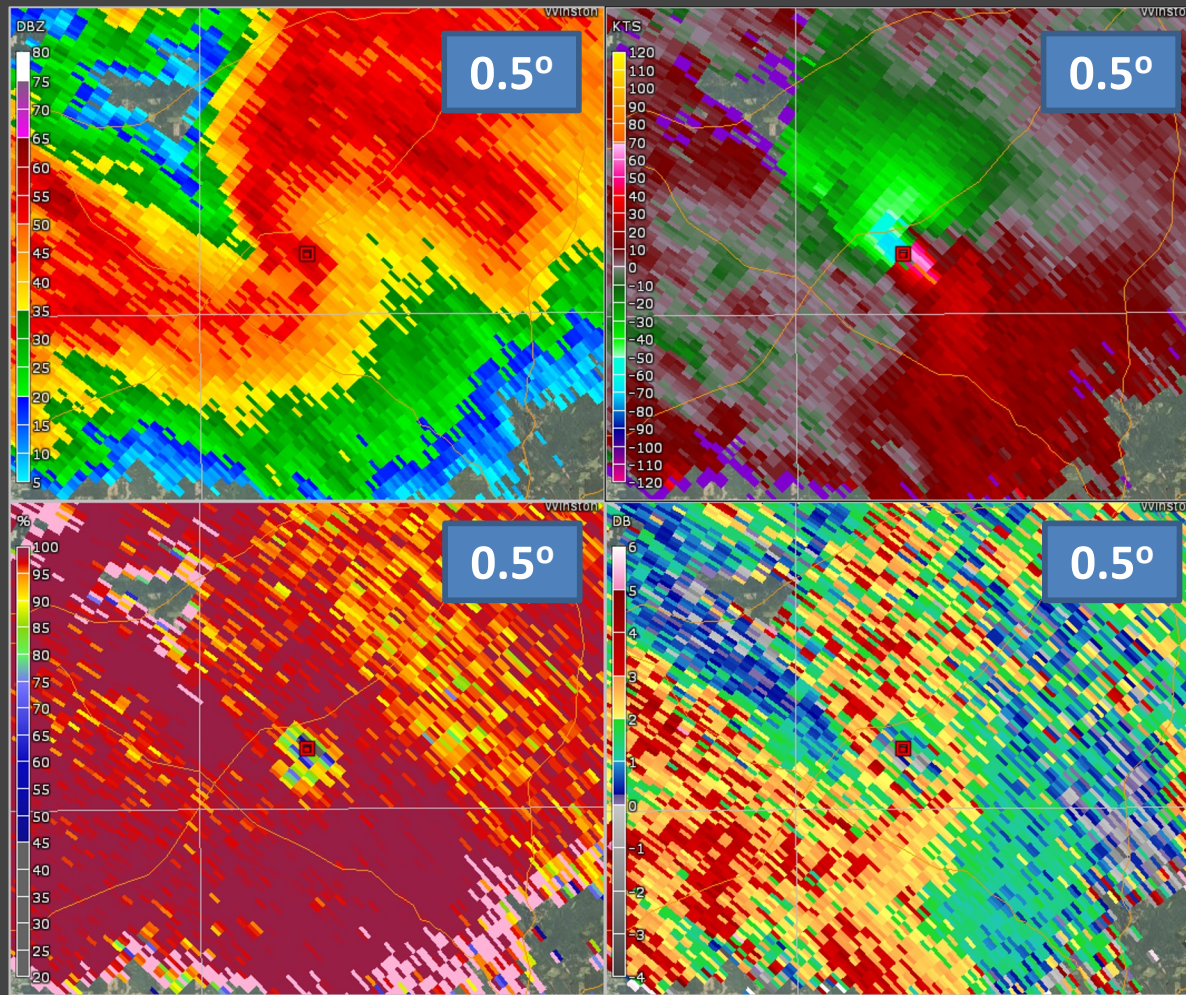
1000 ft ARL

distance (mi)

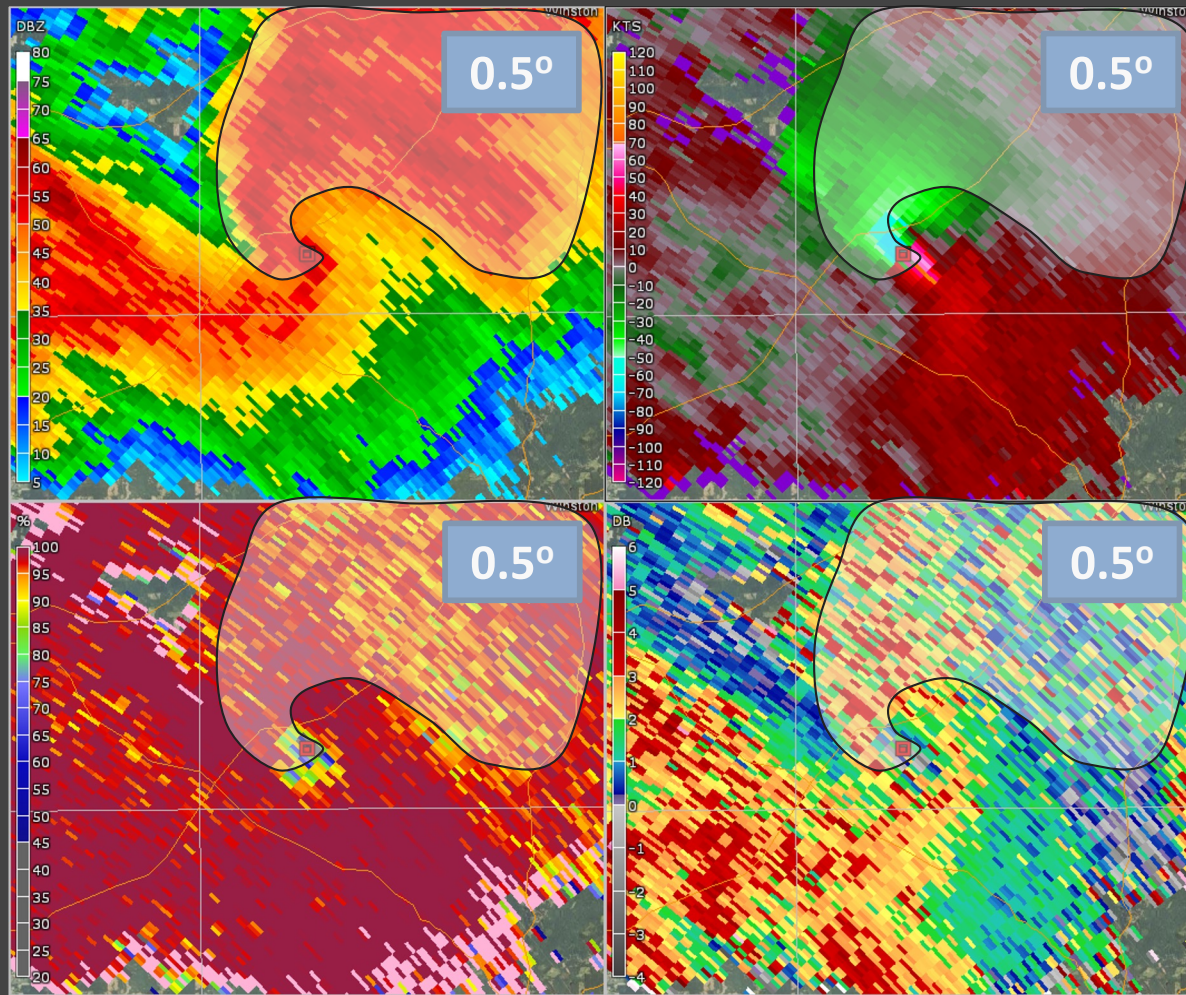
.1 2



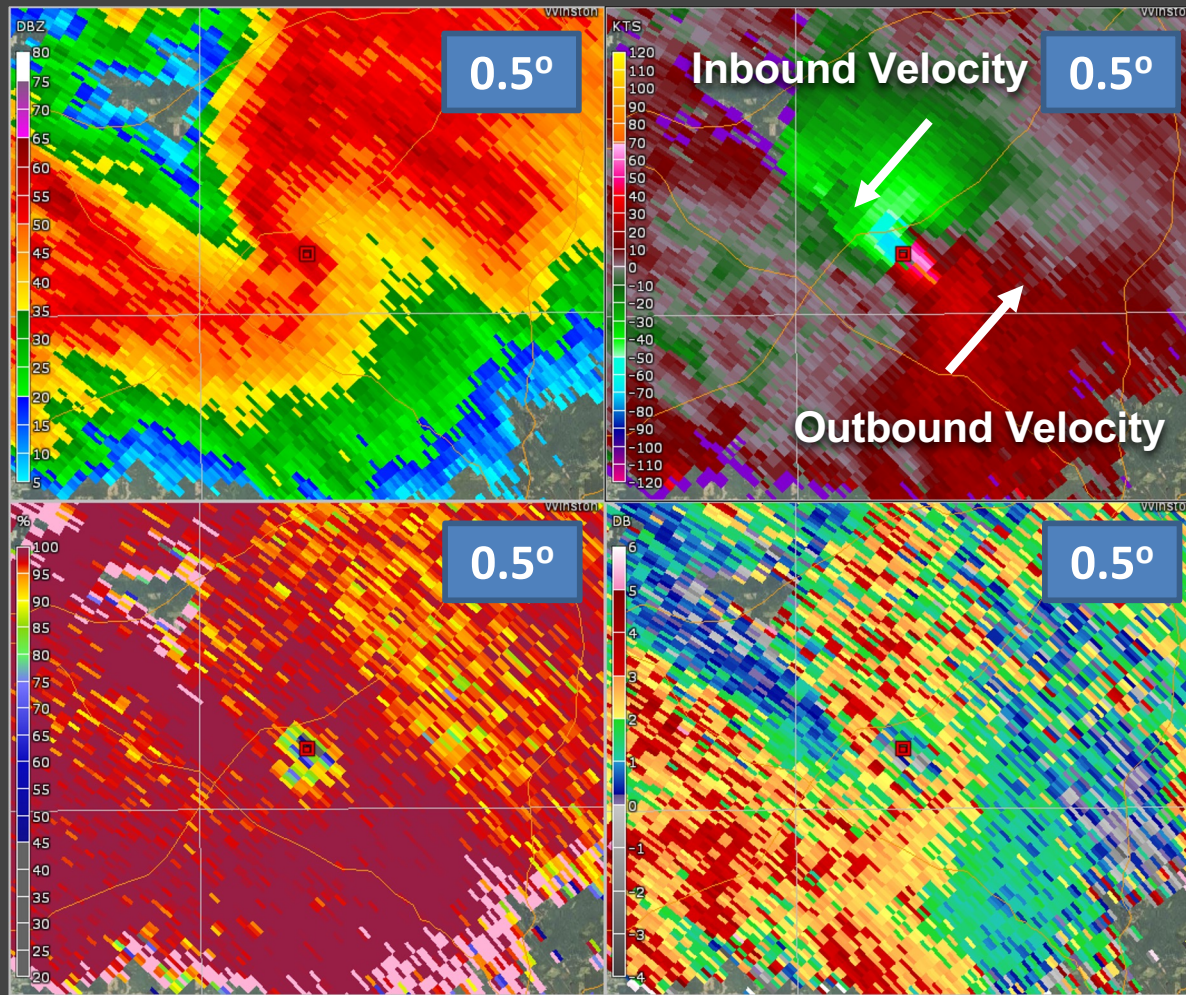
# A Quick Note on WSR-88D Tornado Signatures



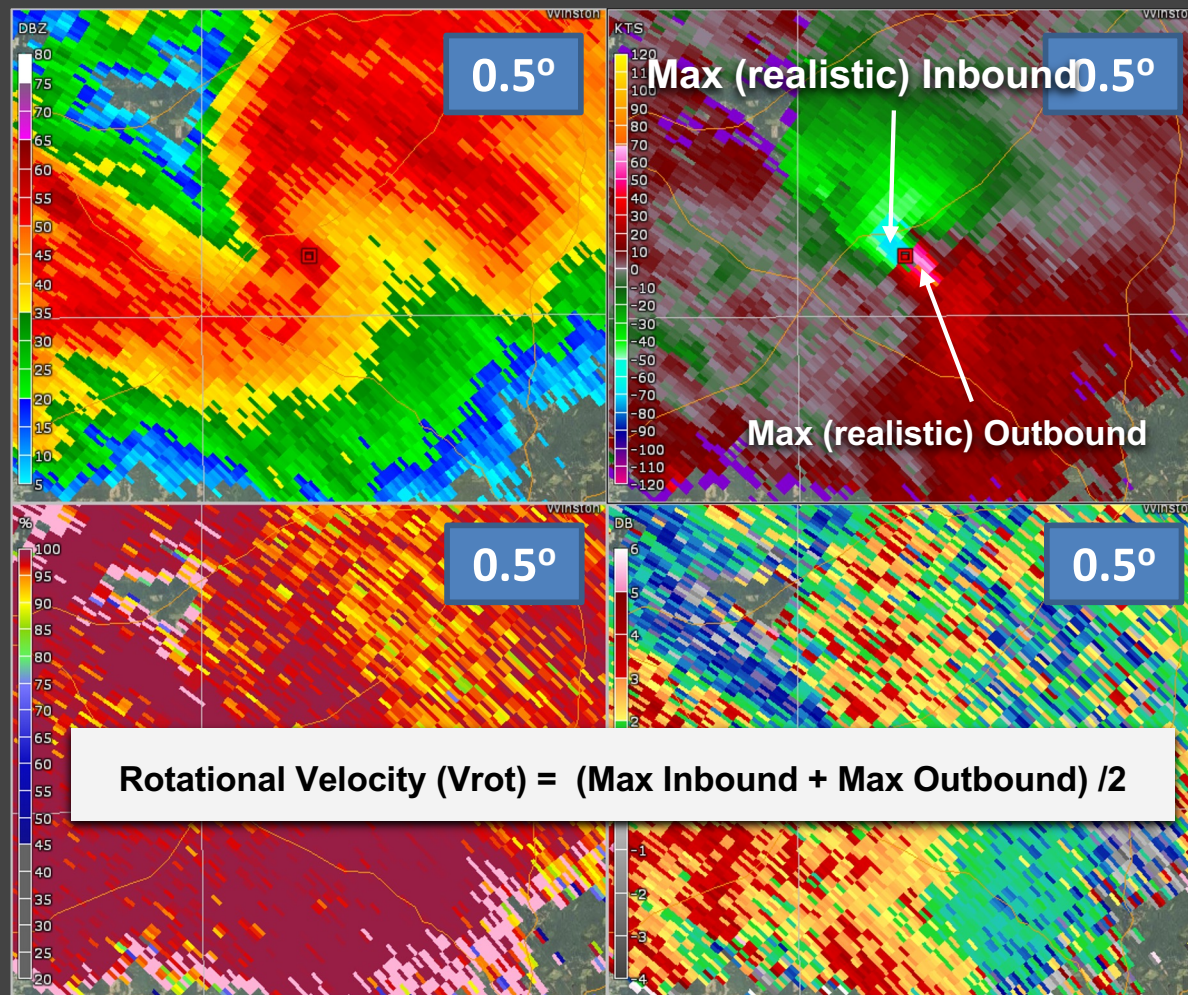
# A Quick Note on WSR-88D Tornado Signatures



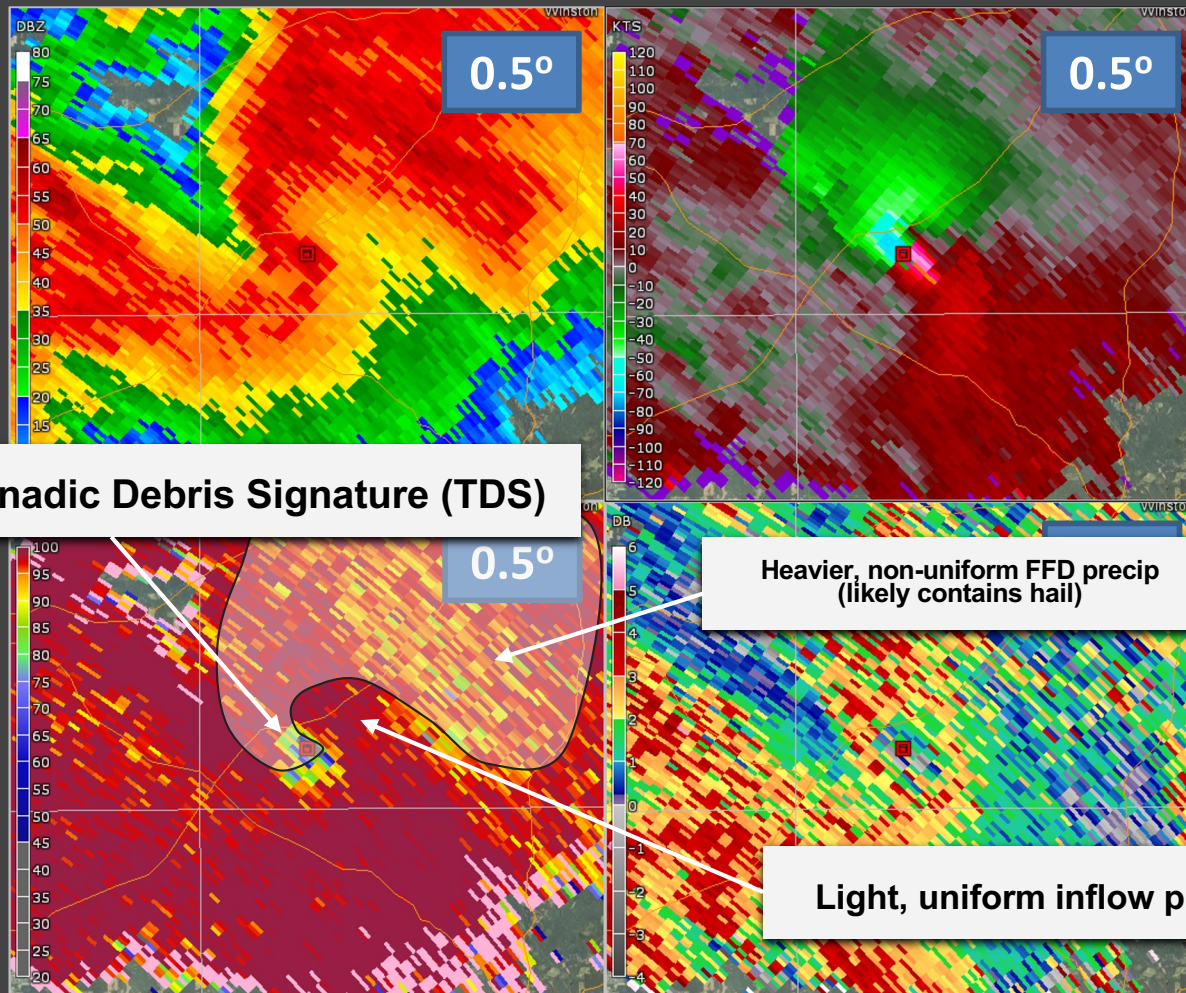
# A Quick Note on WSR-88D Tornado Signatures



