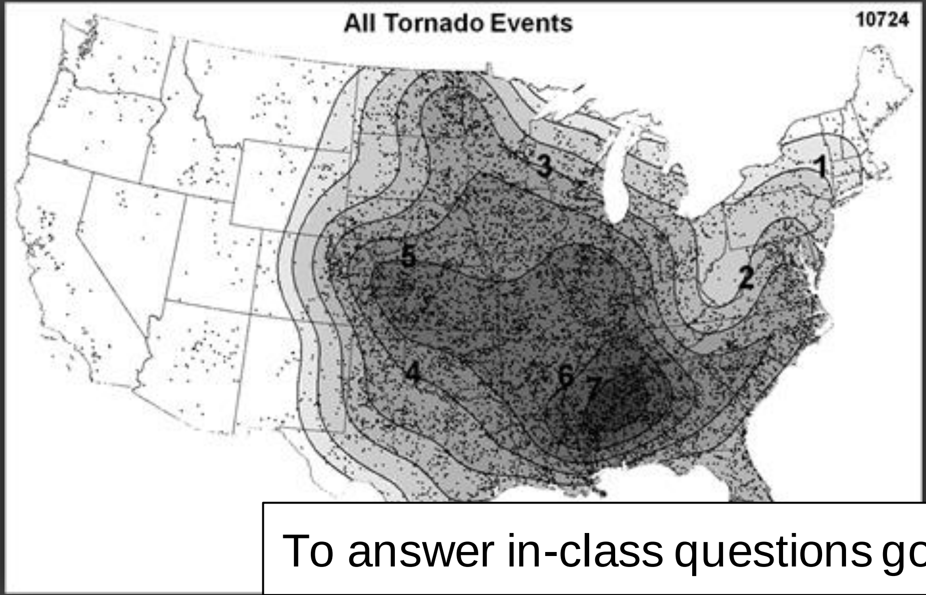
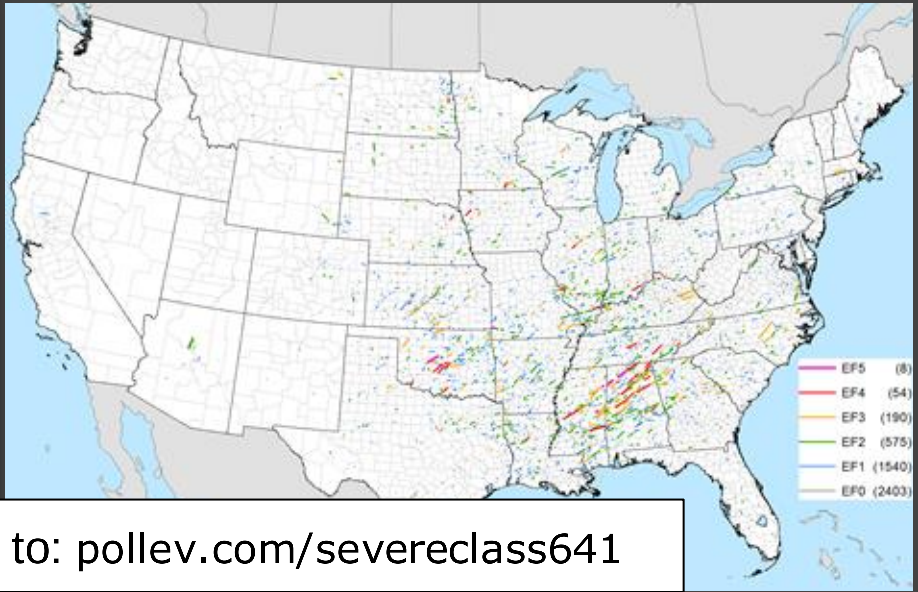
Tornado Climatology





To answer in-class questions go to: pollev.com/severeclass641

Climatology: Why Should We Care?

I'm here to learn about tornadoes!