# A Quick Note on WSR-88D Tornado Signatures



# A Quick Note on WSR-88D Tornado Signatures

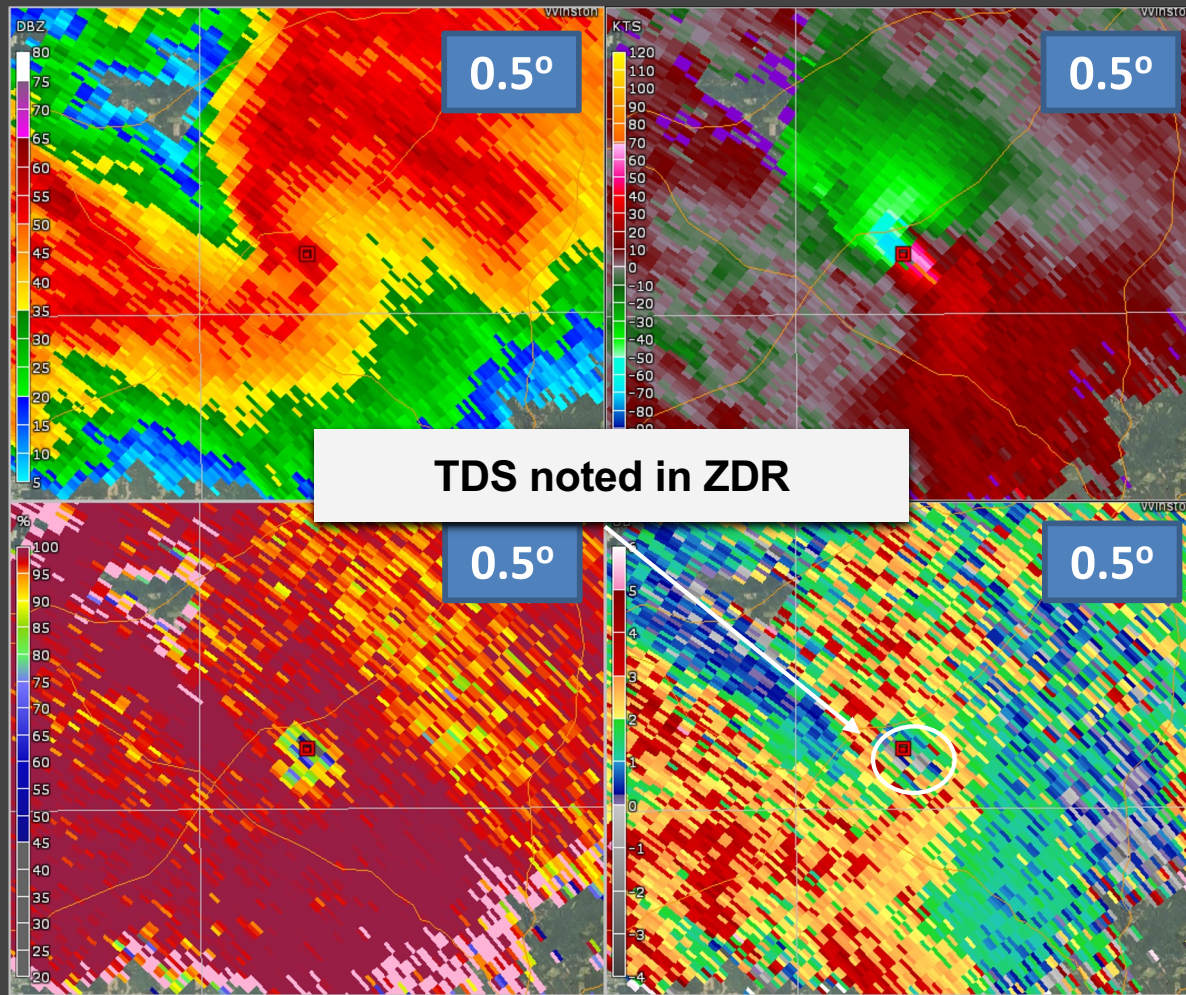


**CC minimum/Tornadic Debris Signature (TDS)**

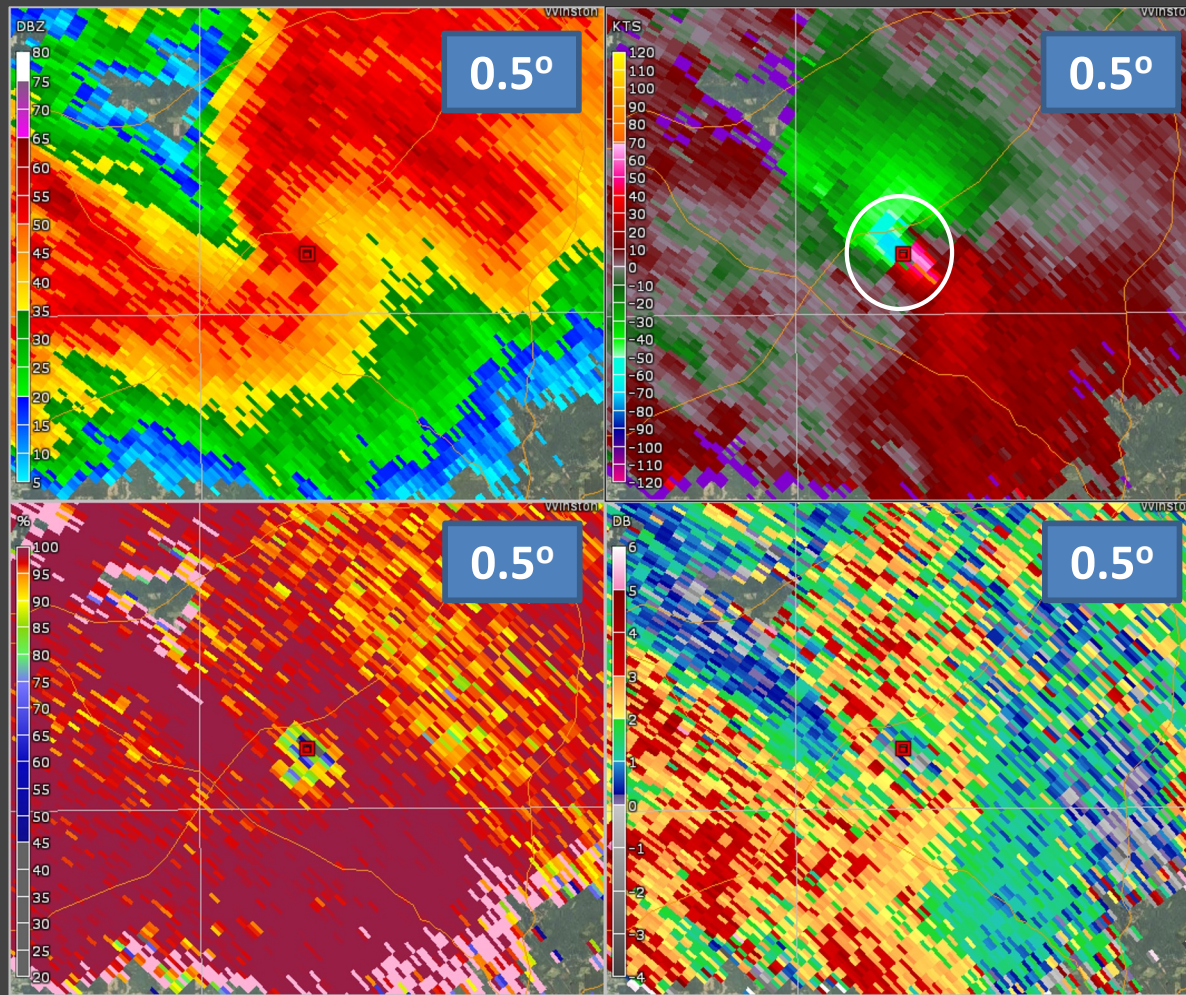
**Heavier, non-uniform FFD precip  
(likely contains hail)**

**Light, uniform inflow precipitation**

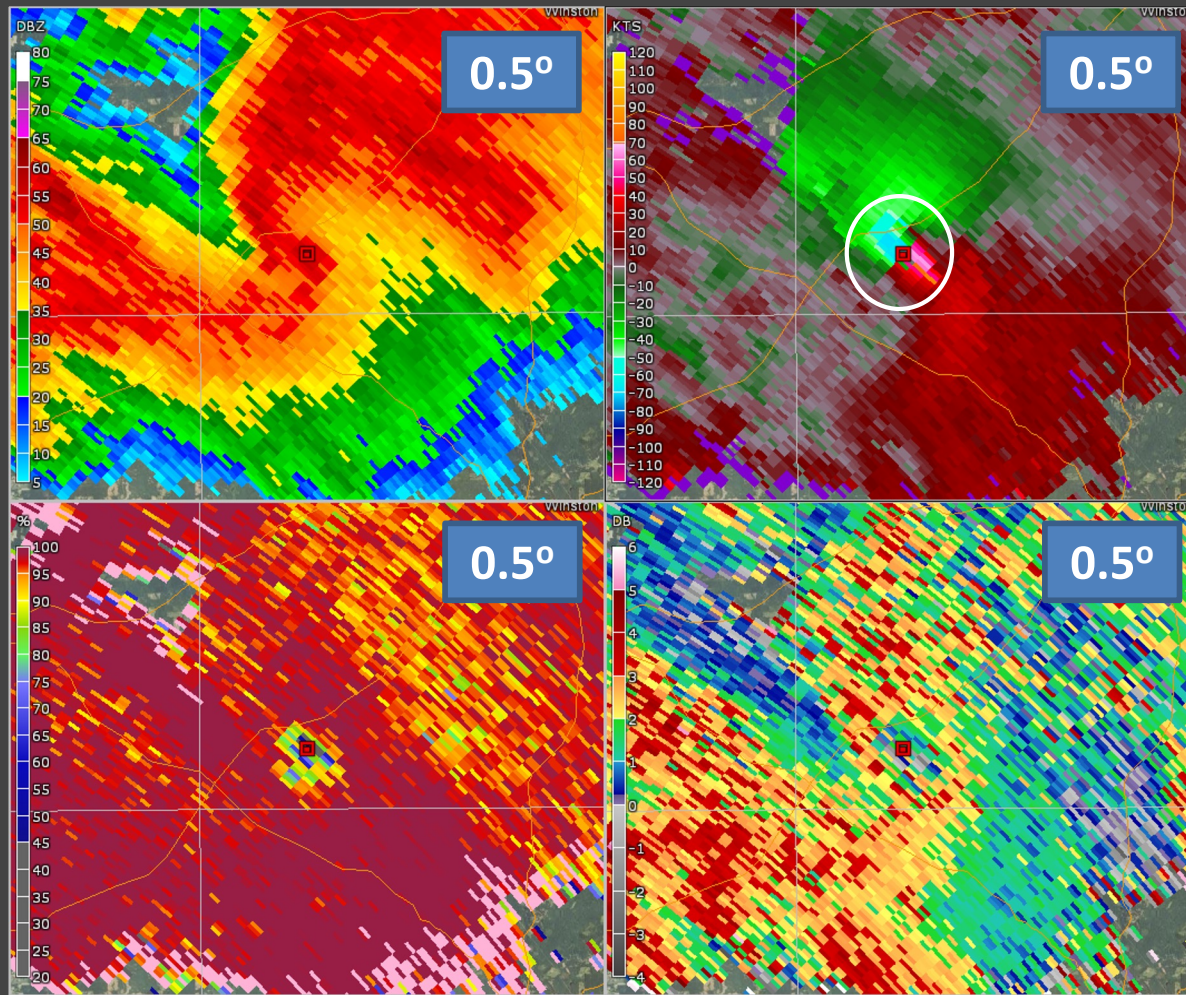
# A Quick Note on WSR-88D Tornado Signatures



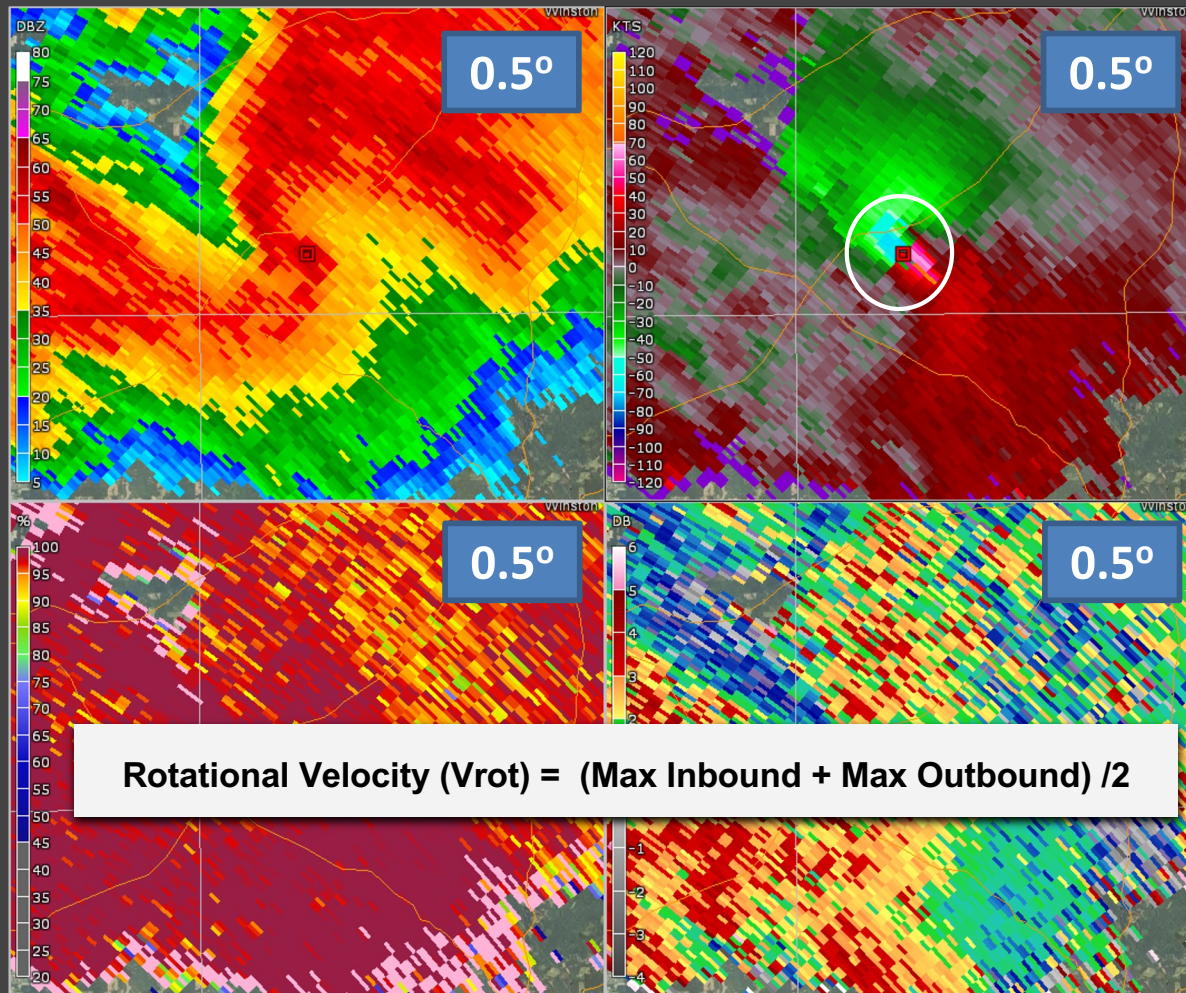
# Step 1: Identify a velocity couplet



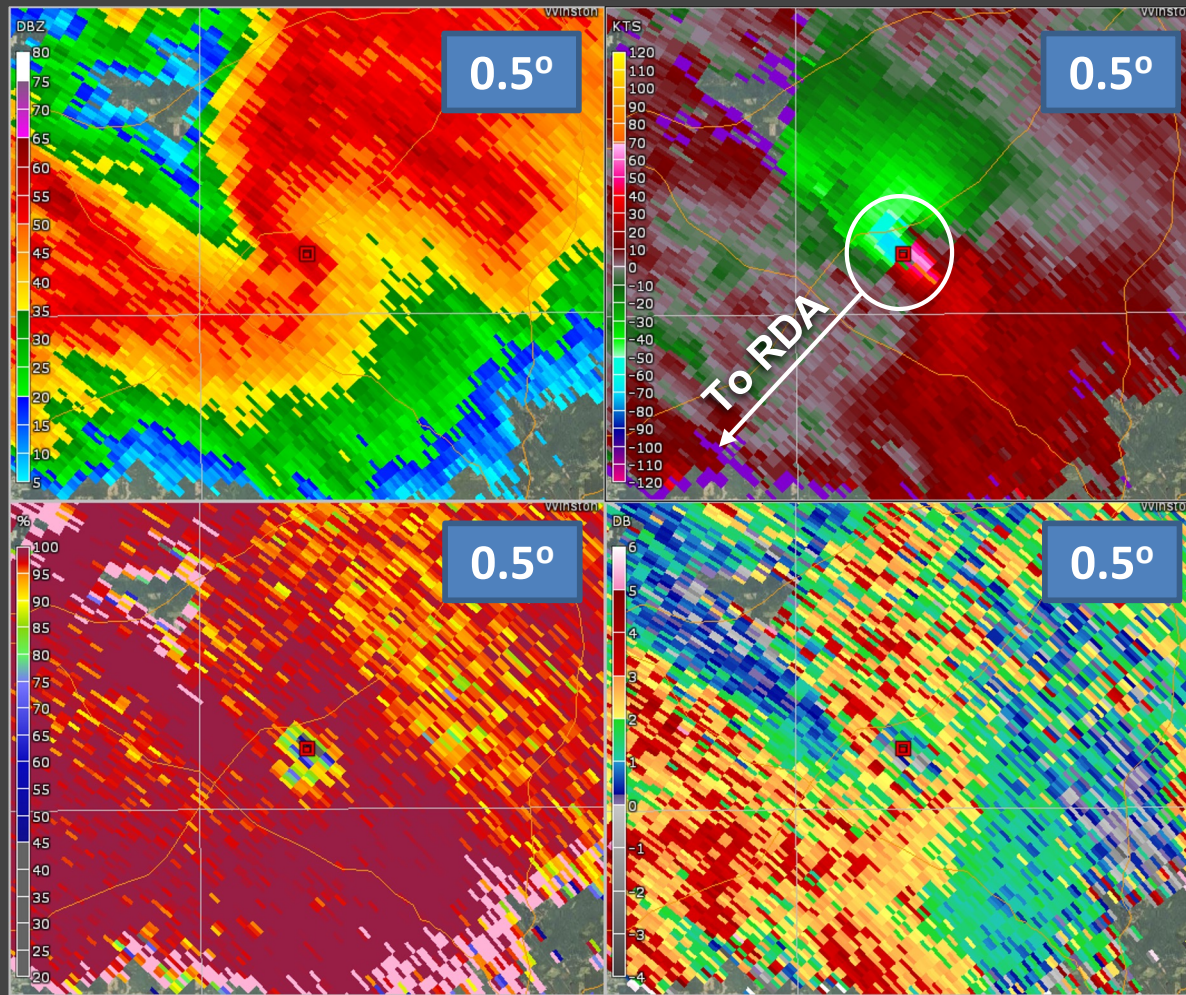
Step 2: Note distance between maxima (closer = better)



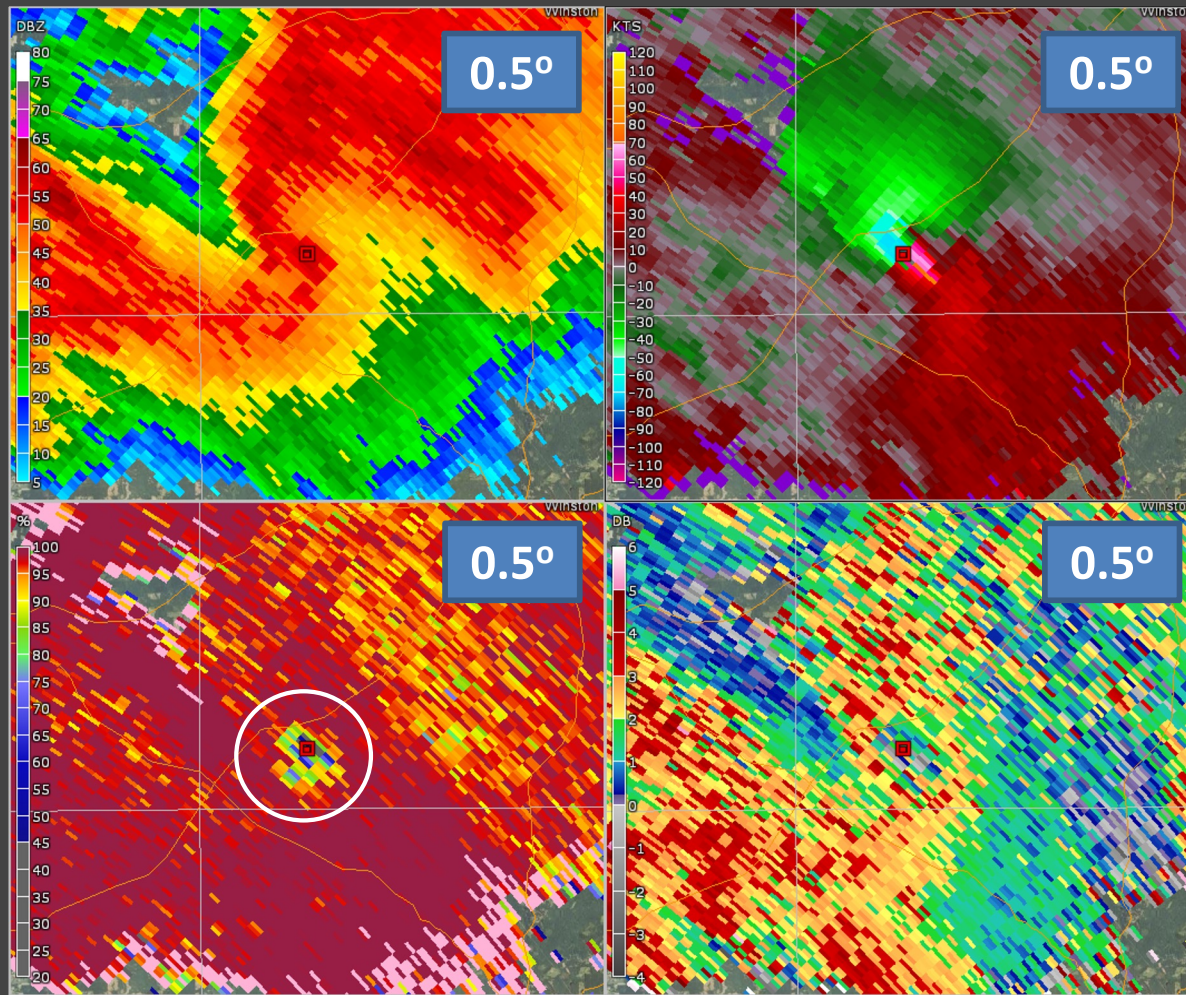
# Step 3: Find Vrot



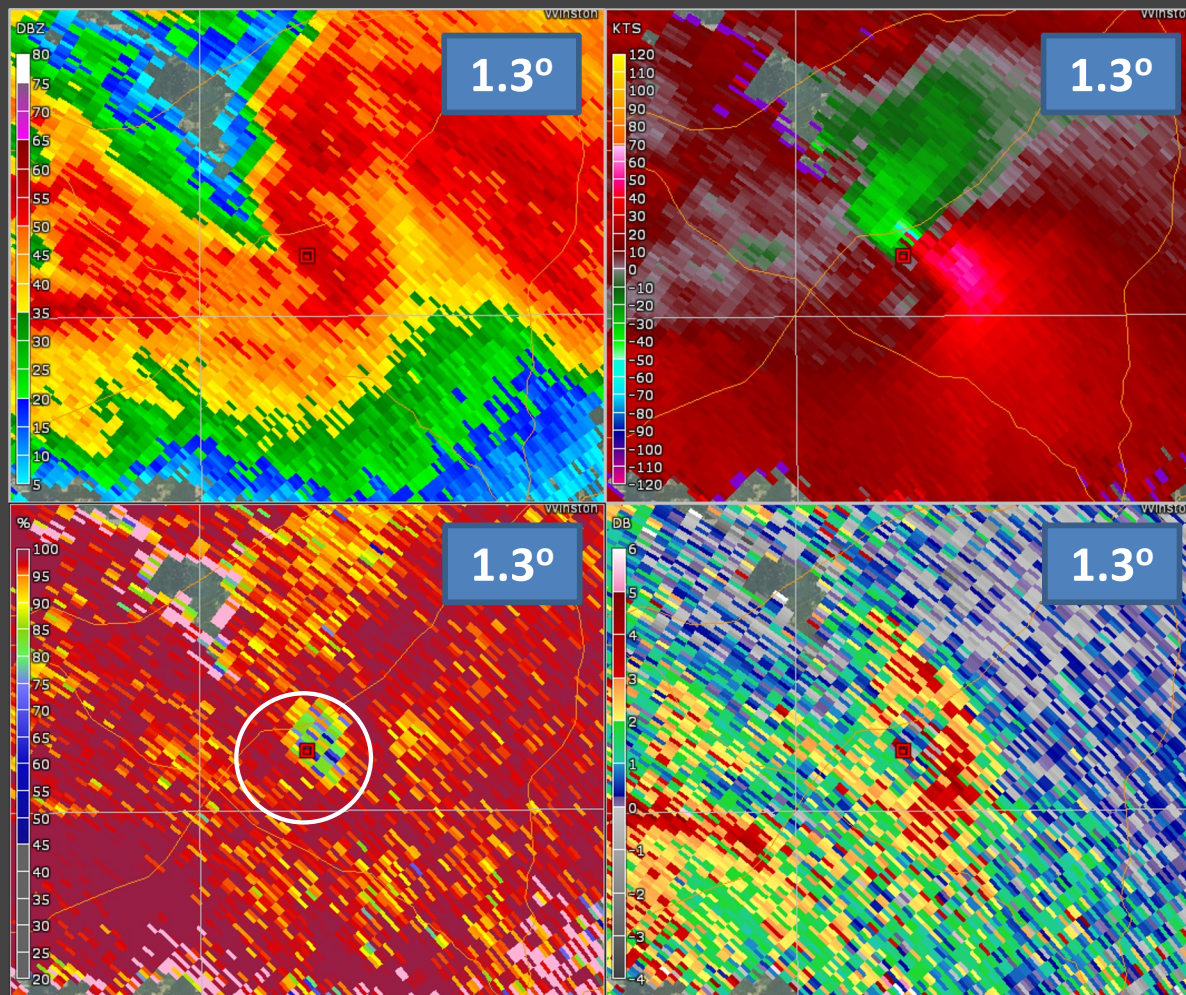
# Step 4: Note beam height/distance from radar