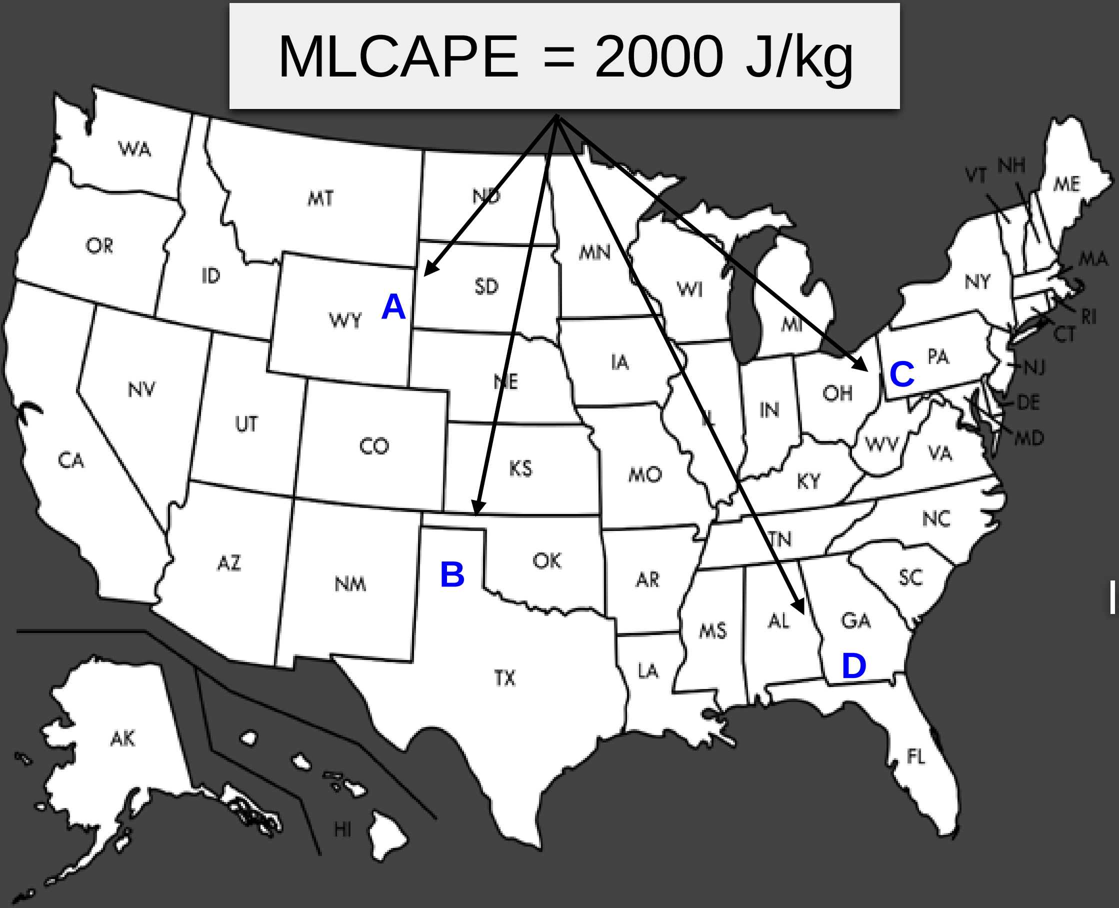
What do I care about climatology?!

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

In turn, this allows us to identify

anomalous environments

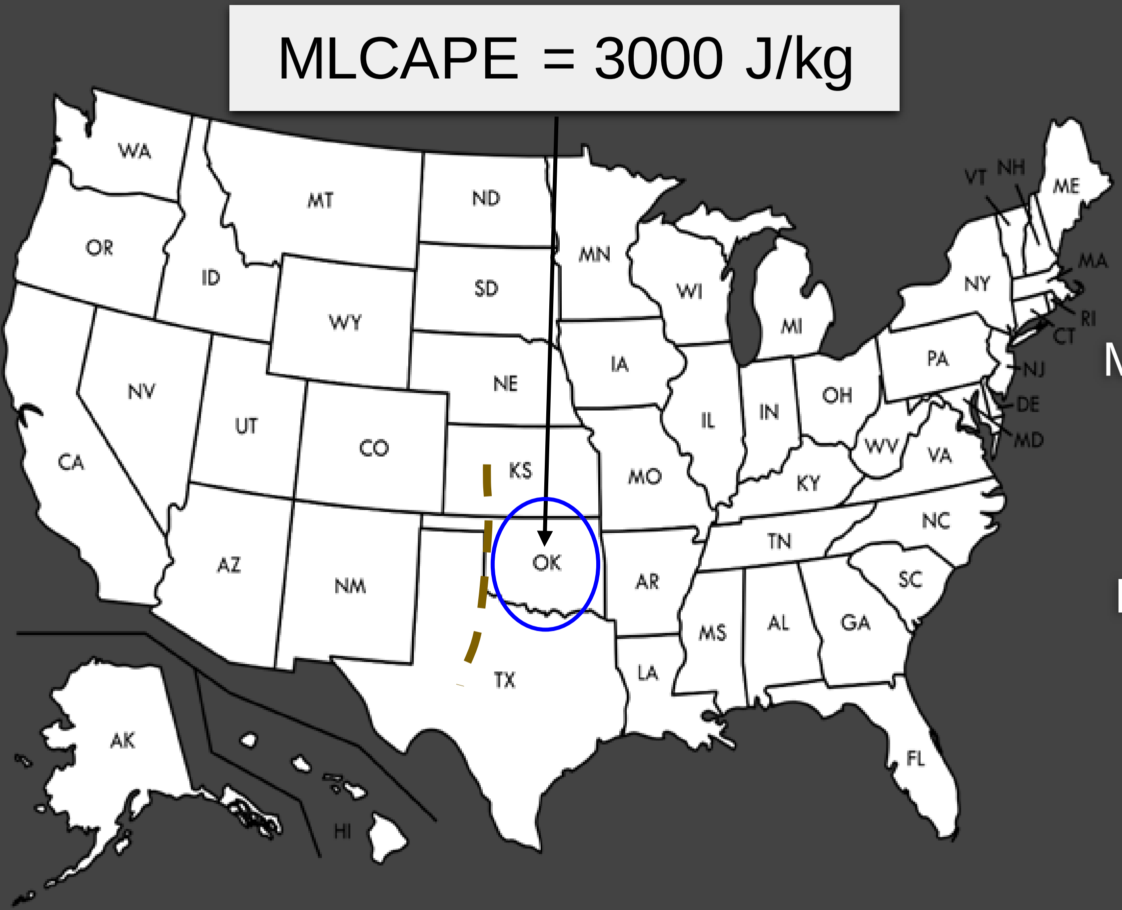
(whether anomalously low or high).



MLCAPE 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?