# Step 5: Check for TDS



# Step 6: Check TDS Height



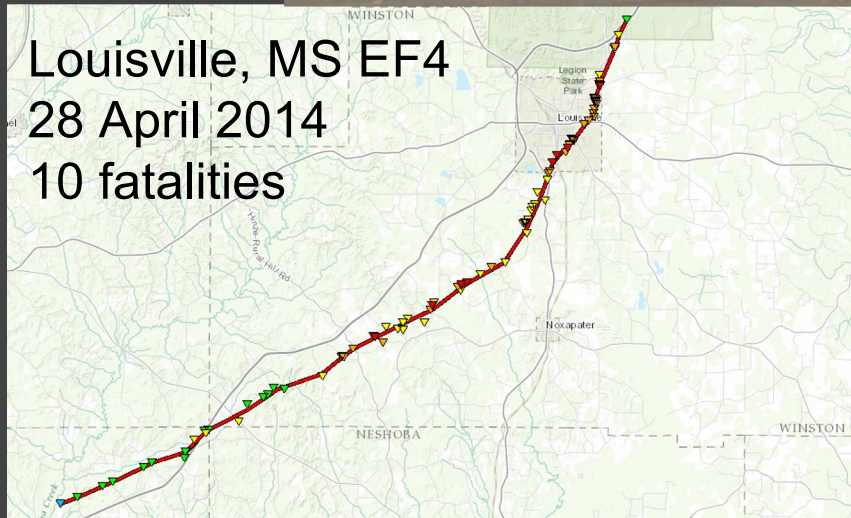
# Step 7: Check Conditional Tornado Probs

These are conditional probabilities

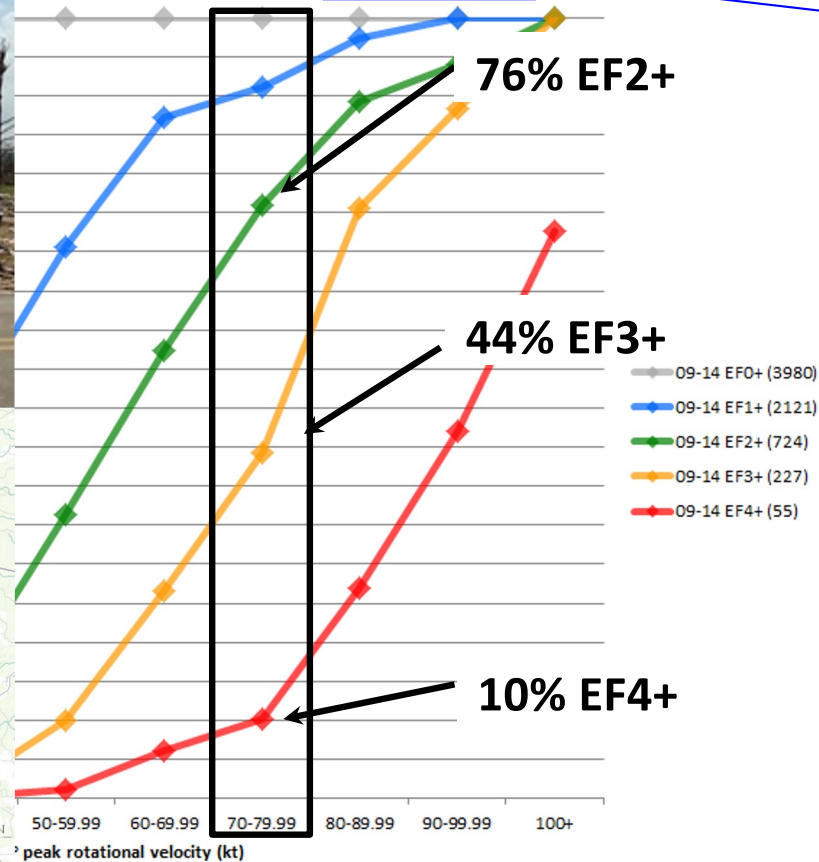
You know a tornado is occurring (TDS)



Louisville, MS EF4  
28 April 2014  
10 fatalities



RM+OICS Tornadoes (2009-2014): 0-5900 ft ARL



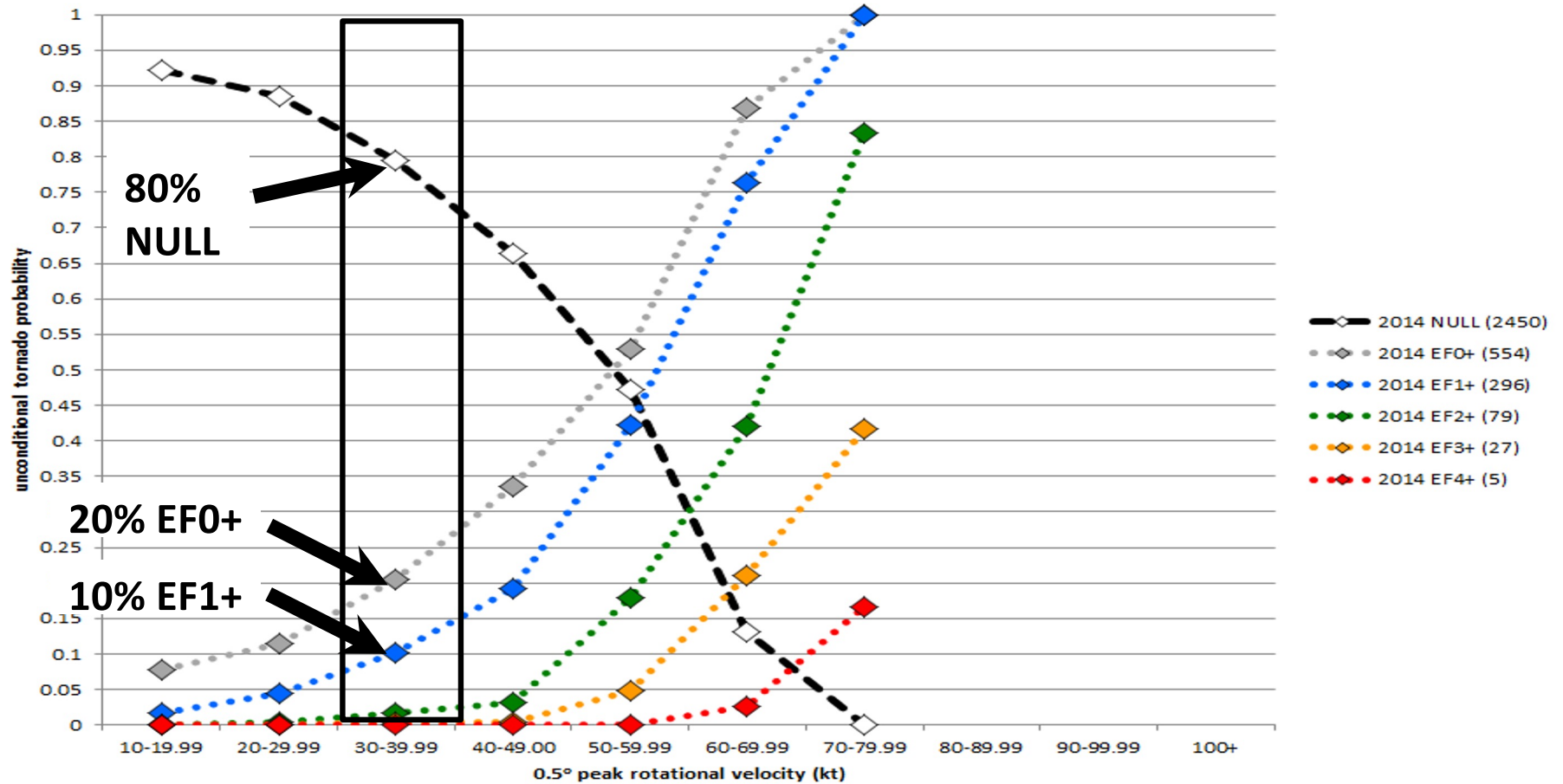
Valid for this range

# Unconditional Tornado Probabilities

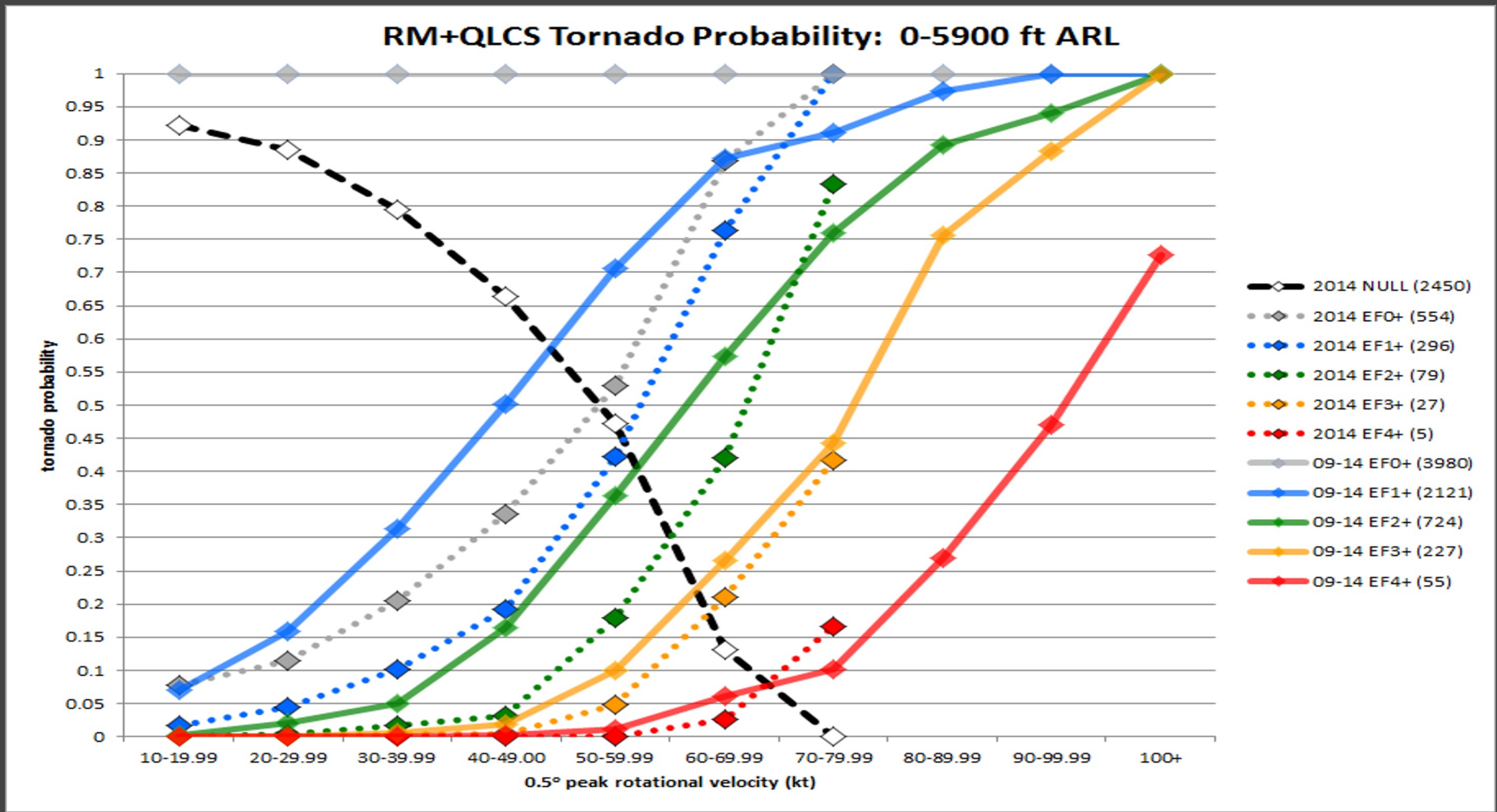
- Often don't know if a tornado is occurring in remote areas or at night
- Must consider "null" cases with low-level storm rotation to develop unconditional tornado probabilities

# Is a tornado occurring?

RM+QLCS Tornadoes and NULLs (2014): 0-5900 ft ARL



# Combined Tornado Probabilities

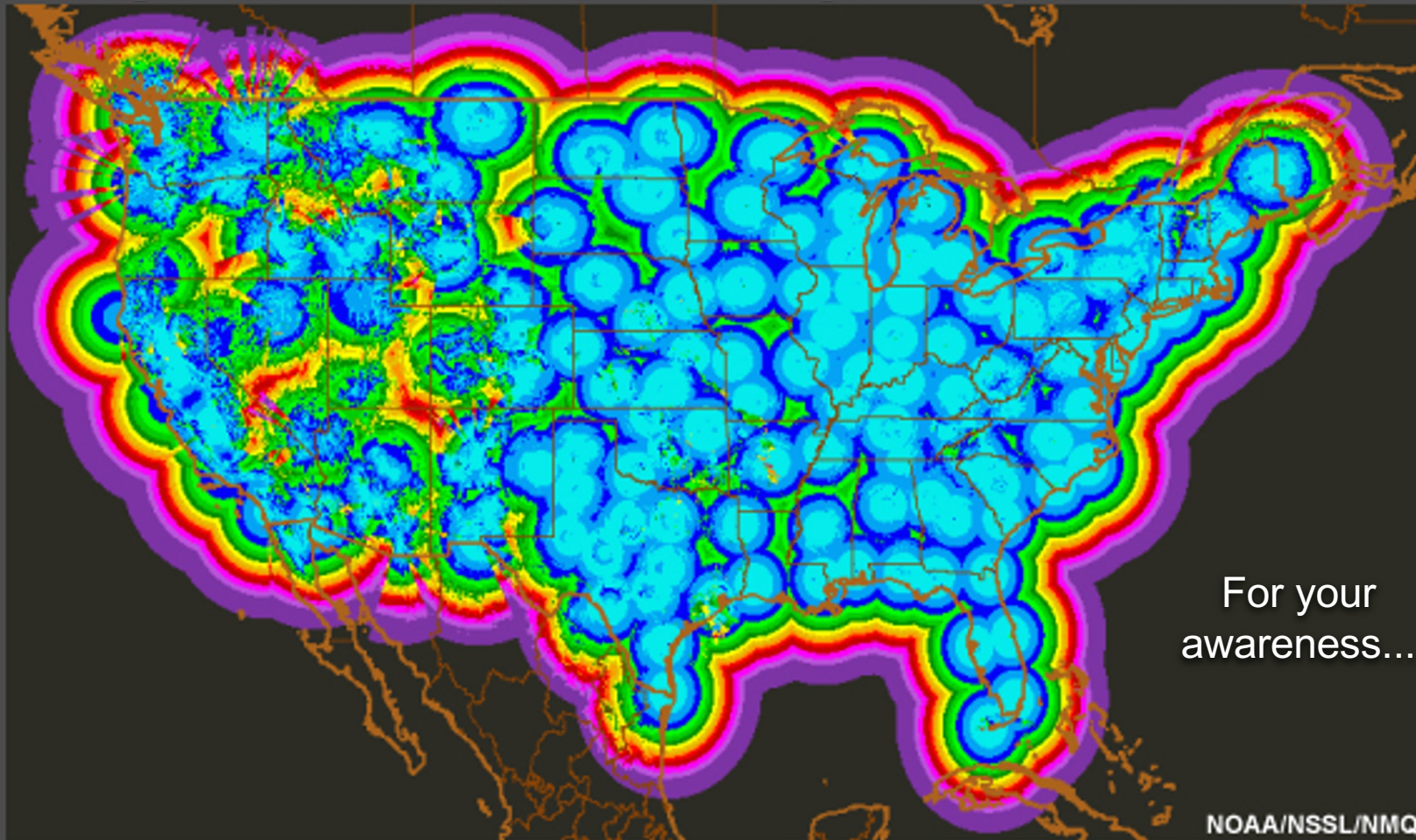


# Need to consider influences of beam height/range

- Lower tornado probabilities with distant circulations sampled well above ground
- Higher tornado probabilities with closer circulations sampled near the ground



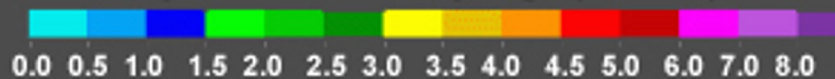
# Height Above Ground Level of Radar Coverage, 1755 UTC 10 November 2008



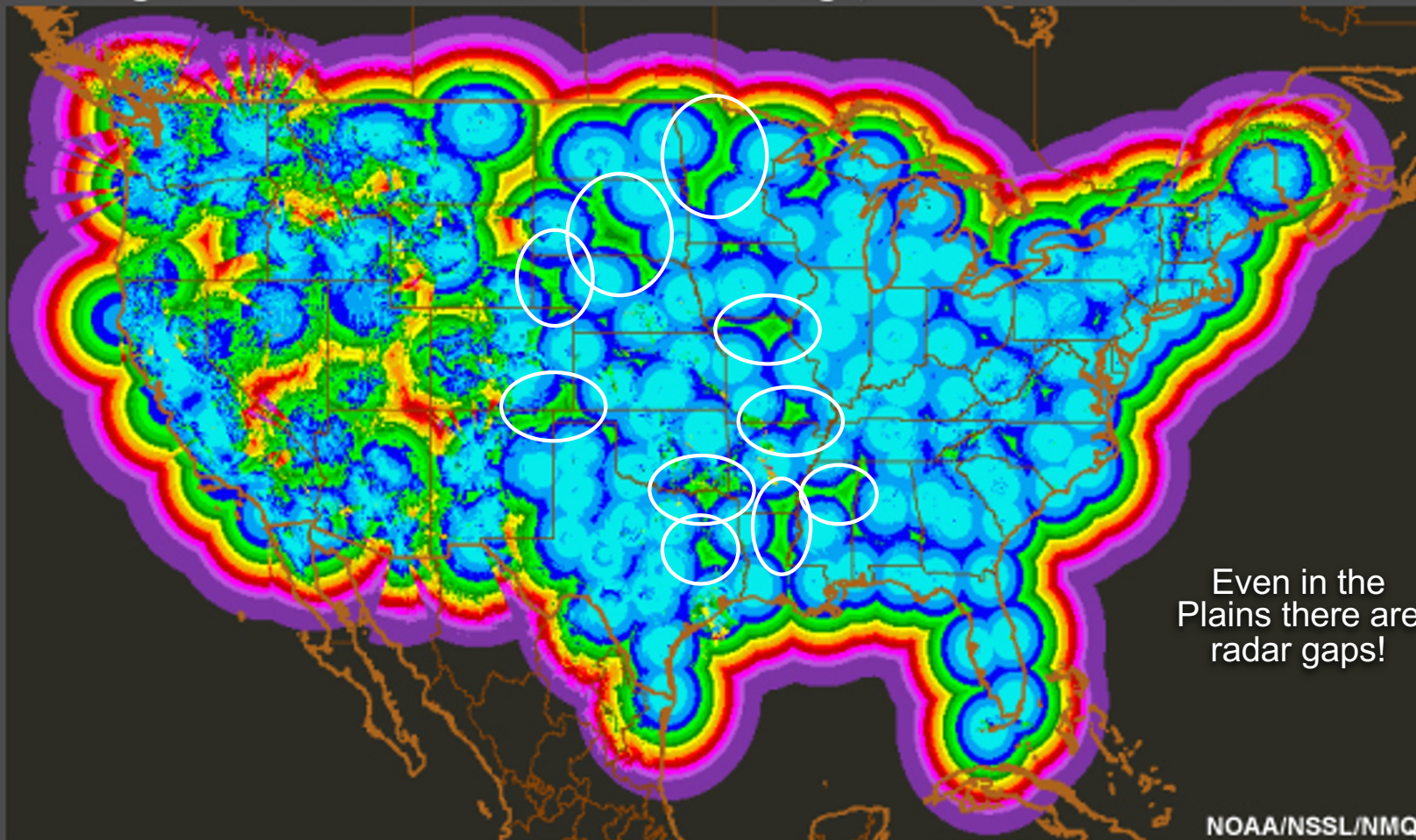
For your awareness...

NOAA/NSSL/NMQ

Hybrid Scan Reflectivity Height (km - AGL)



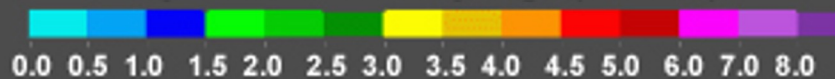
# Height Above Ground Level of Radar Coverage, 1755 UTC 10 November 2008



Even in the  
Plains there are  
radar gaps!