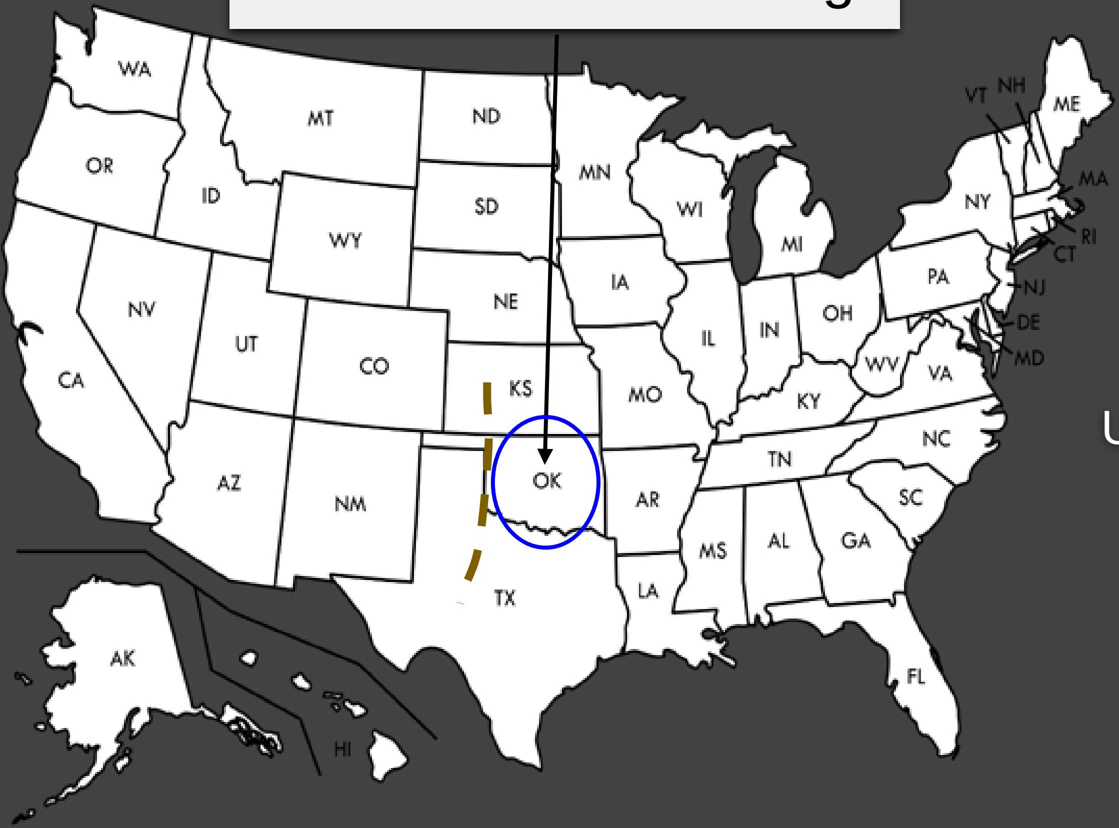


It's mid-May with an

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

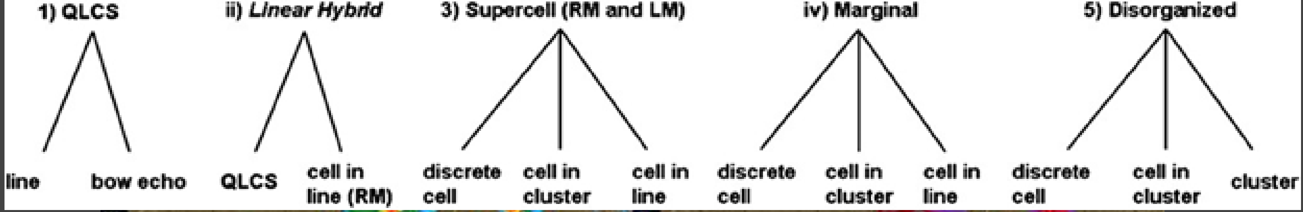