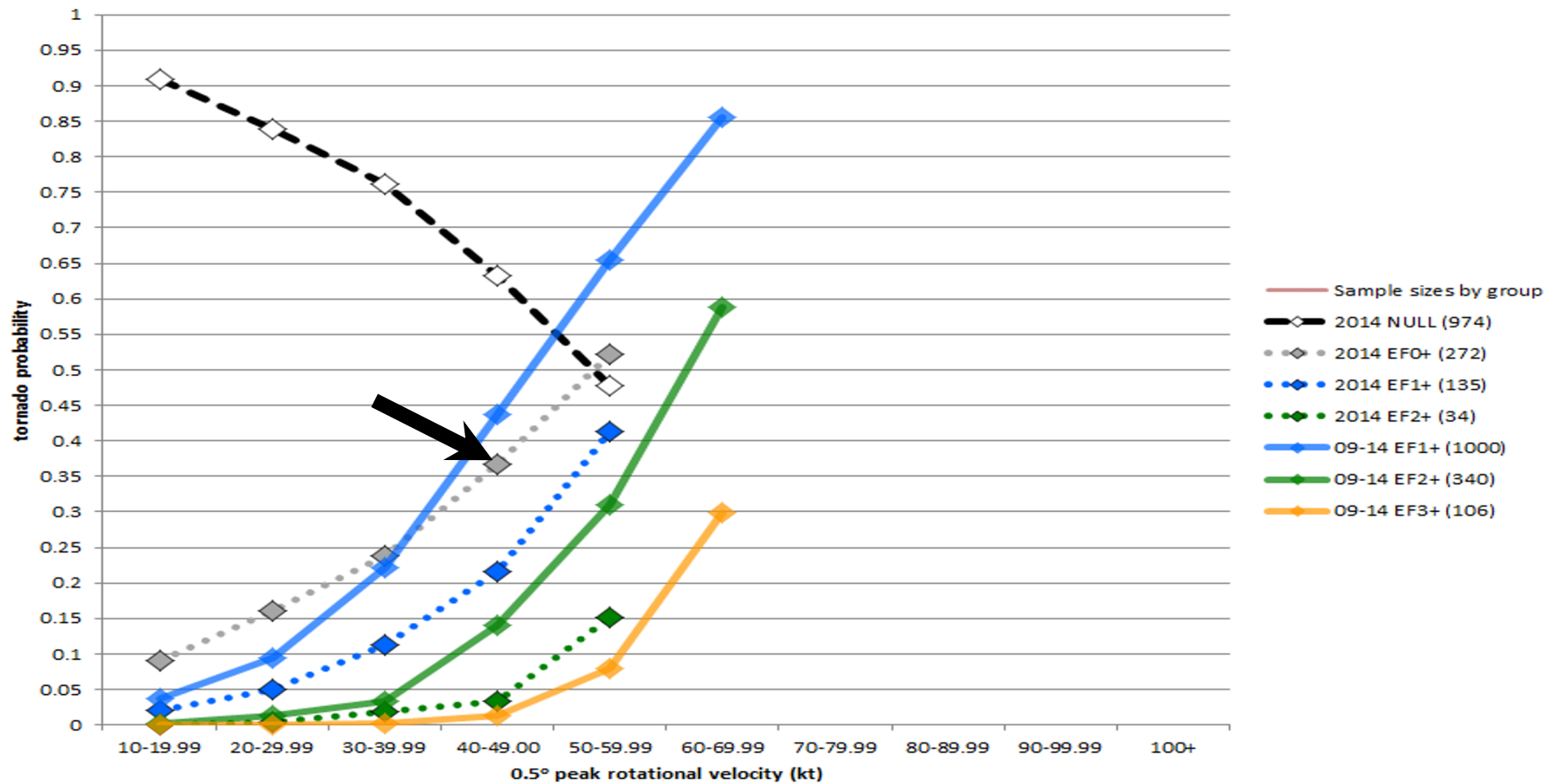
NOAA/NSSL/NMQ

Hybrid Scan Reflectivity Height (km - AGL)



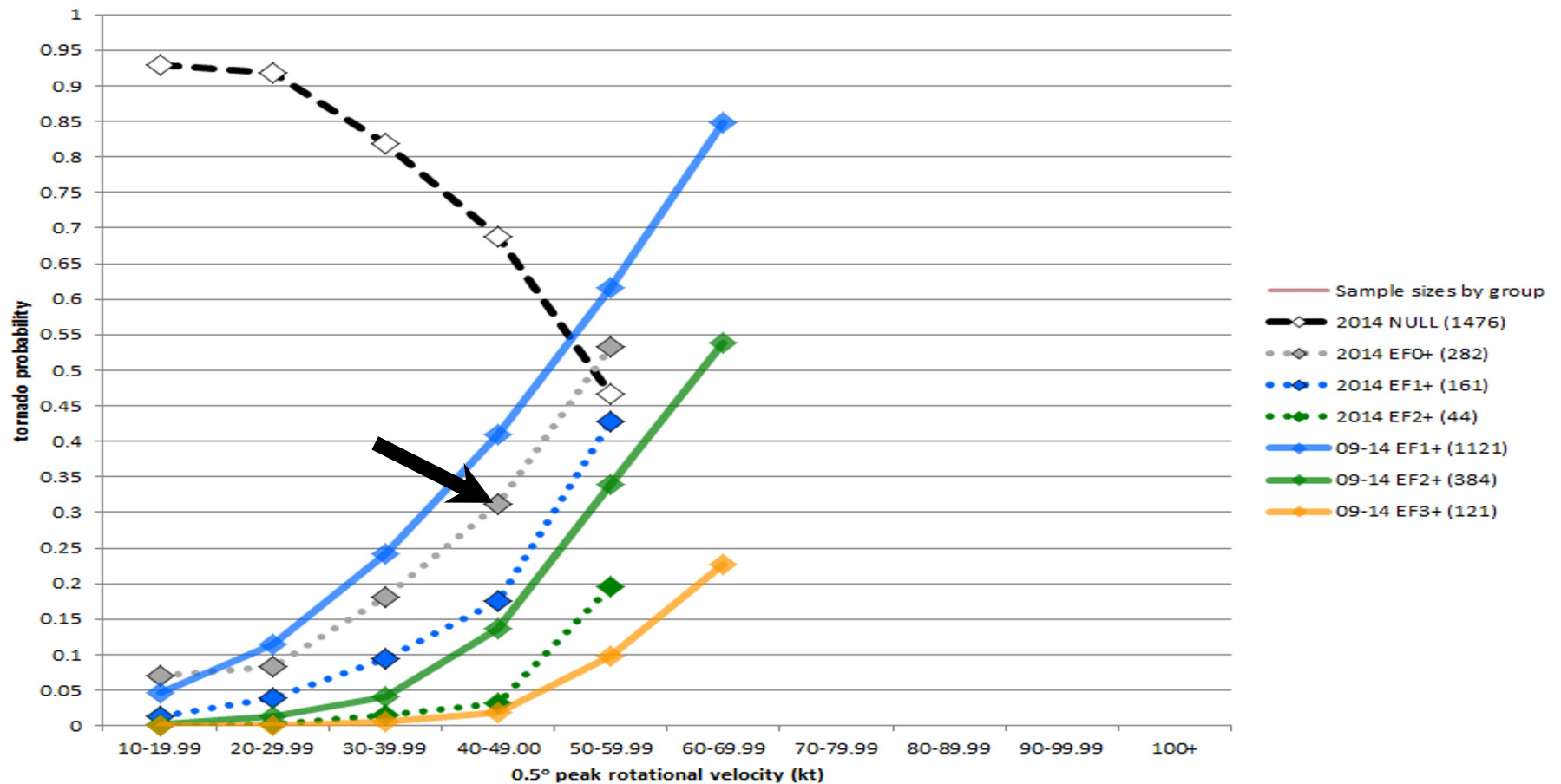
# Variations by height ARL

RM+QLCS Tornadoes: 0-2900 ft ARL



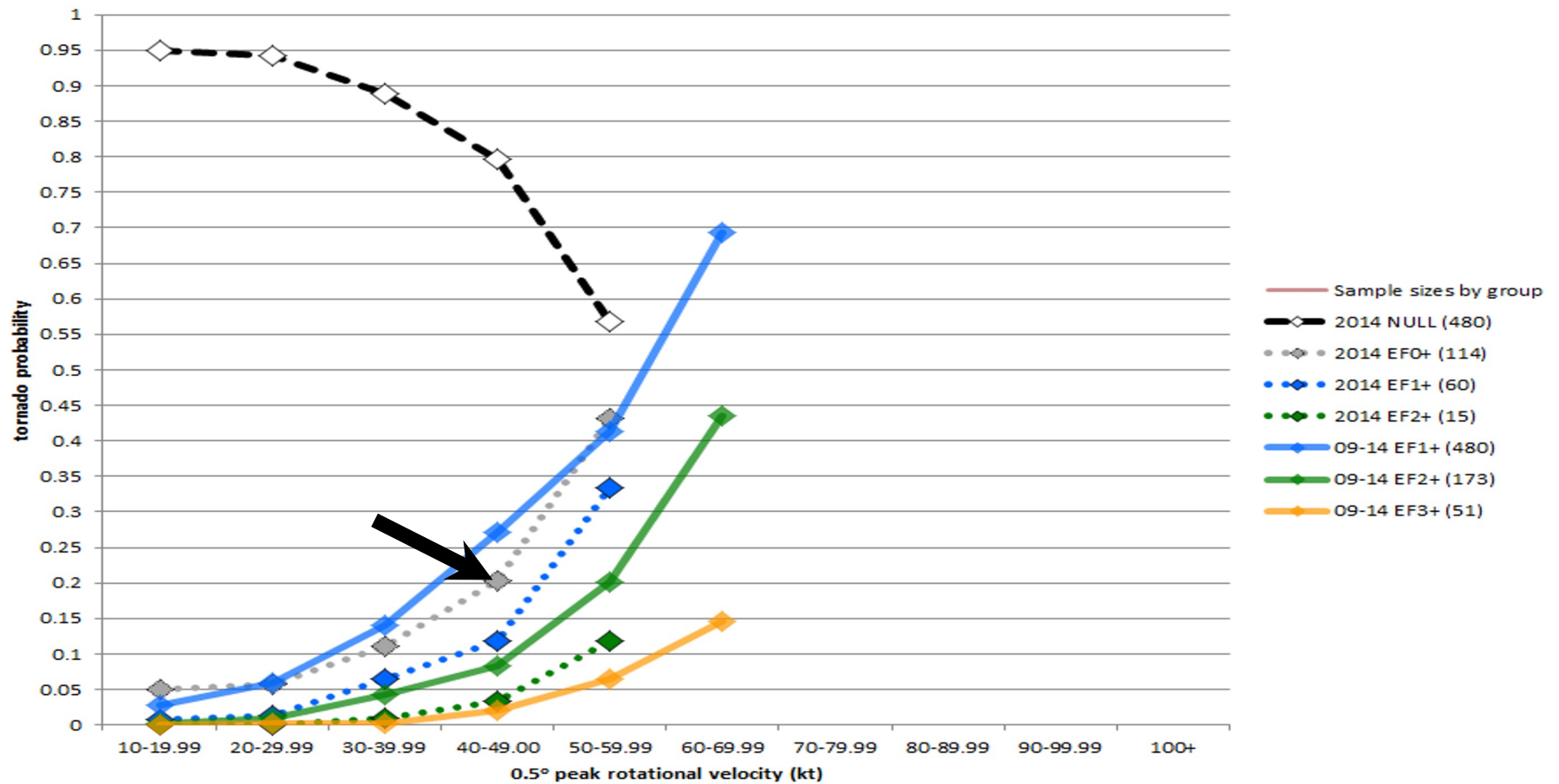
# Variations by height ARL

RM+QLCS Tornadoes: 3000-5900 ft ARL



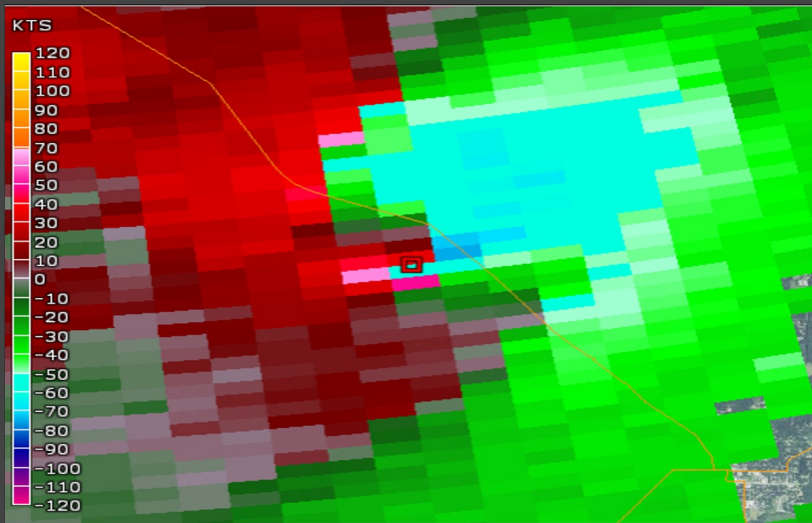
# Variations by height ARL

RM+QLCS Tornadoes: 6000-9900 ft ARL

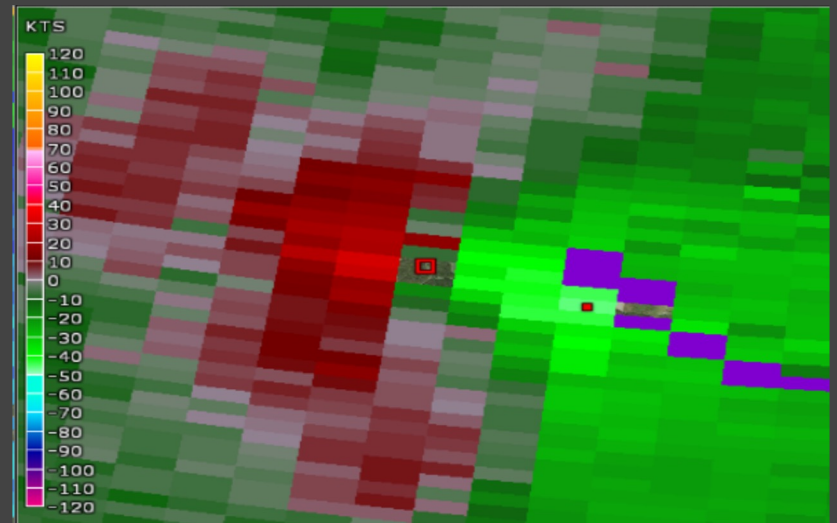


# Need to consider influences of circulation diameter

- Lower tornado probabilities with broad circulations
- Higher tornado probabilities with tight circulations

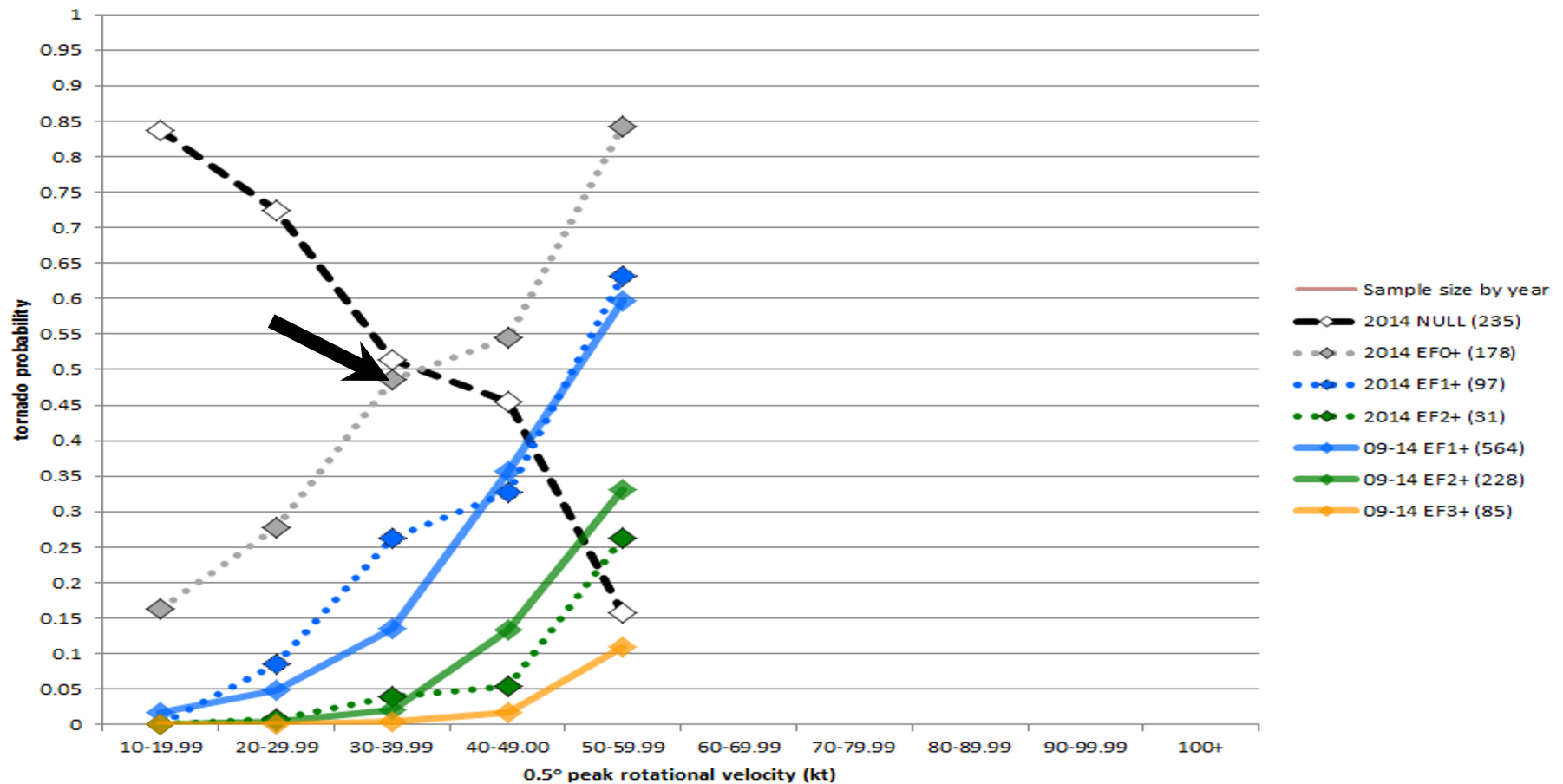


VS.