Fig 2. Smith et al. 2012

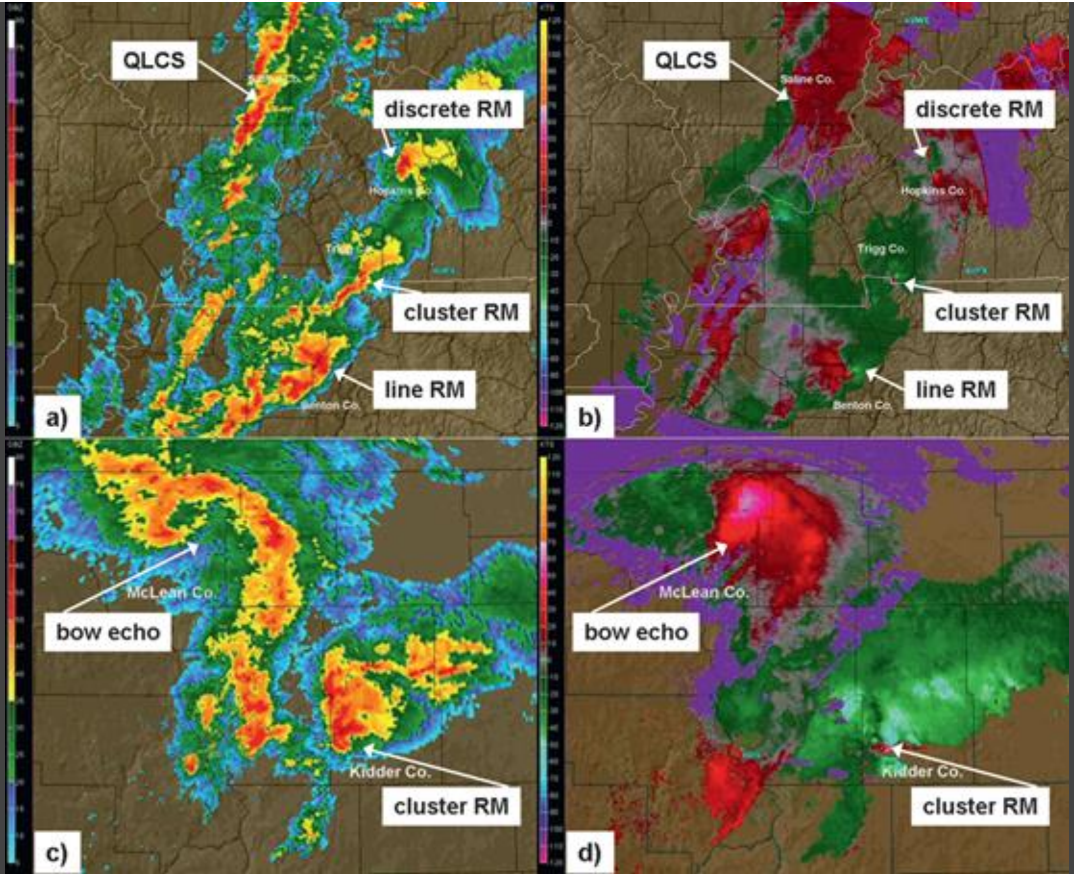


Fig 3. Smith et al. 2012

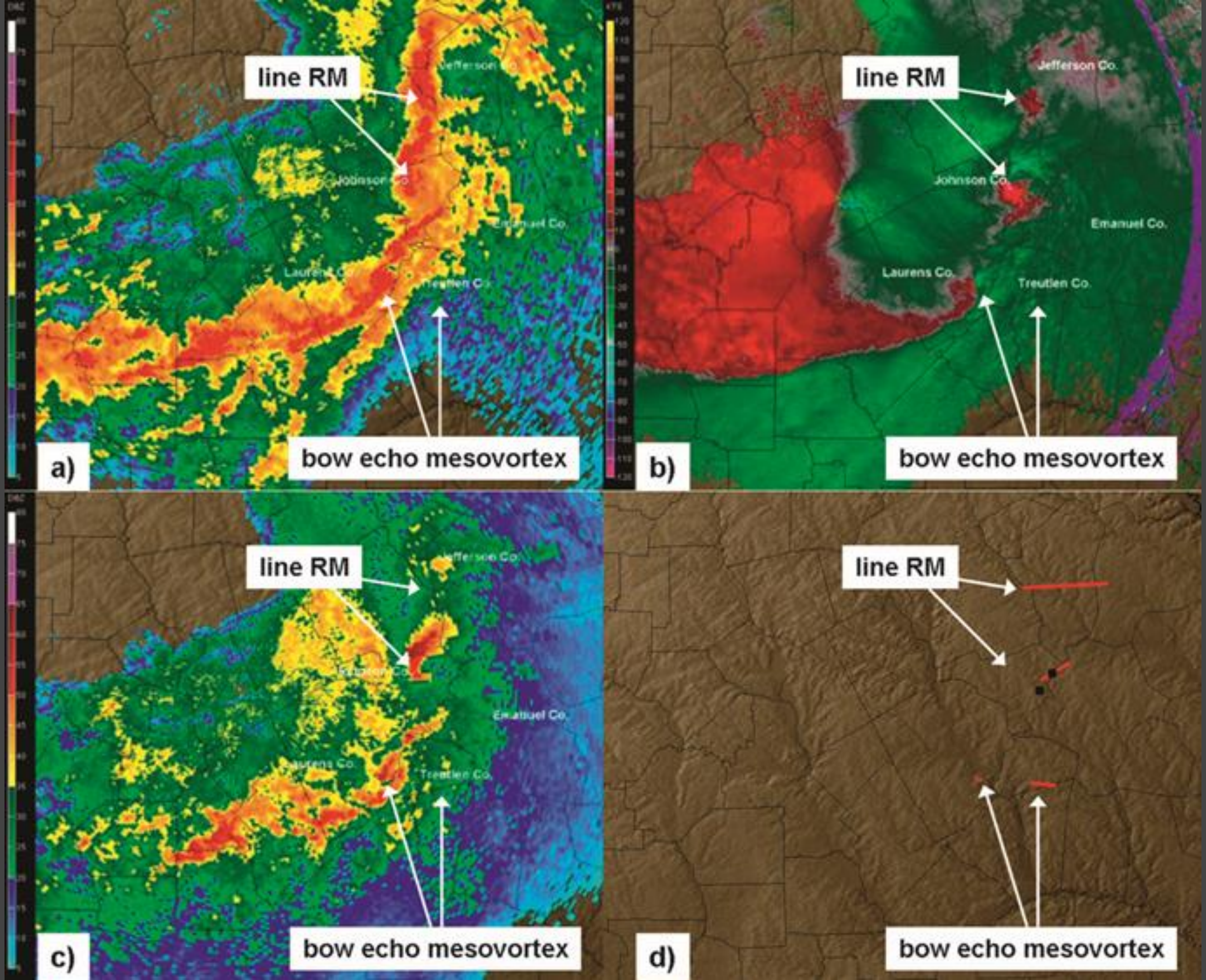


Fig 4. Smith et al. 2012