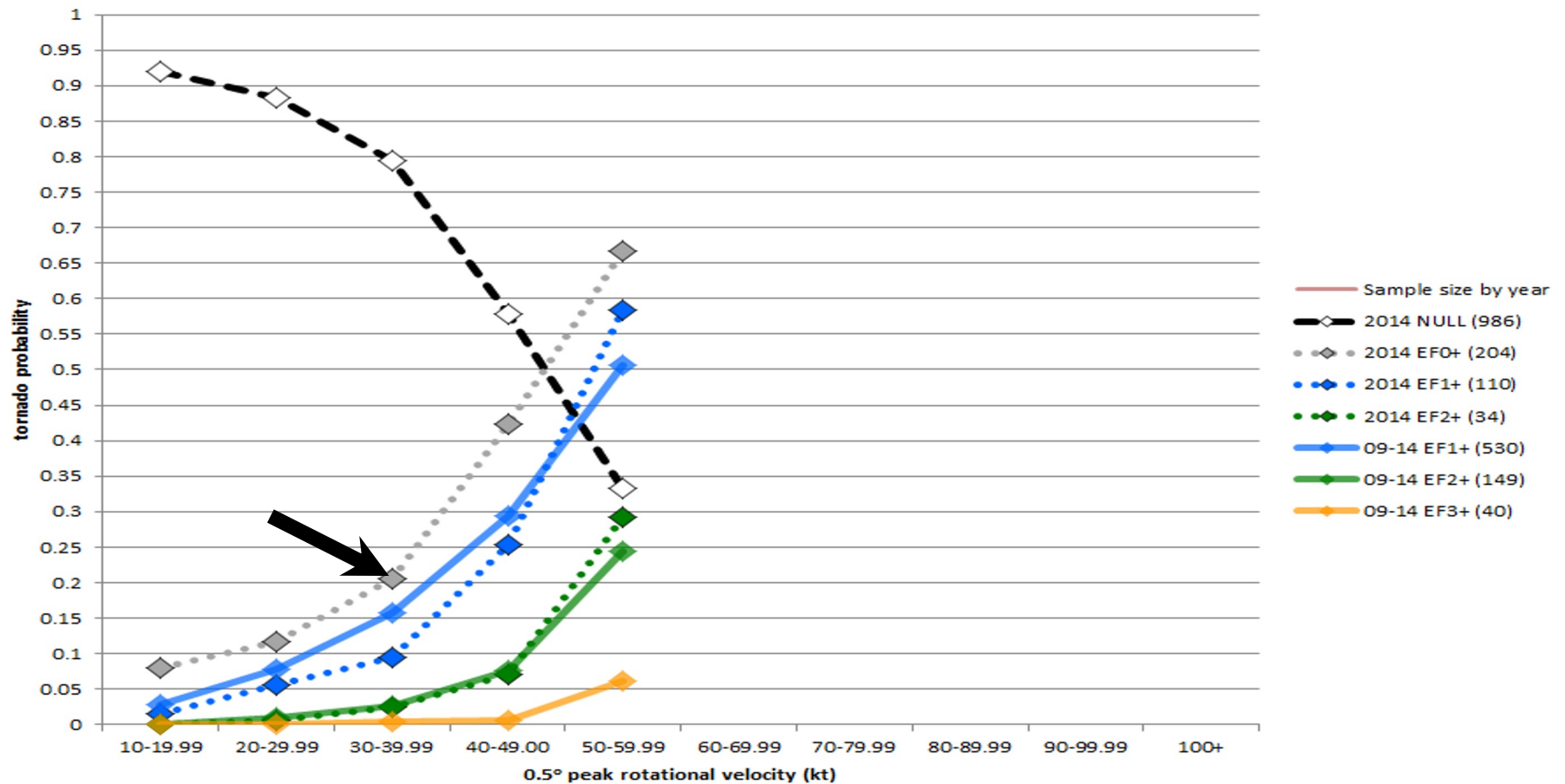
# Variations by circulation diameter

RM+QLCS Tornadoes: 0-5900 ft ARL and <1 nmi diameter



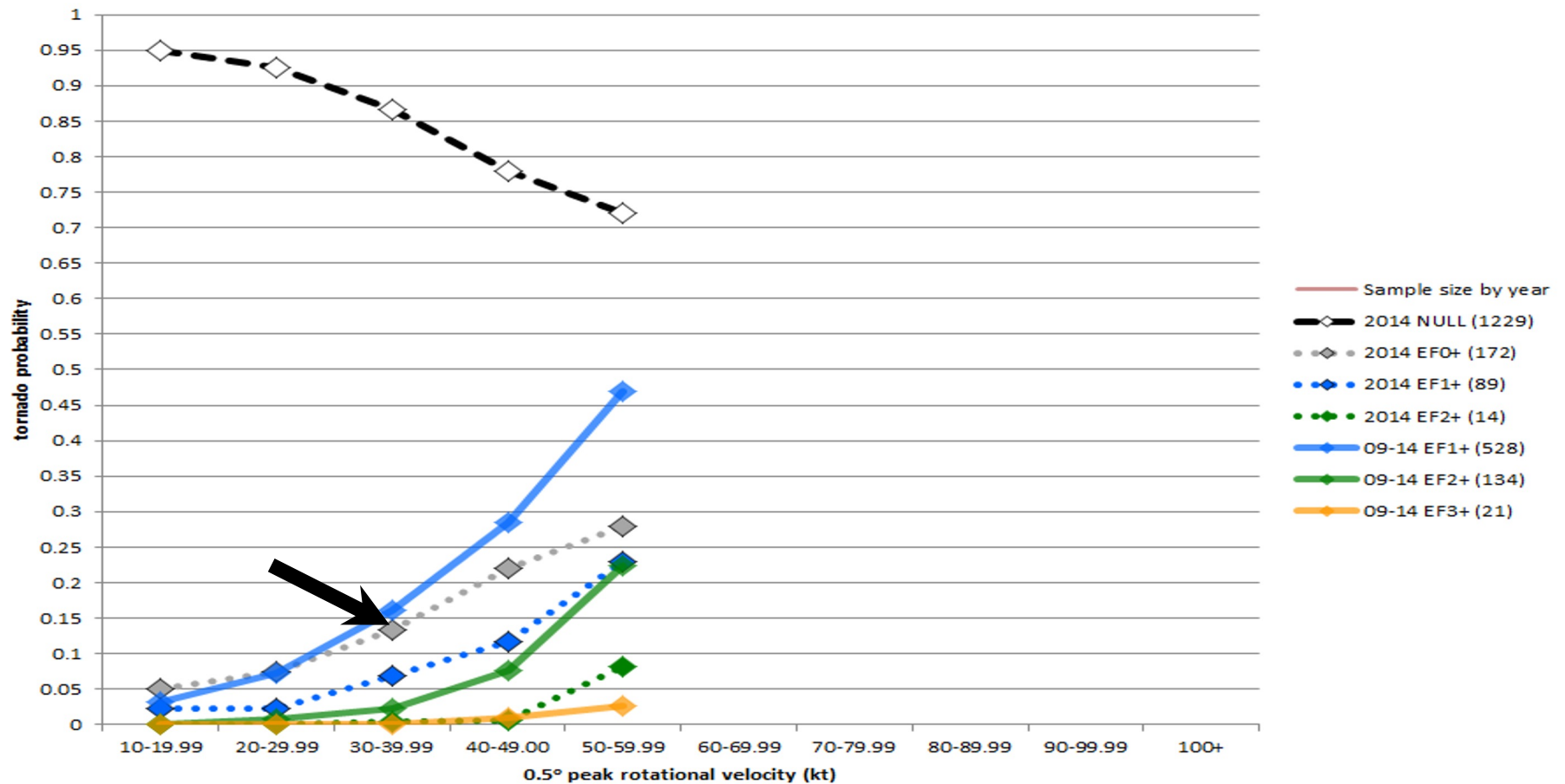
# Variations by circulation diameter

RM+QLCS Tornadoes: 0-5900 ft ARL and 1-2 nmi diameter



# Variations by circulation diameter

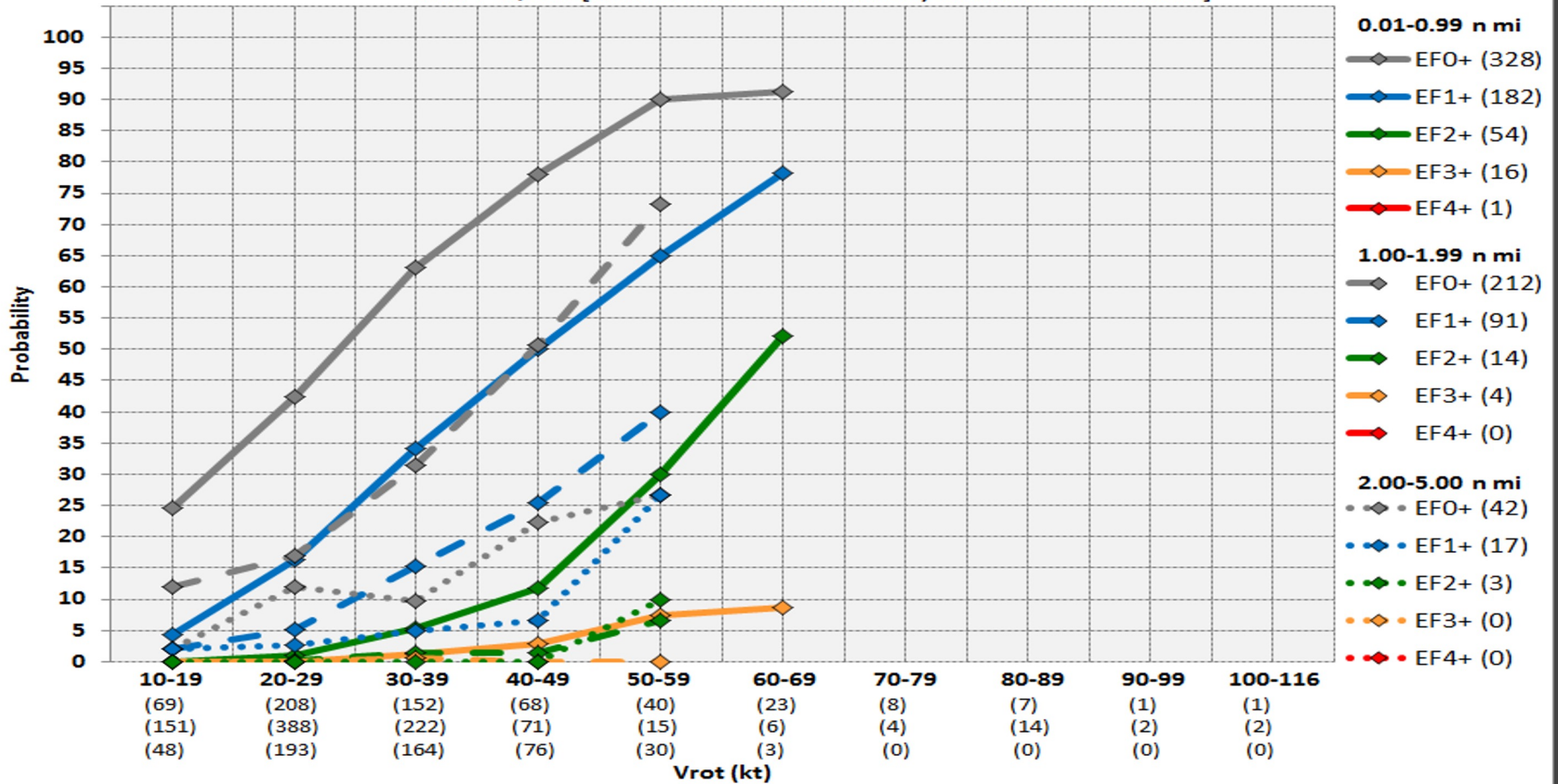
RM+QLCS Tornadoes: 0-5900 ft ARL and >2 nmi diameter





# Conditional Probs by Distance

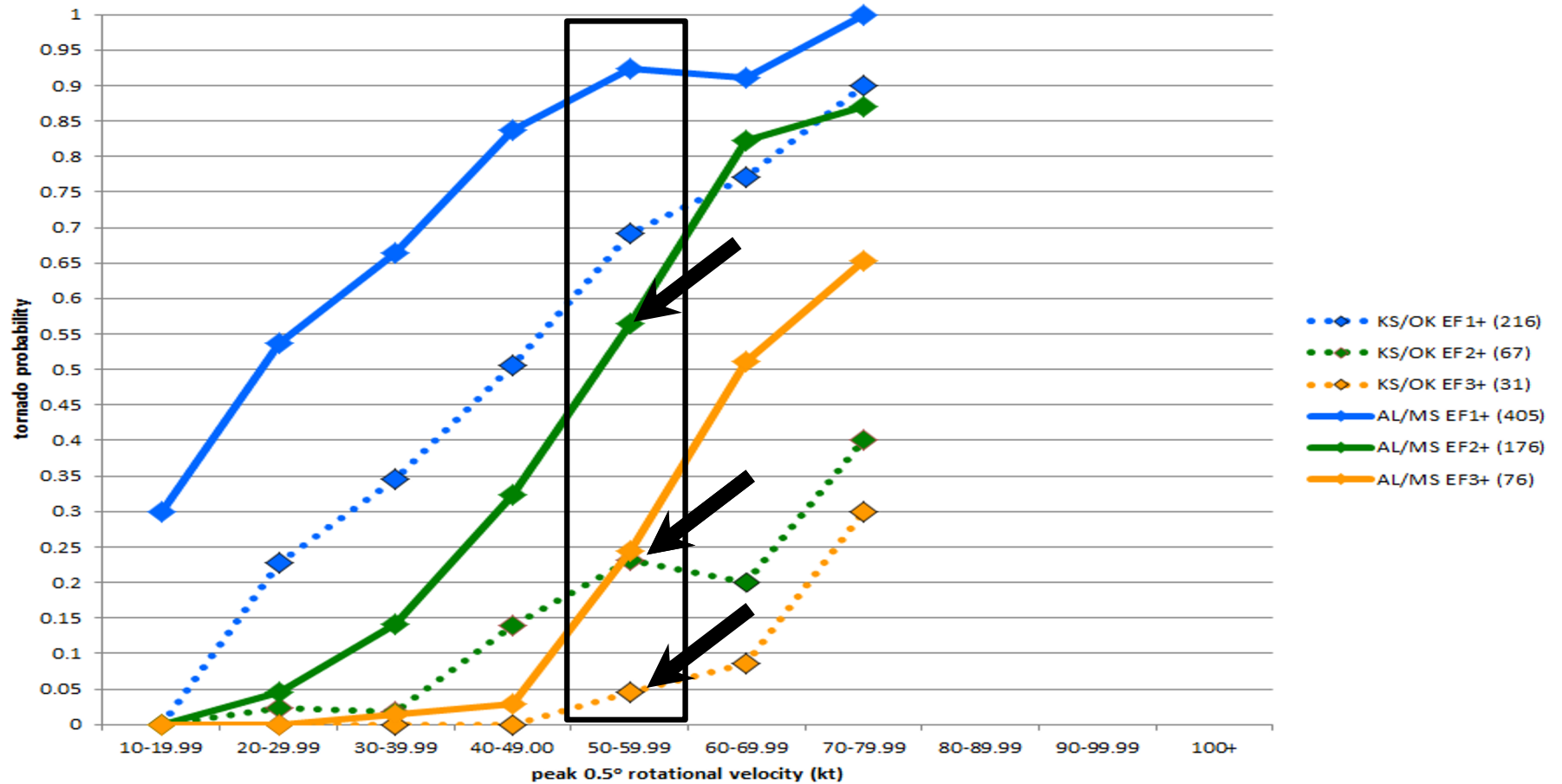
Conditional Probability of tornado damage intensity (0.5° peak rotational velocity)  
 RM + QLCS [events 100-2900 ft ARL by circulation diameter]





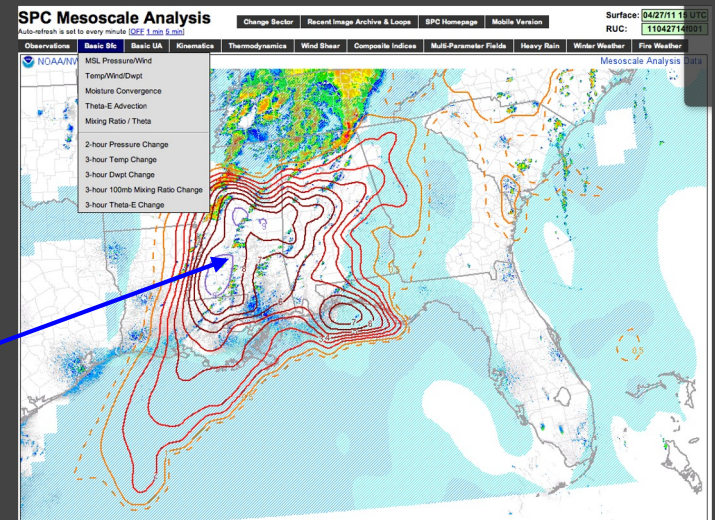
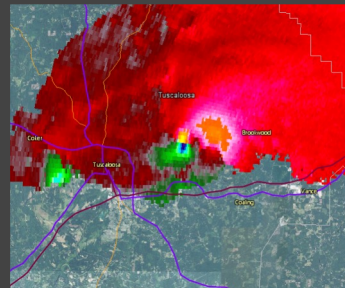
# What about regional differences?

RM+QLCS Tornadoes (2009-2014): 0-5900 ft ARL

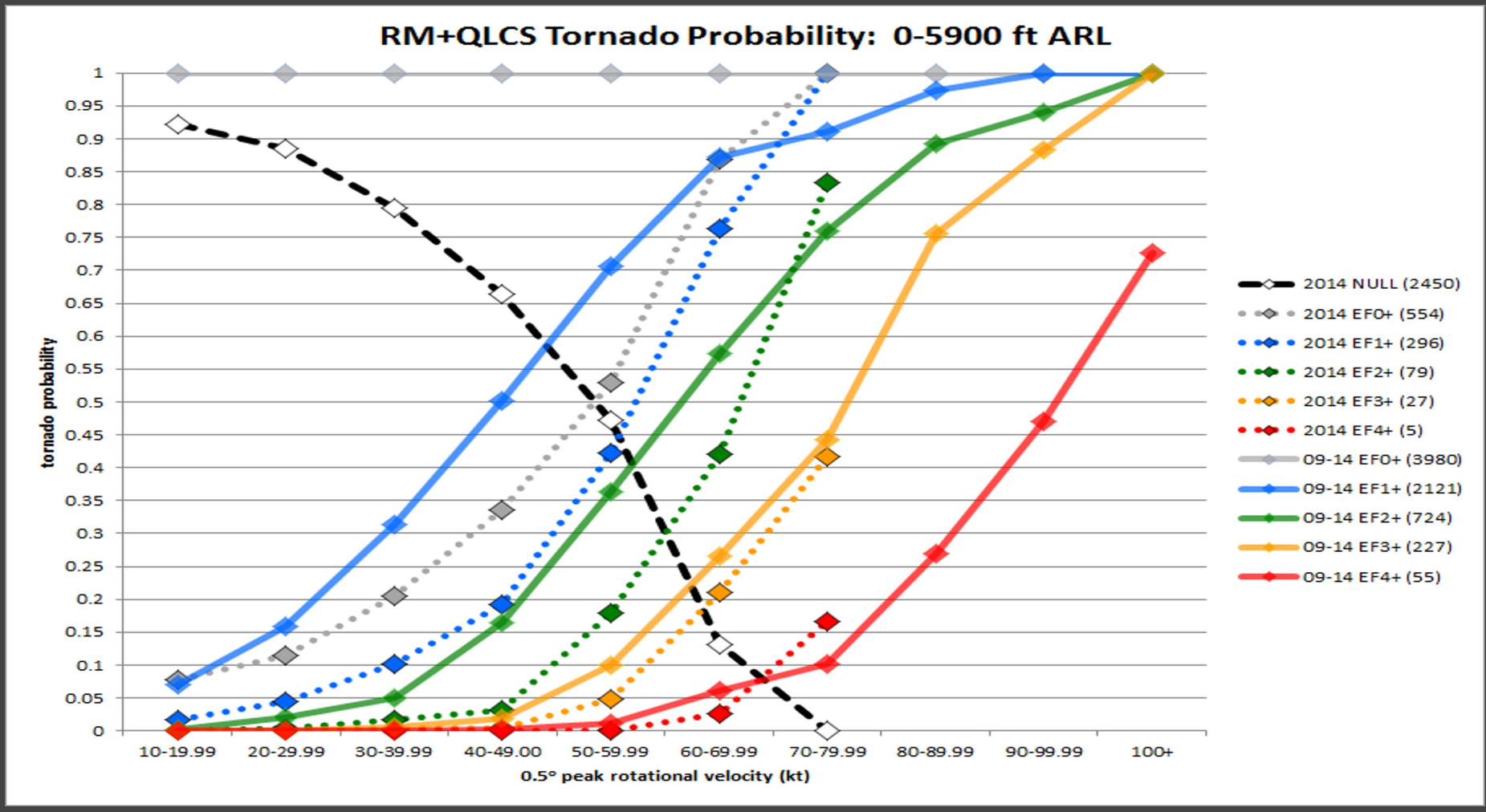


# Need to consider storm environment

- So far we've only considered WSR-88D signatures, but the env can help!
- Try to keep the environment estimate simple
  - Look at significant tornado parameter (STP)
  - Take max value within 80 km of each storm
    - Forecasters consider more than a point value!

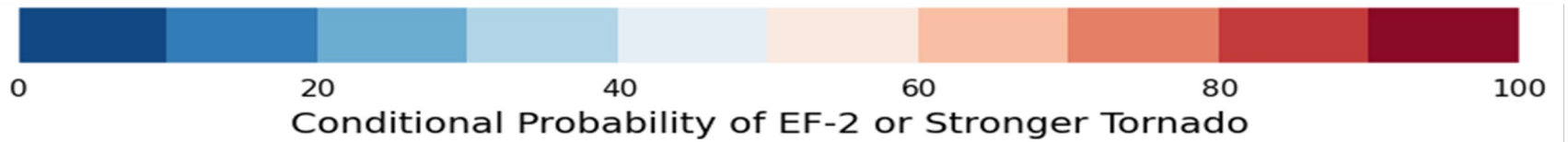
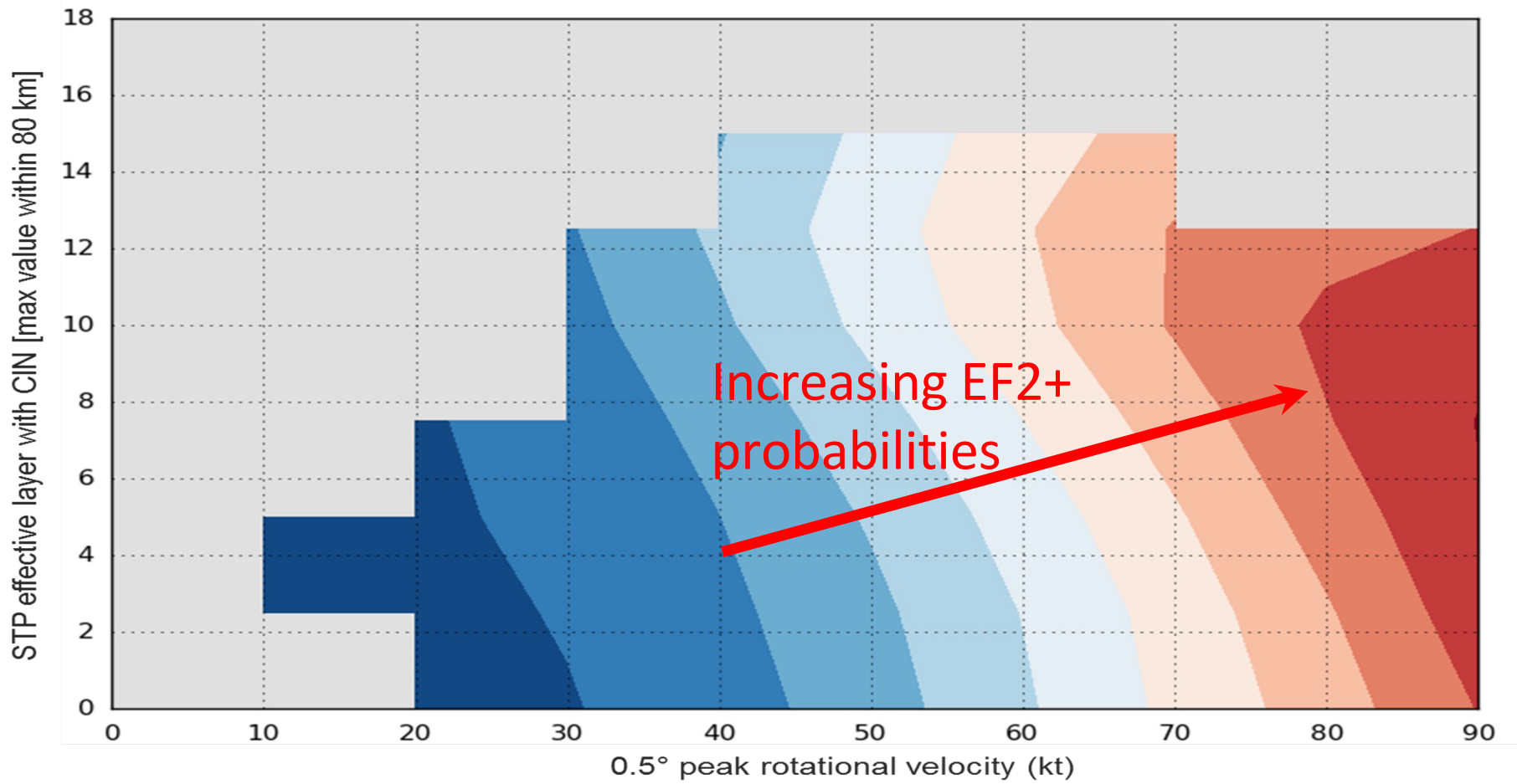


# Tornado Probabilities by Vrot



# Tornado Probabilities by Eff. STP





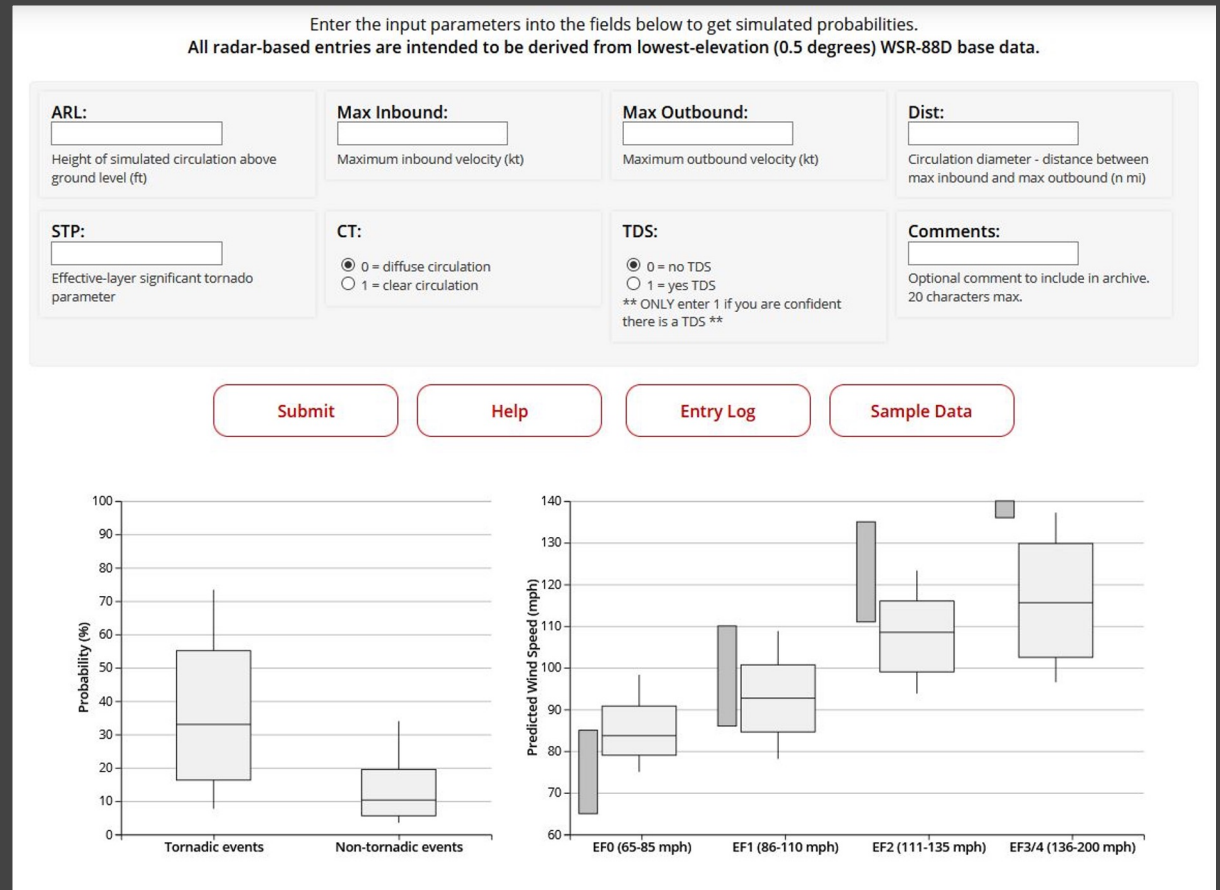
# Tornado Probabilities by Eff. STP

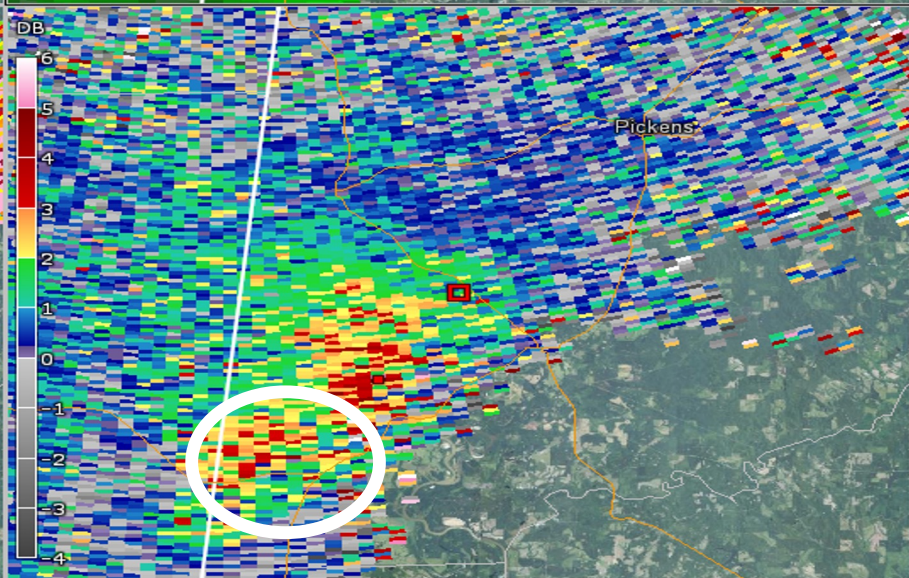
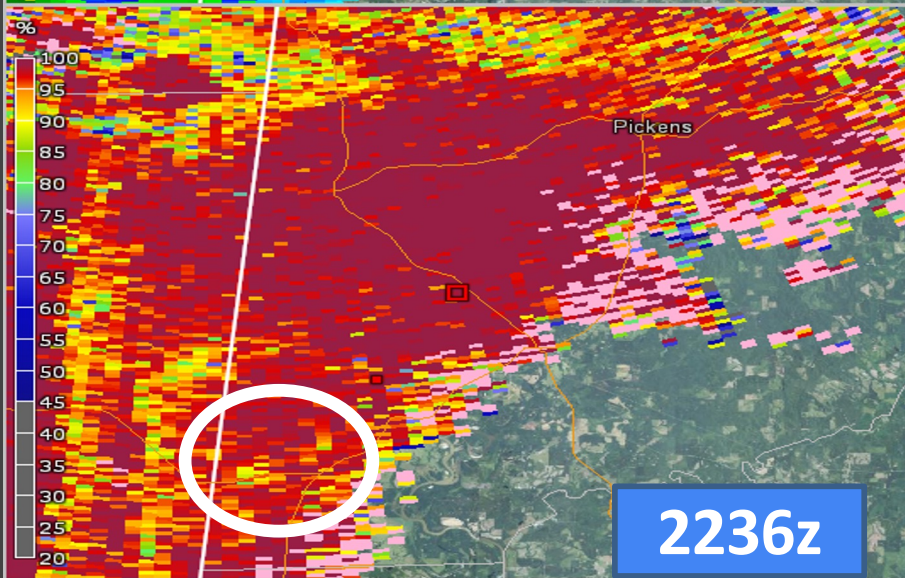
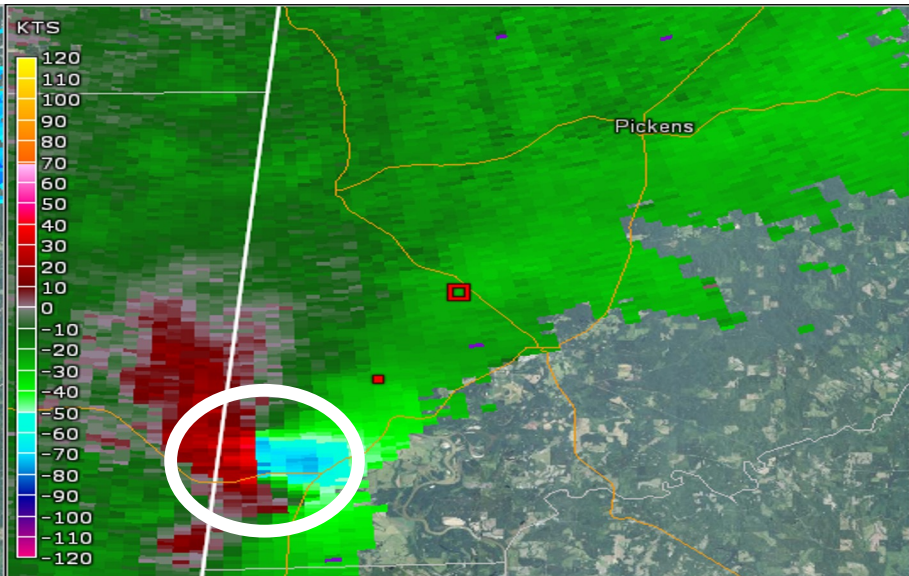
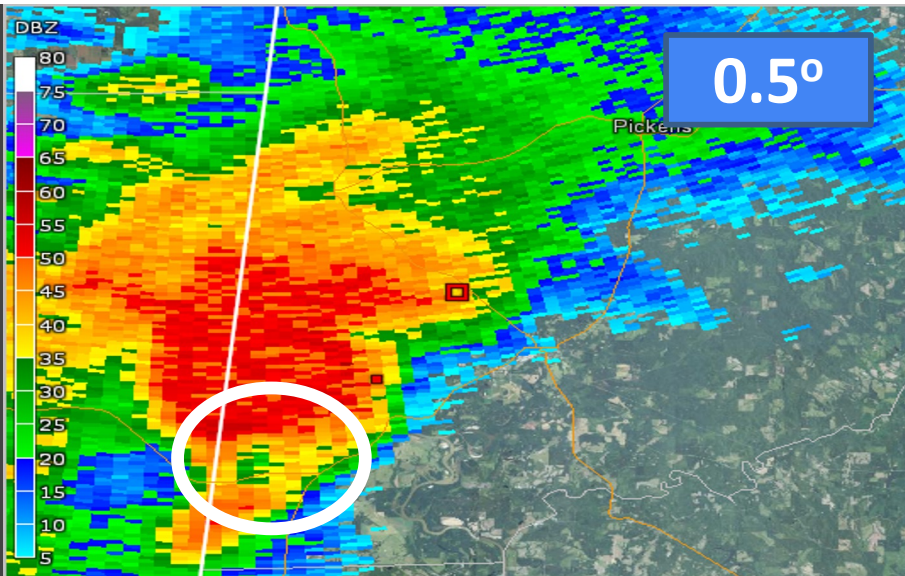
Available at <http://arctic.som.ou.edu/tburg/products/R2O/torprob/>

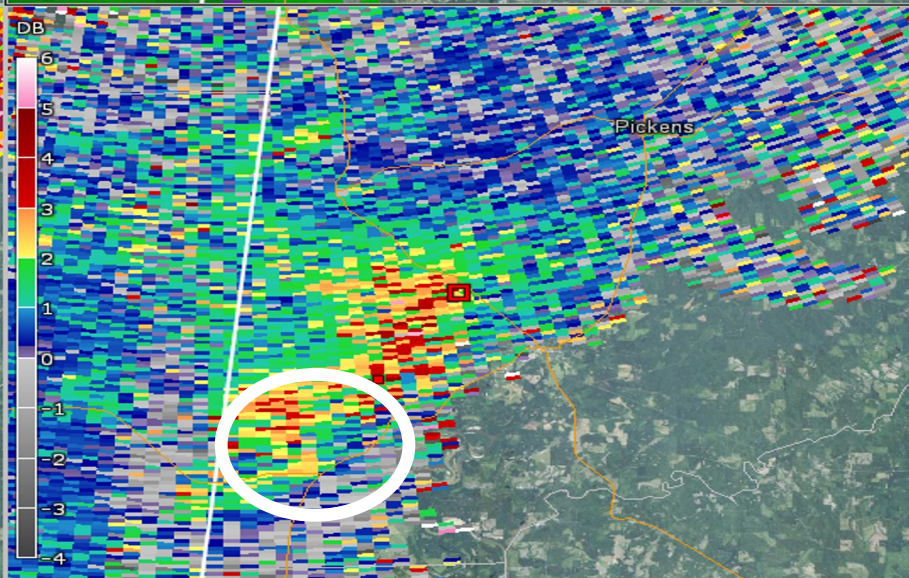
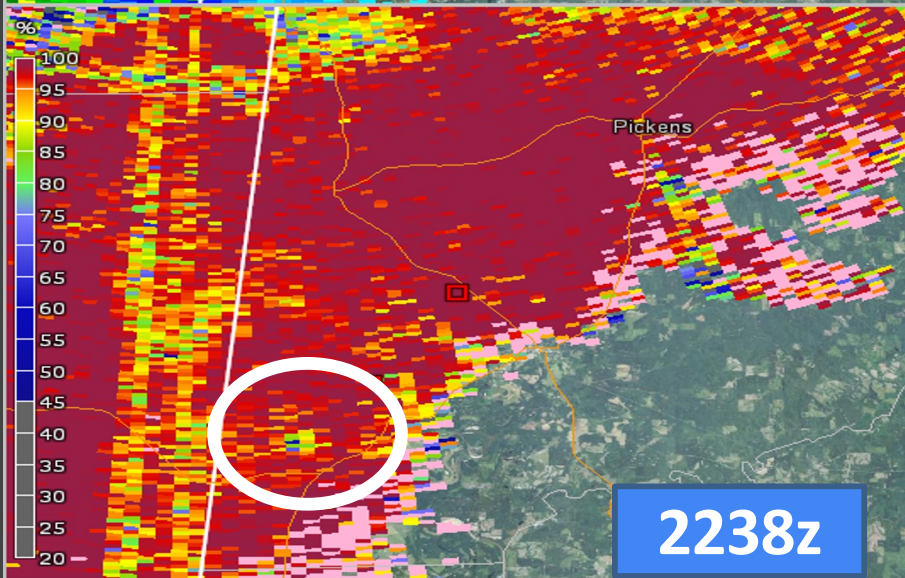
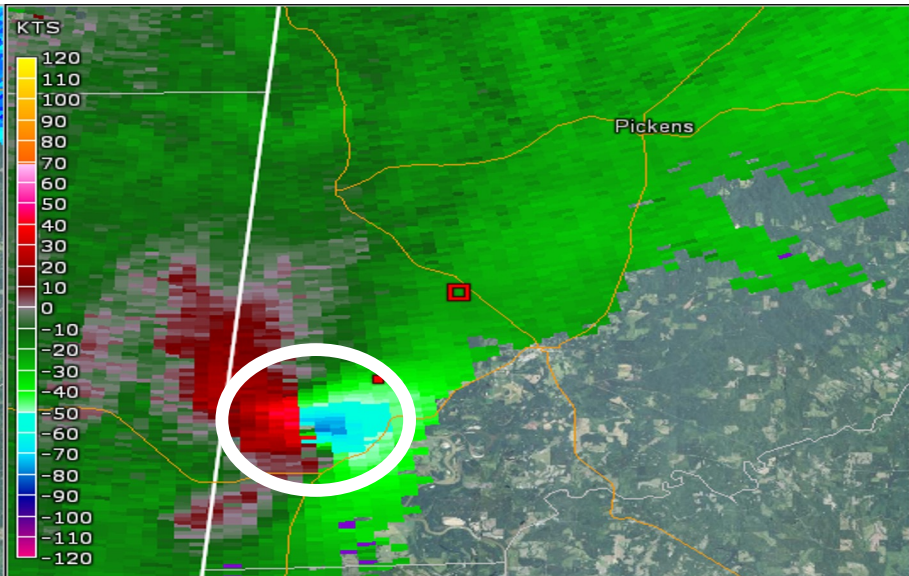
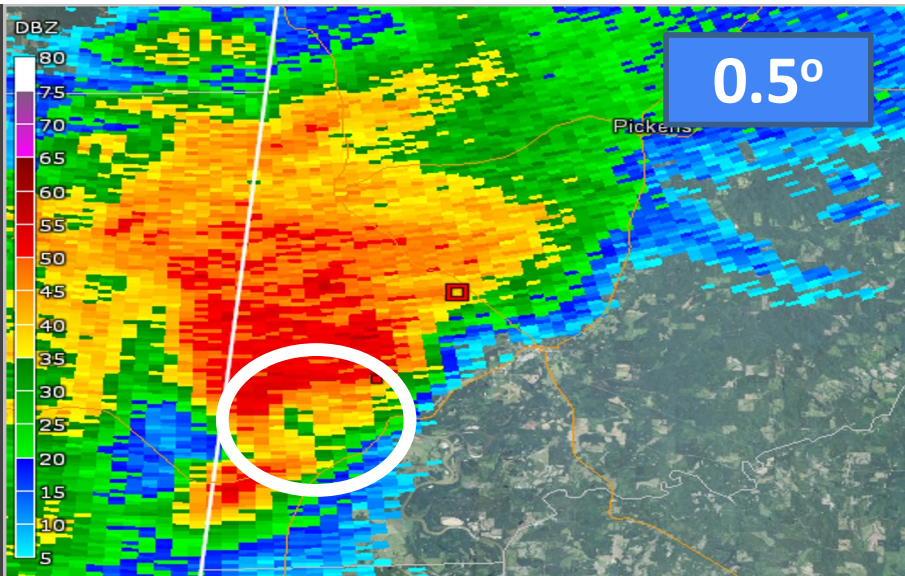
Try it yourself!

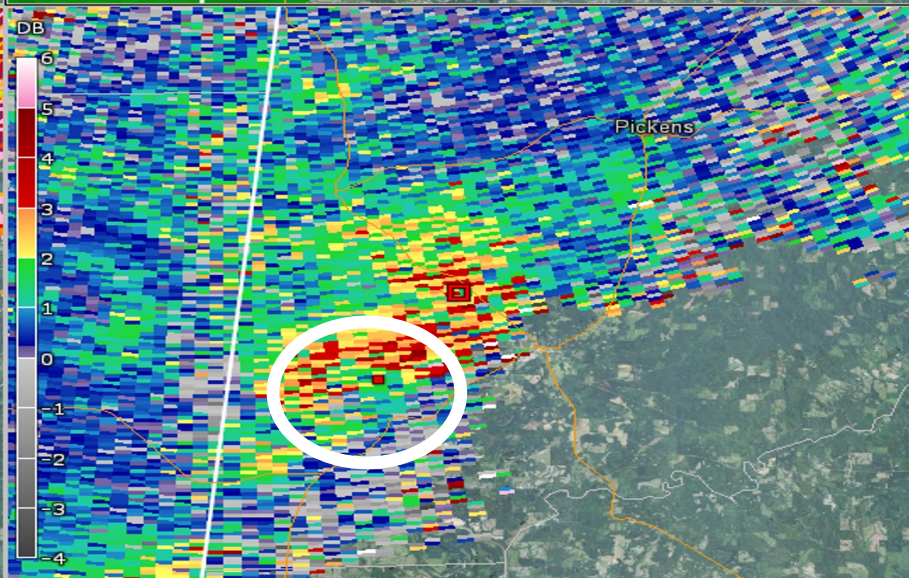
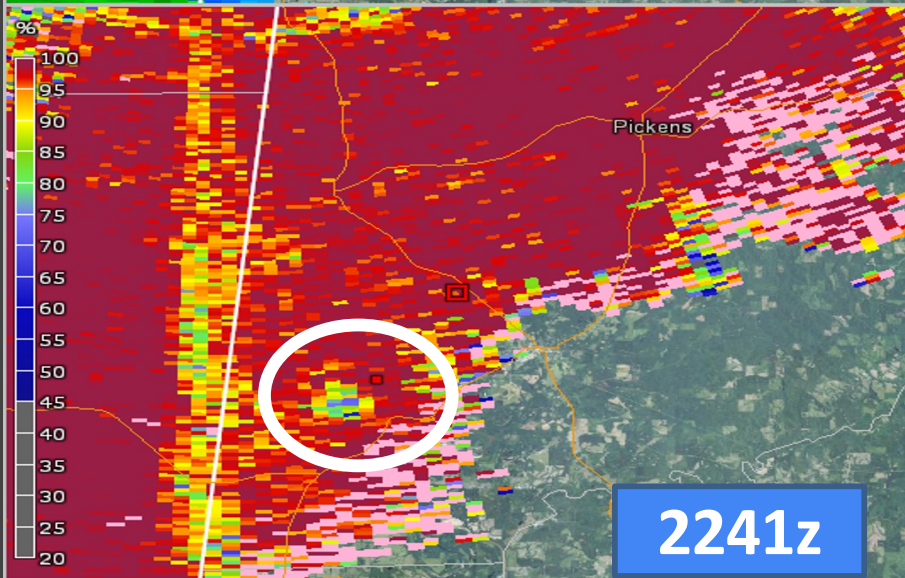
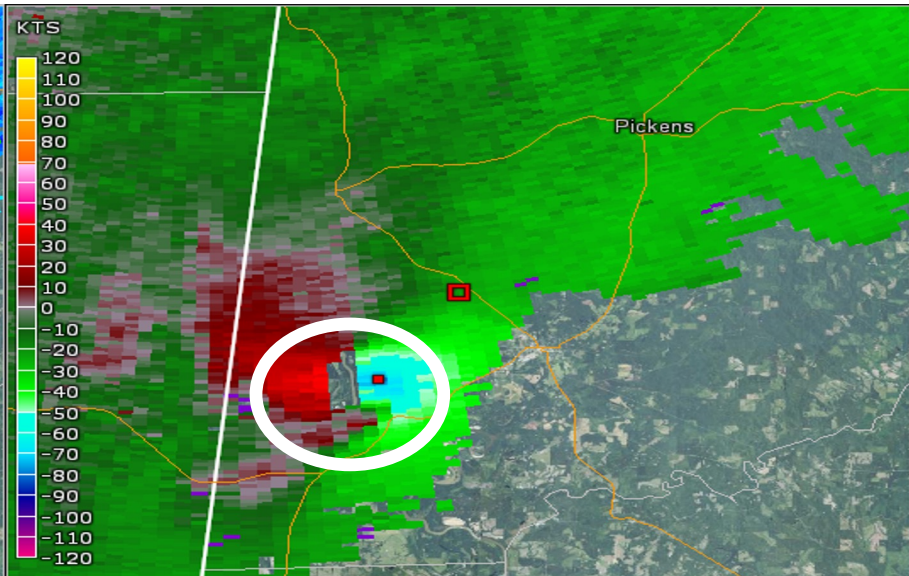
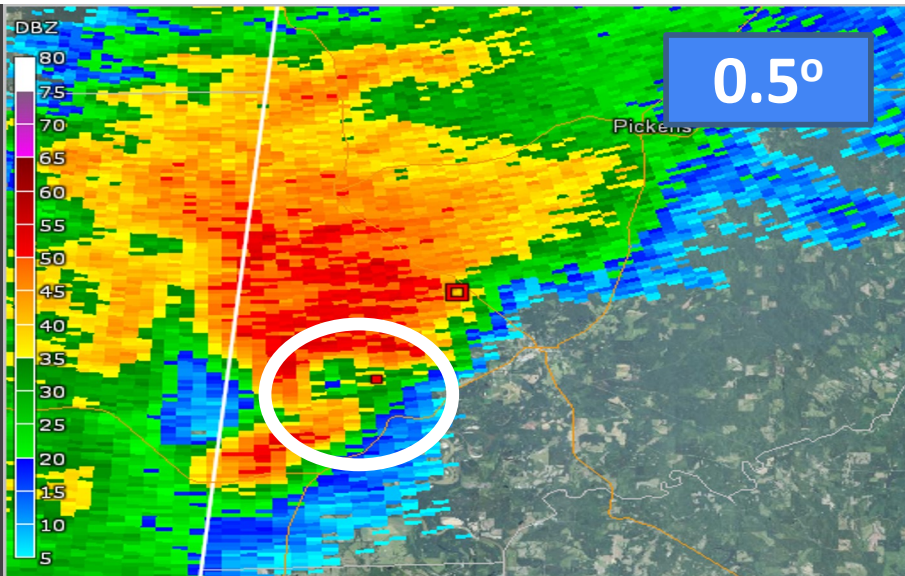
Tornado probability tool  
developed by Tomer Burg.

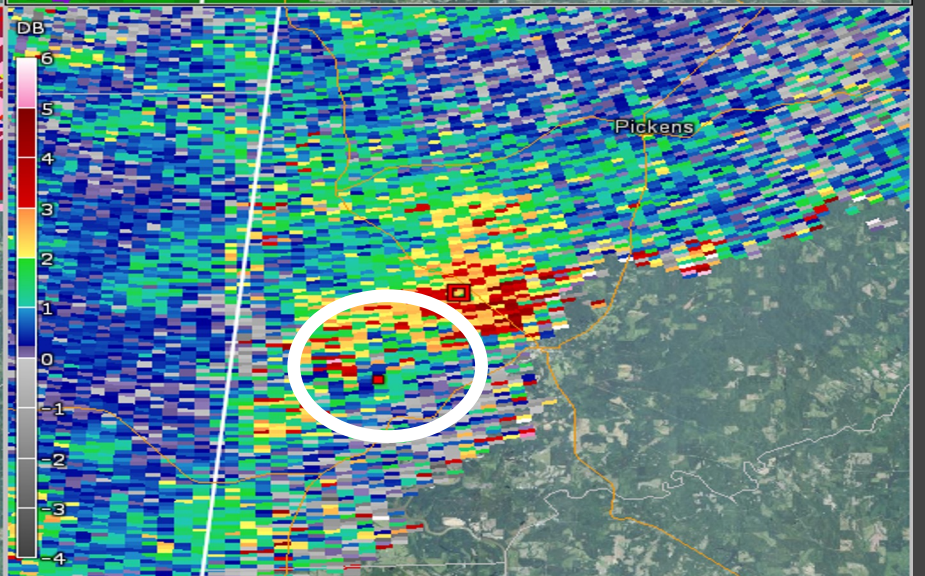
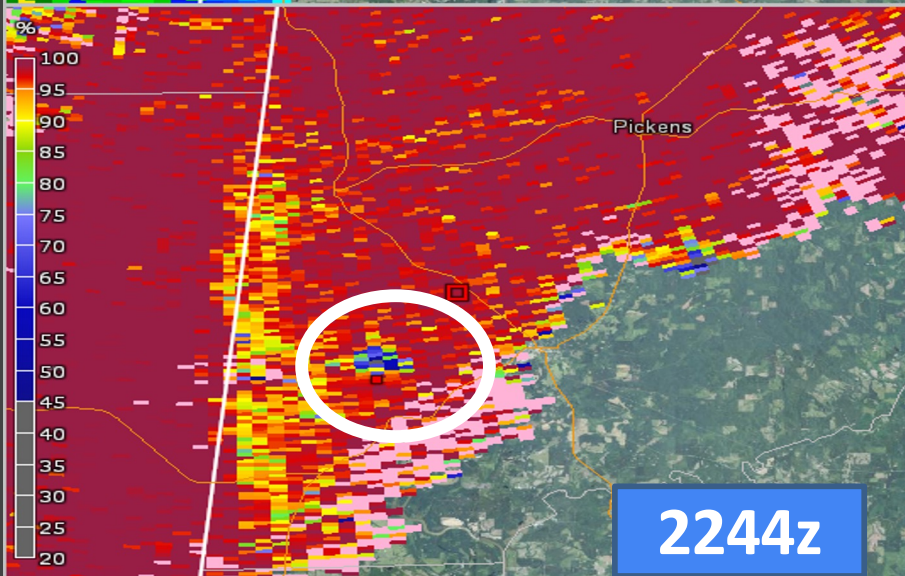
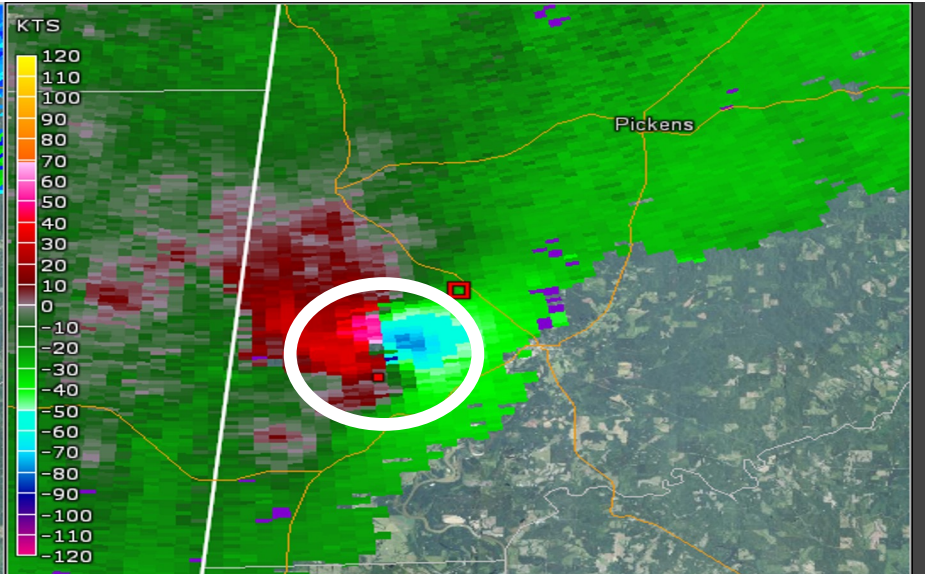
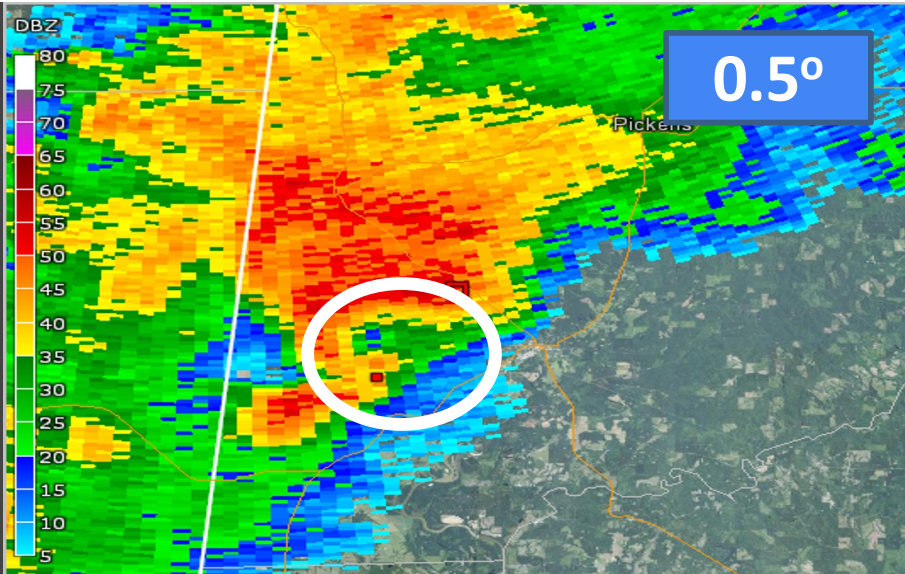
Based on research outlined in  
Cohen et al. 2018

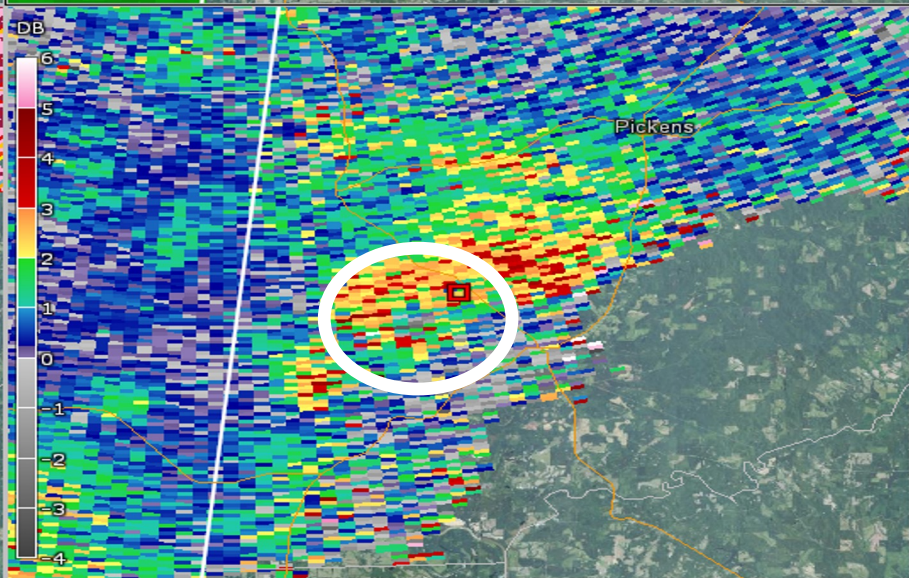
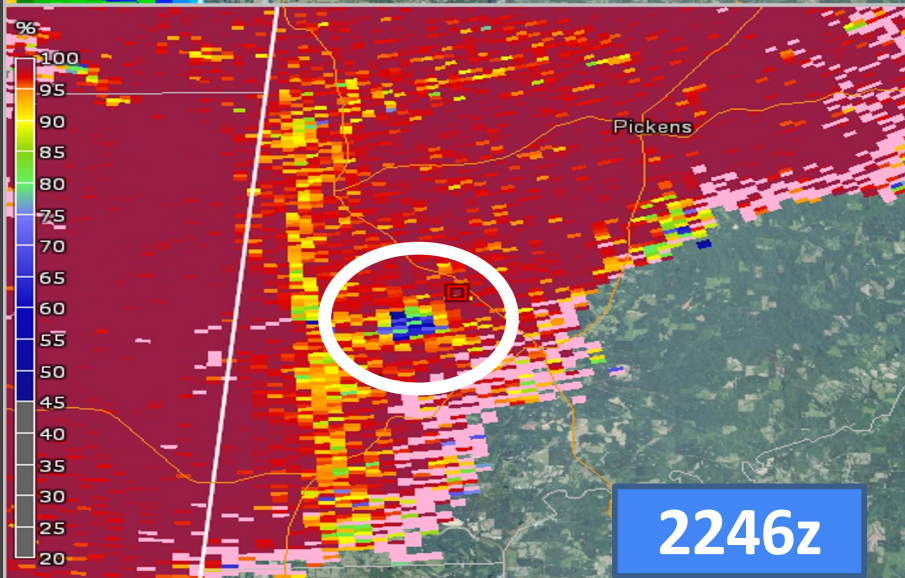
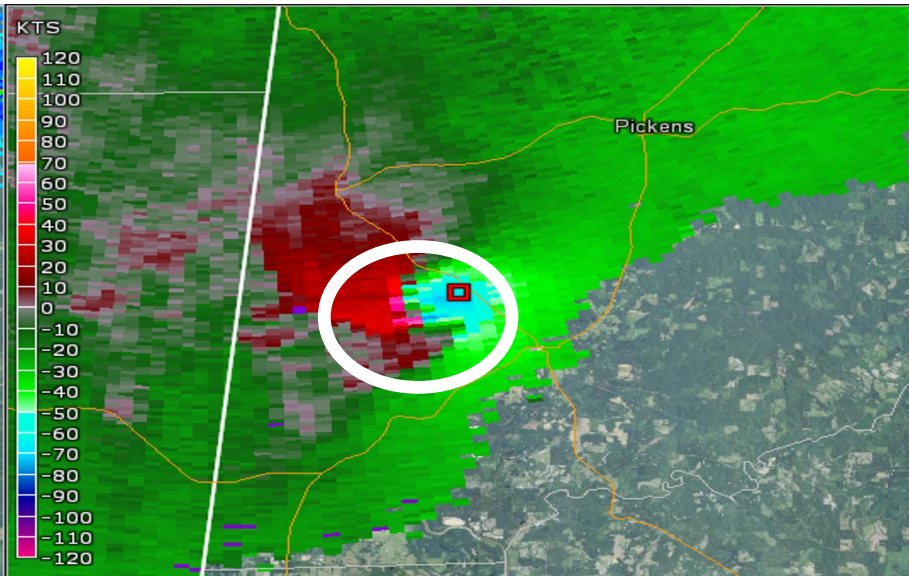
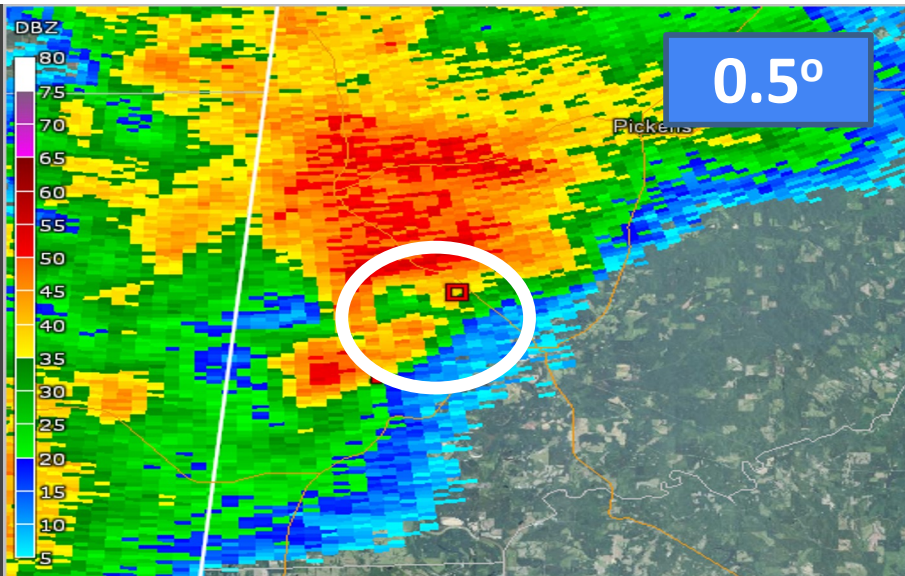


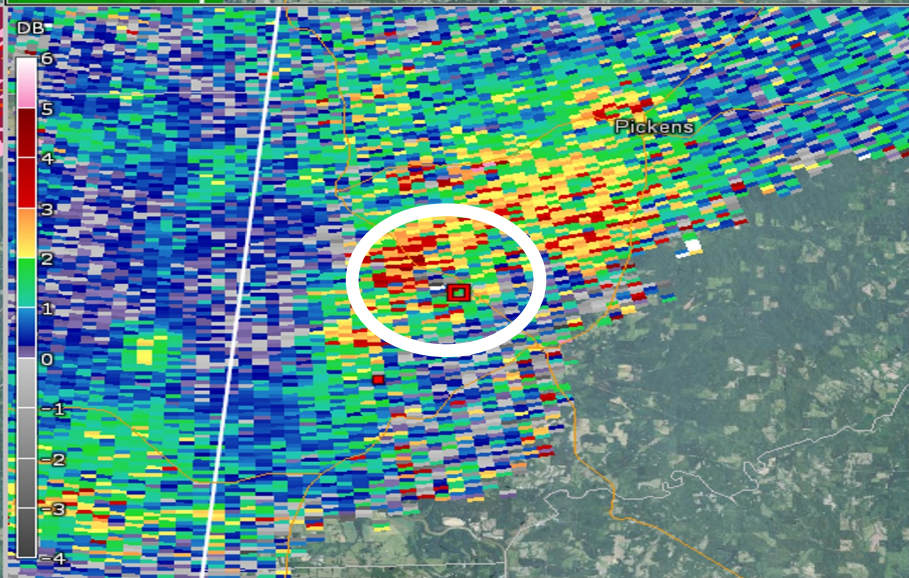
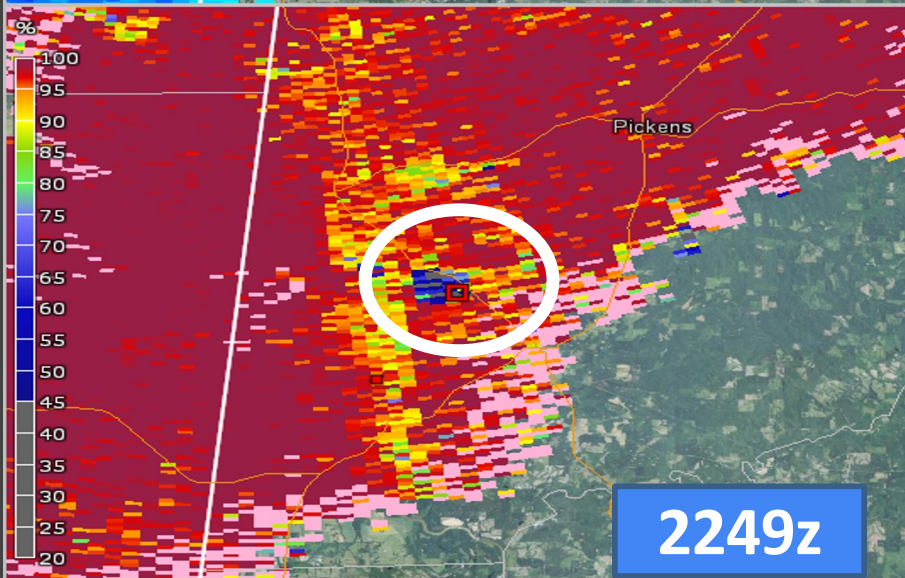
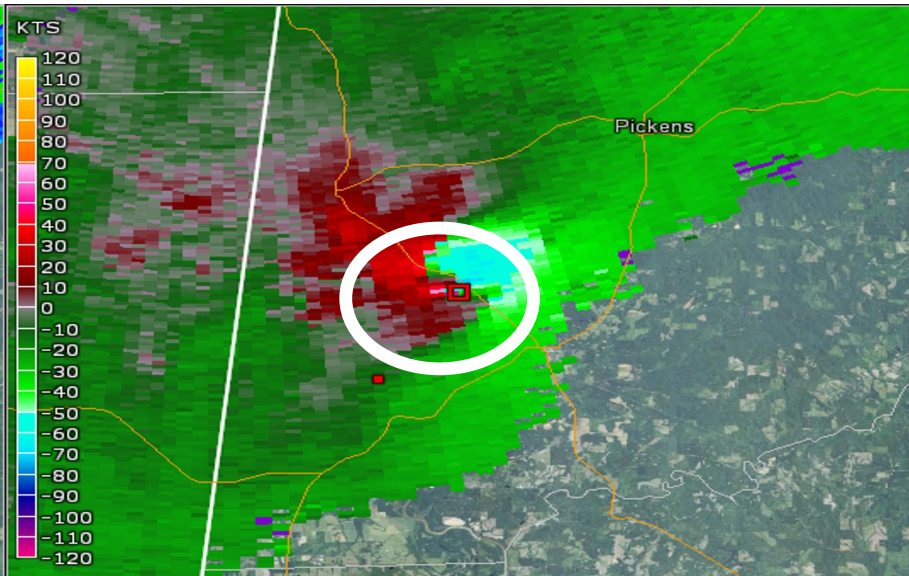
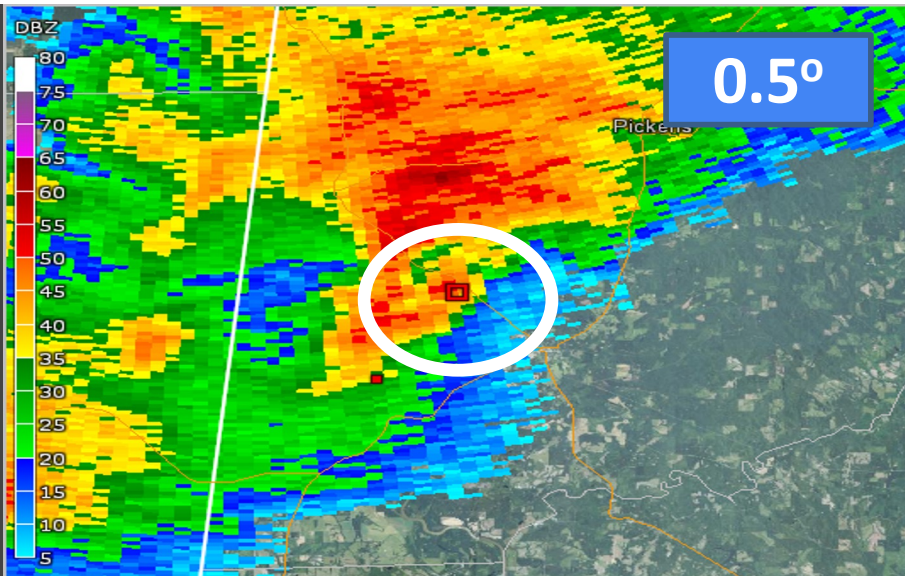


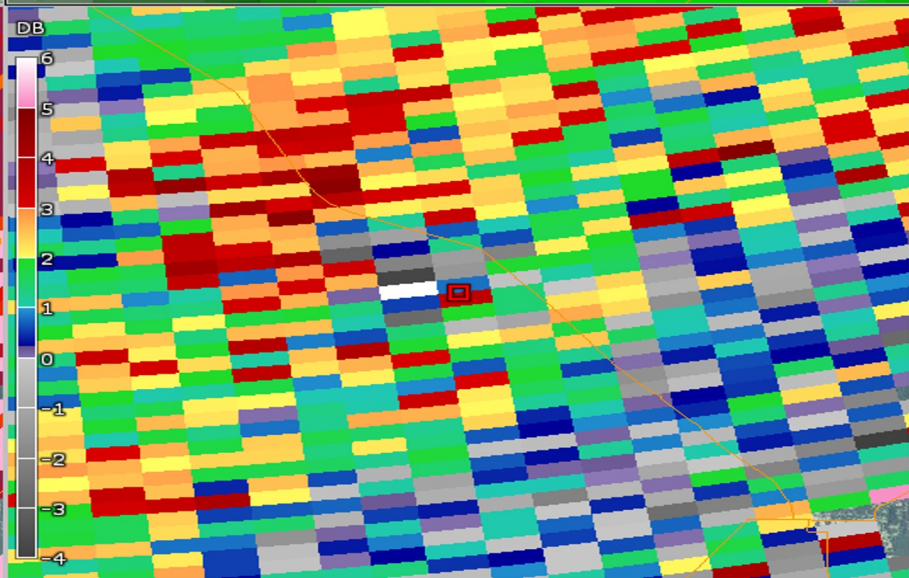
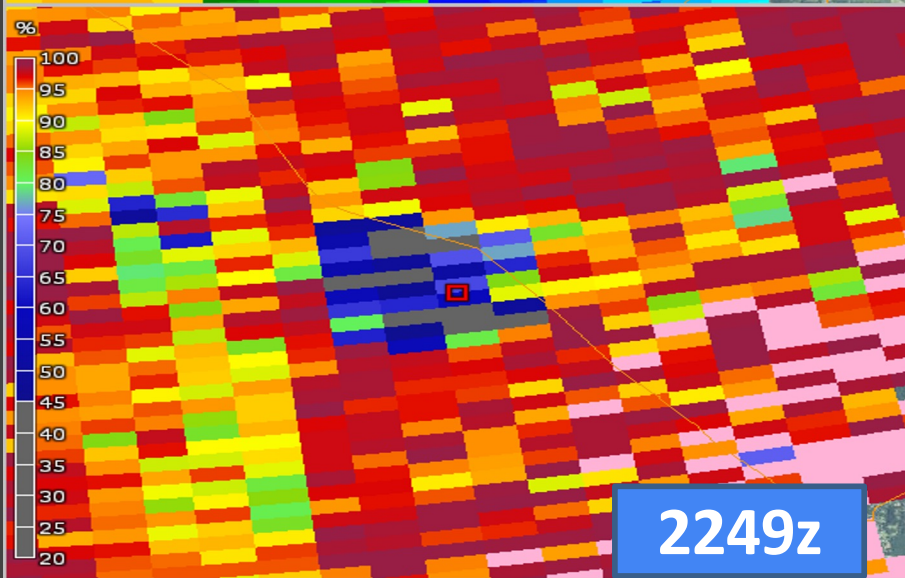
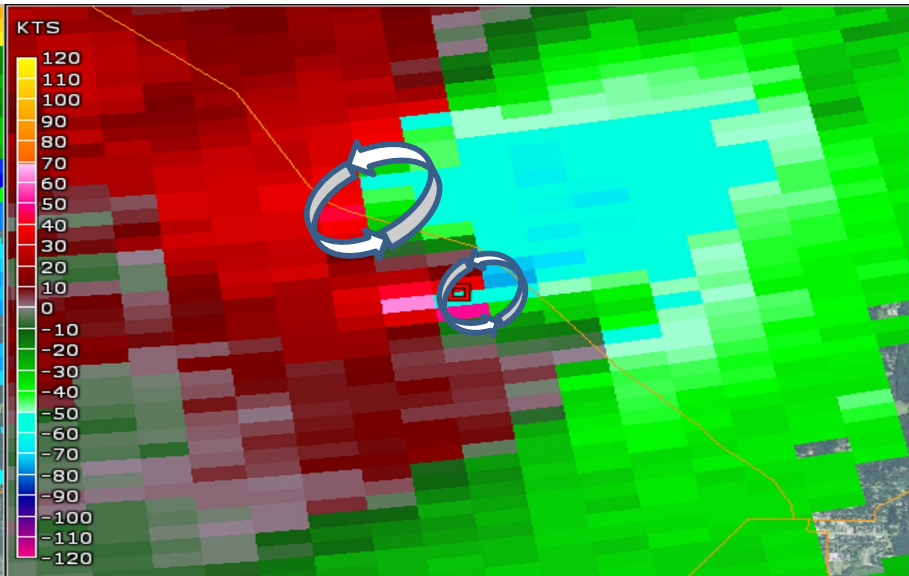
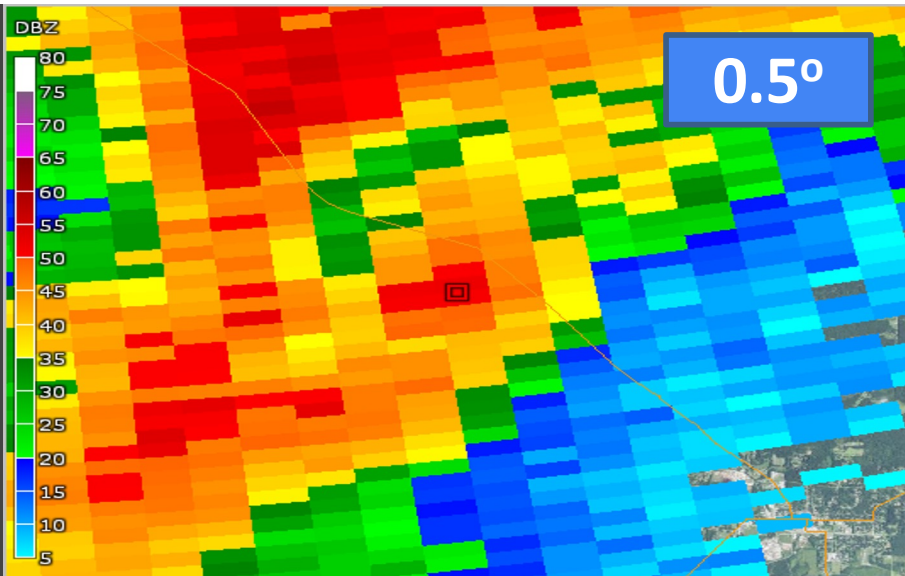


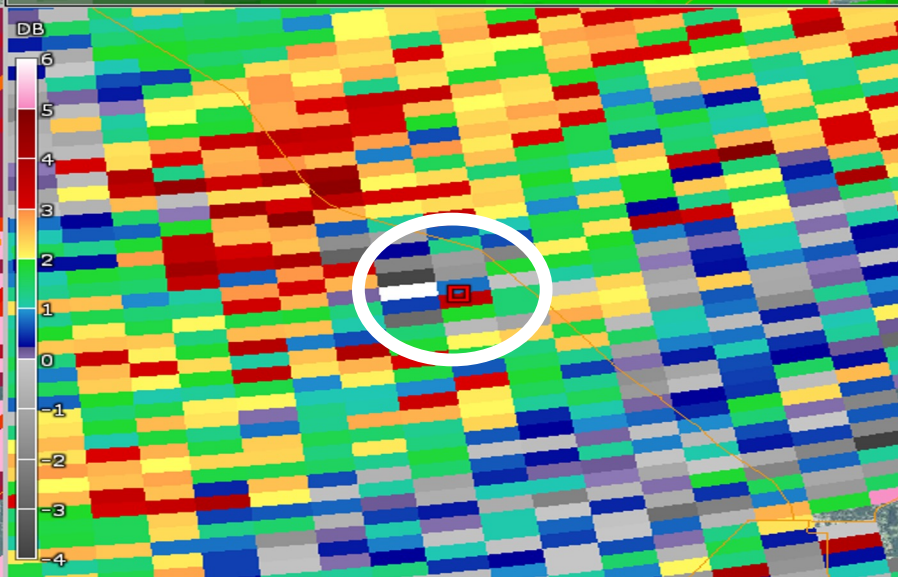
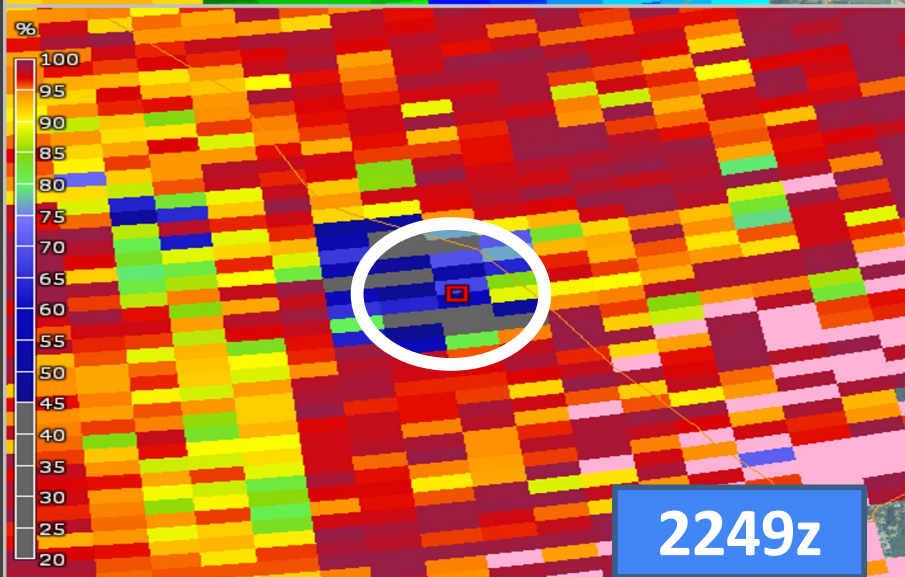
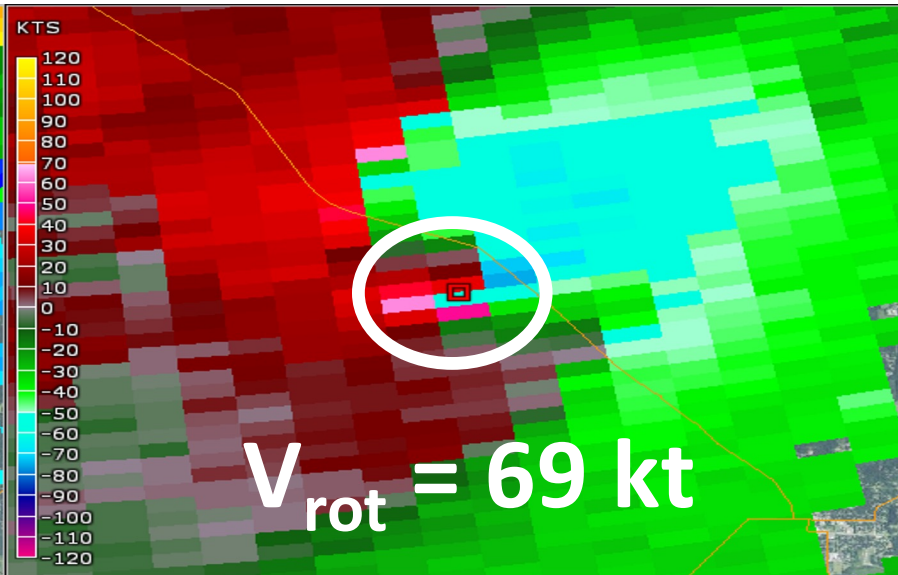
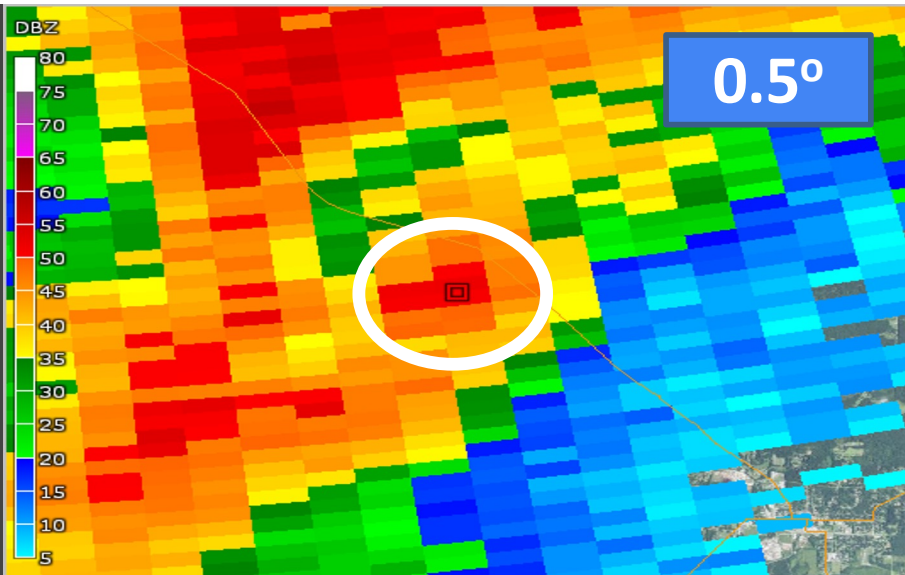


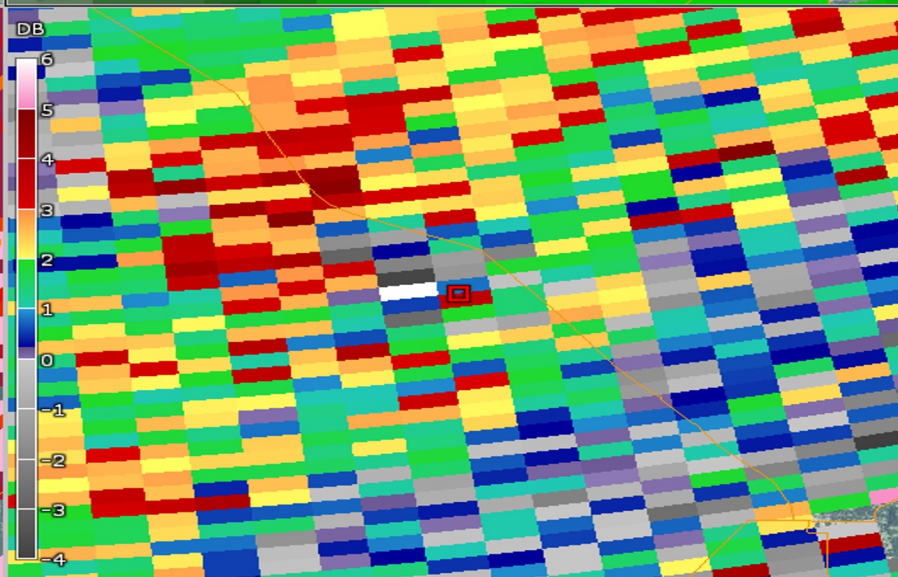
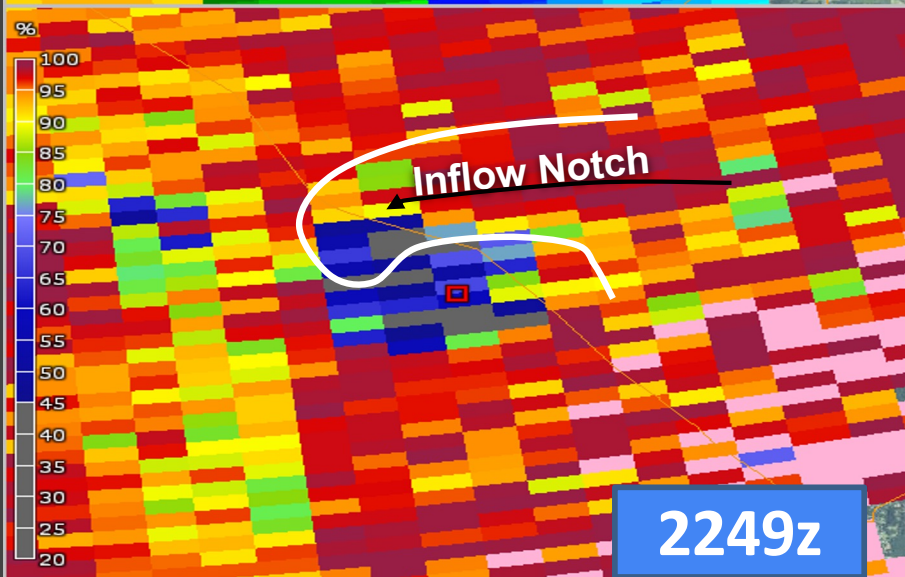
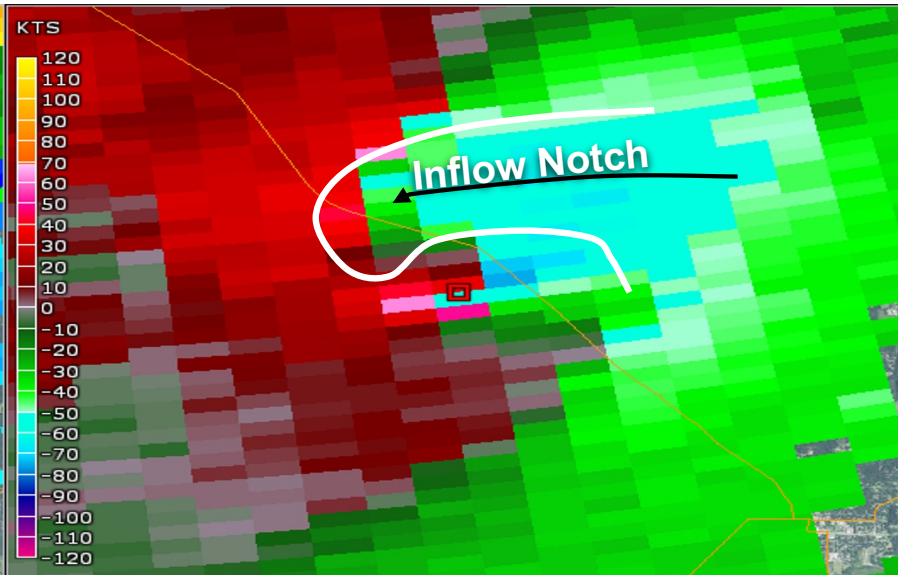
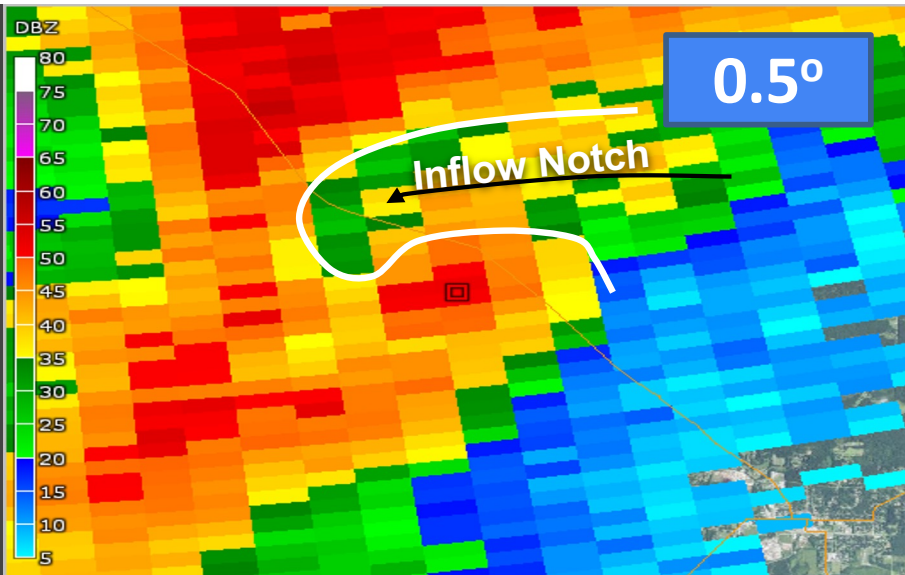


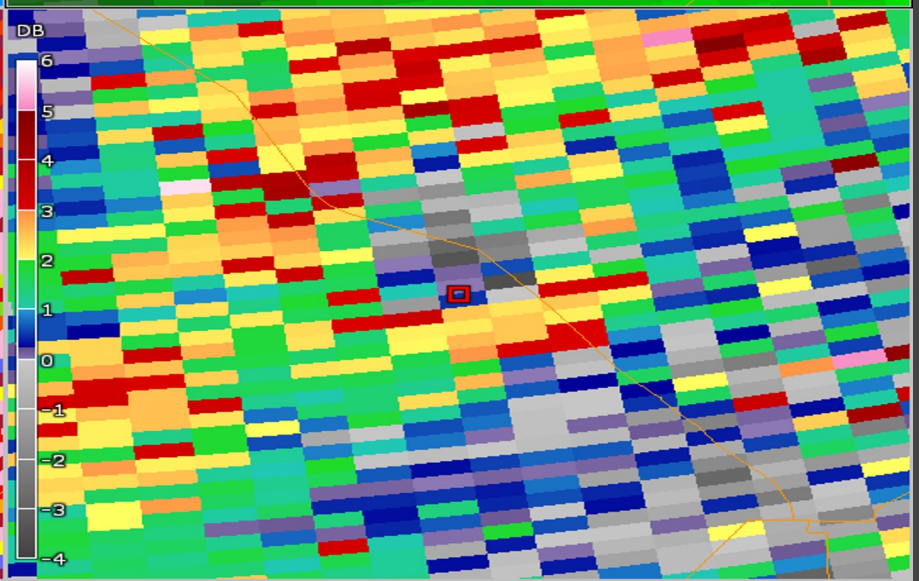
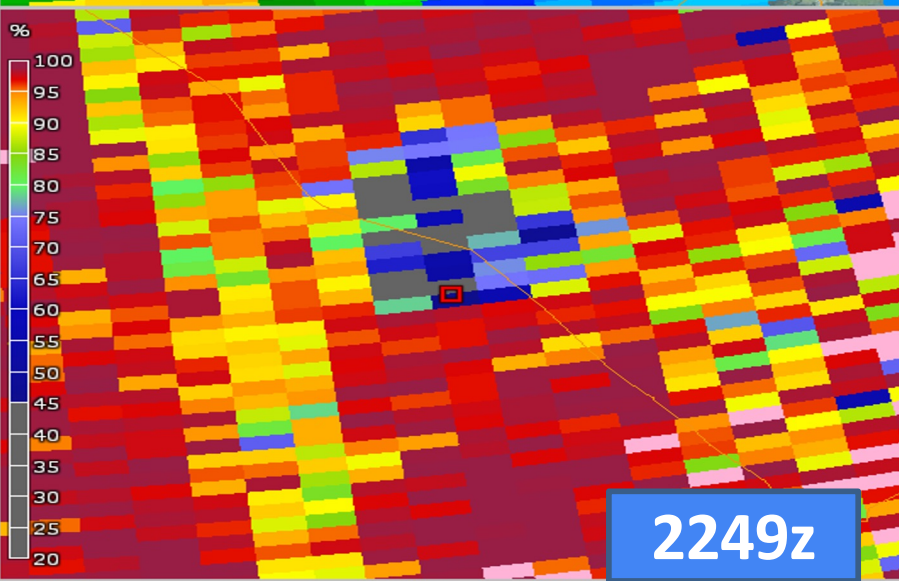
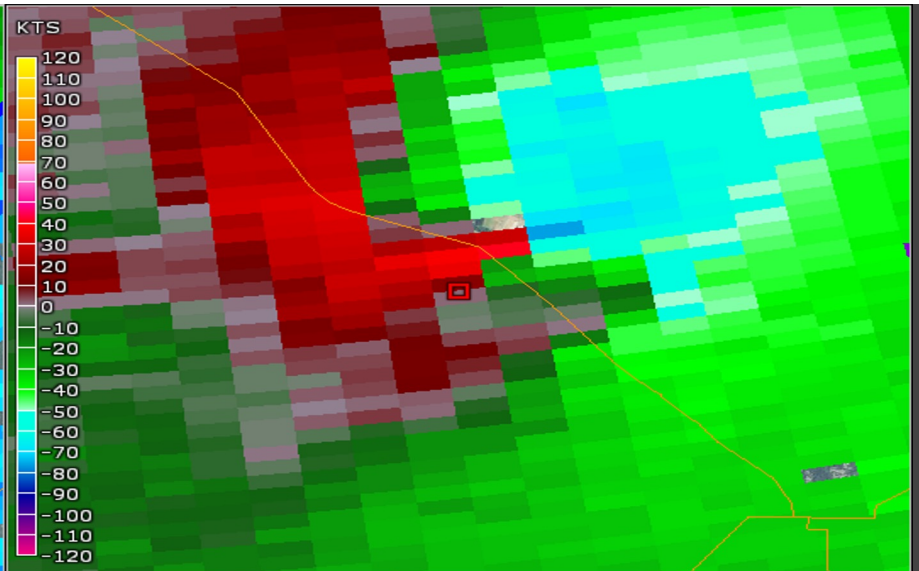
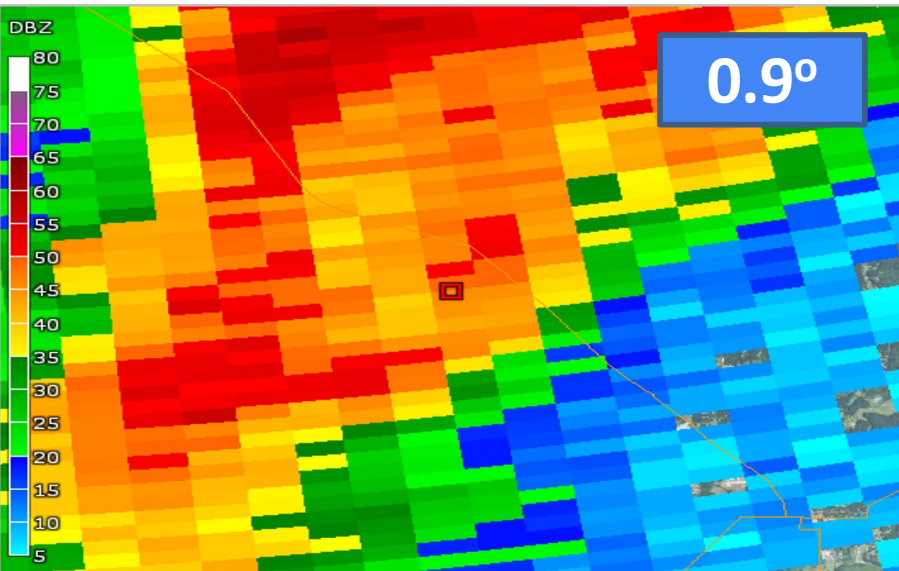








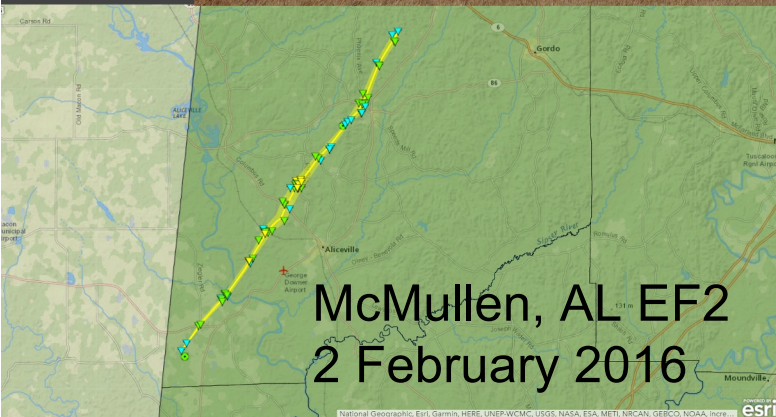




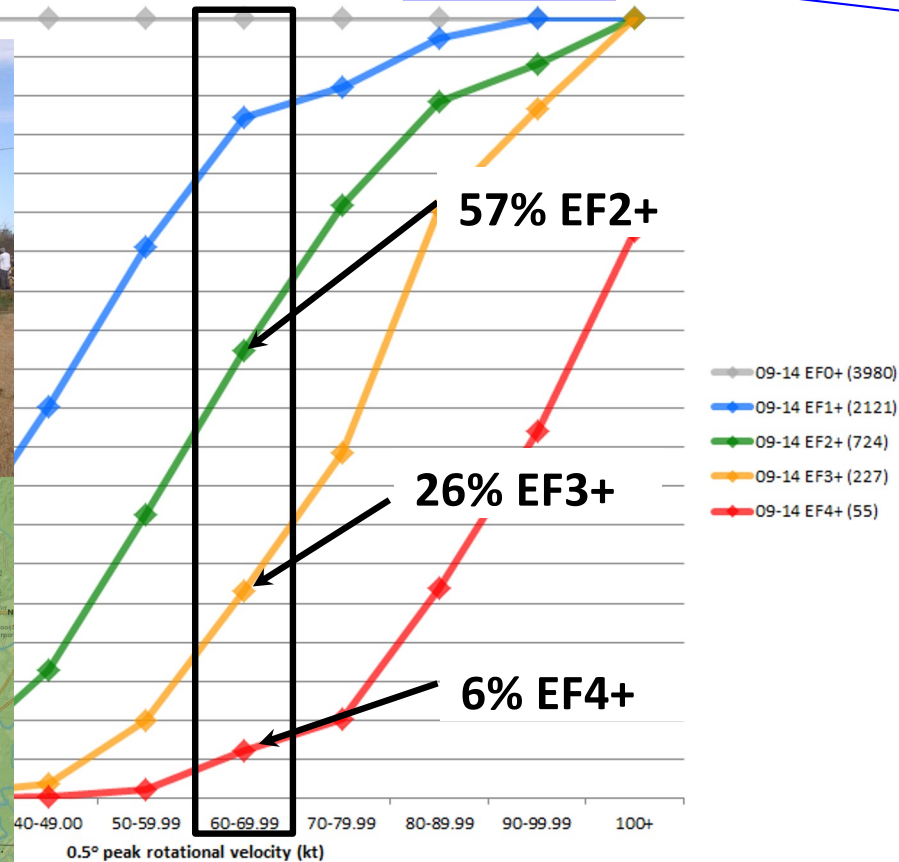
# Step 7: Check Conditional Tornado Probs

These are  
condit  
probab

You kn  
torna  
occur  
(TD



RM+QLCS Tornadoes (2009-2014): 0-5900 ft ARL



Valid for this  
range