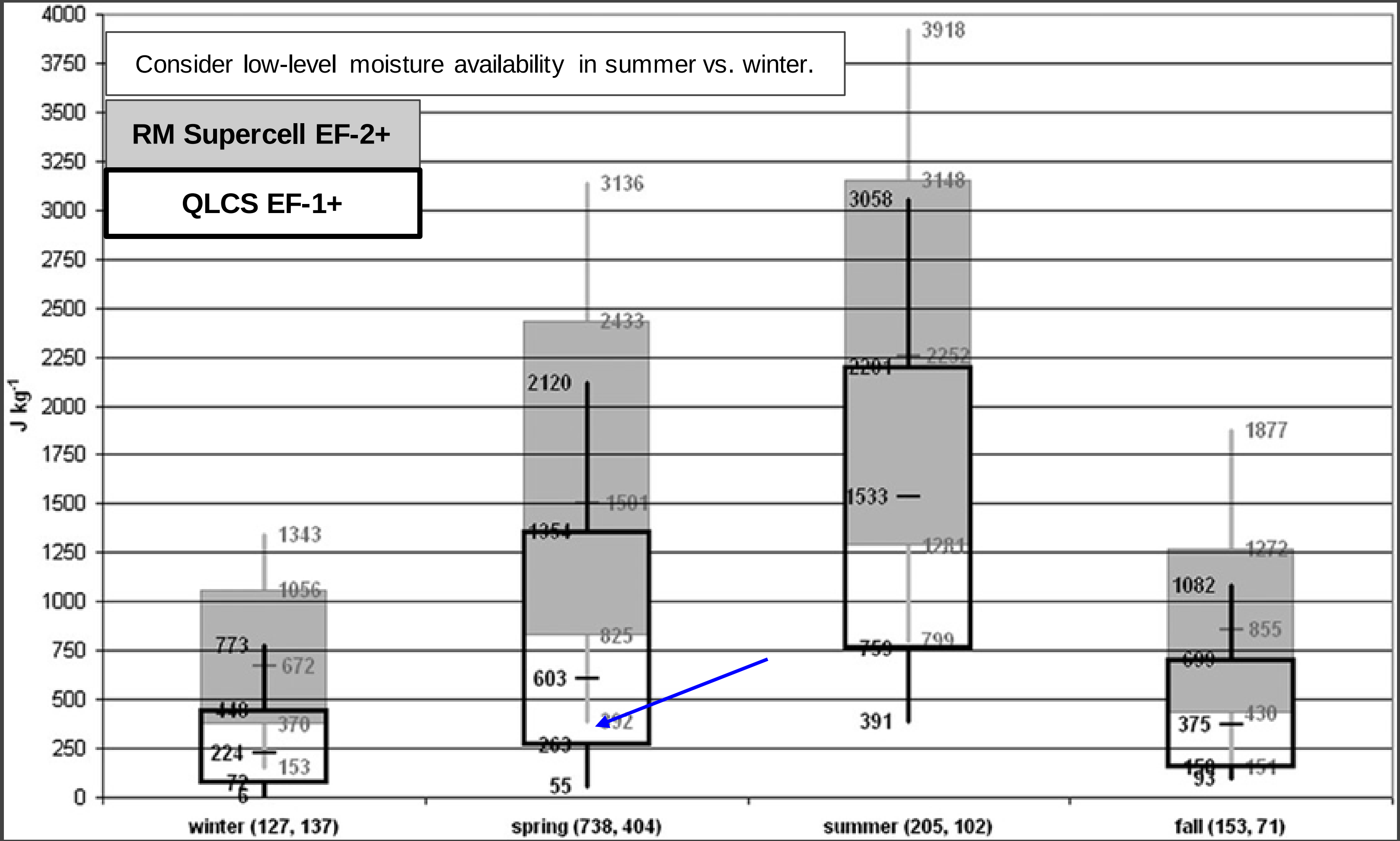
Ingredient Climatology

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

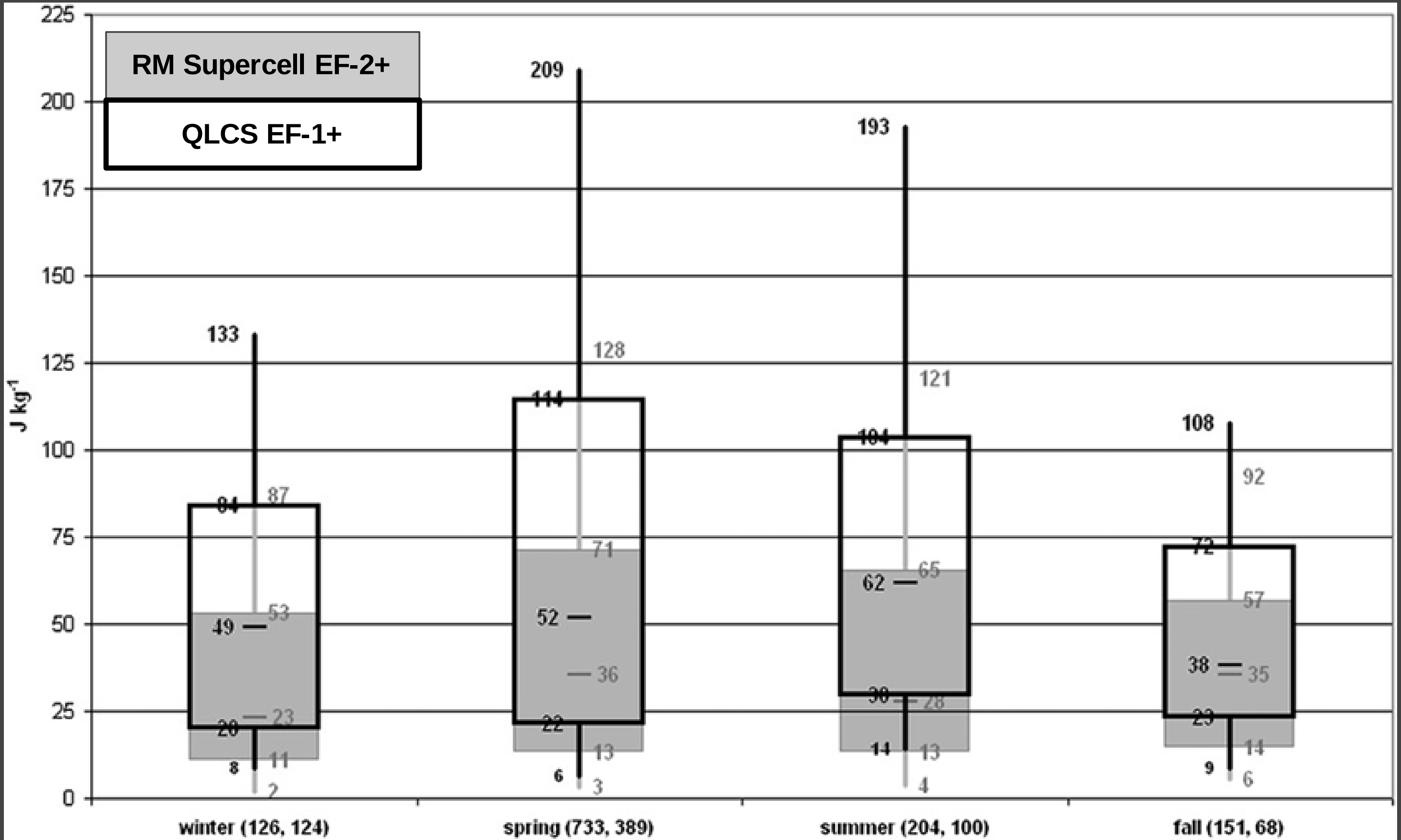
What is the 10th percentile MLCAPE for springtime RM supercells?

- < 250 J/kg
- 250-500 J/kg
- 500-1000 J/kg
- 1000-1500 J/kg
- 1500-2000 J/kg

MLCAPE

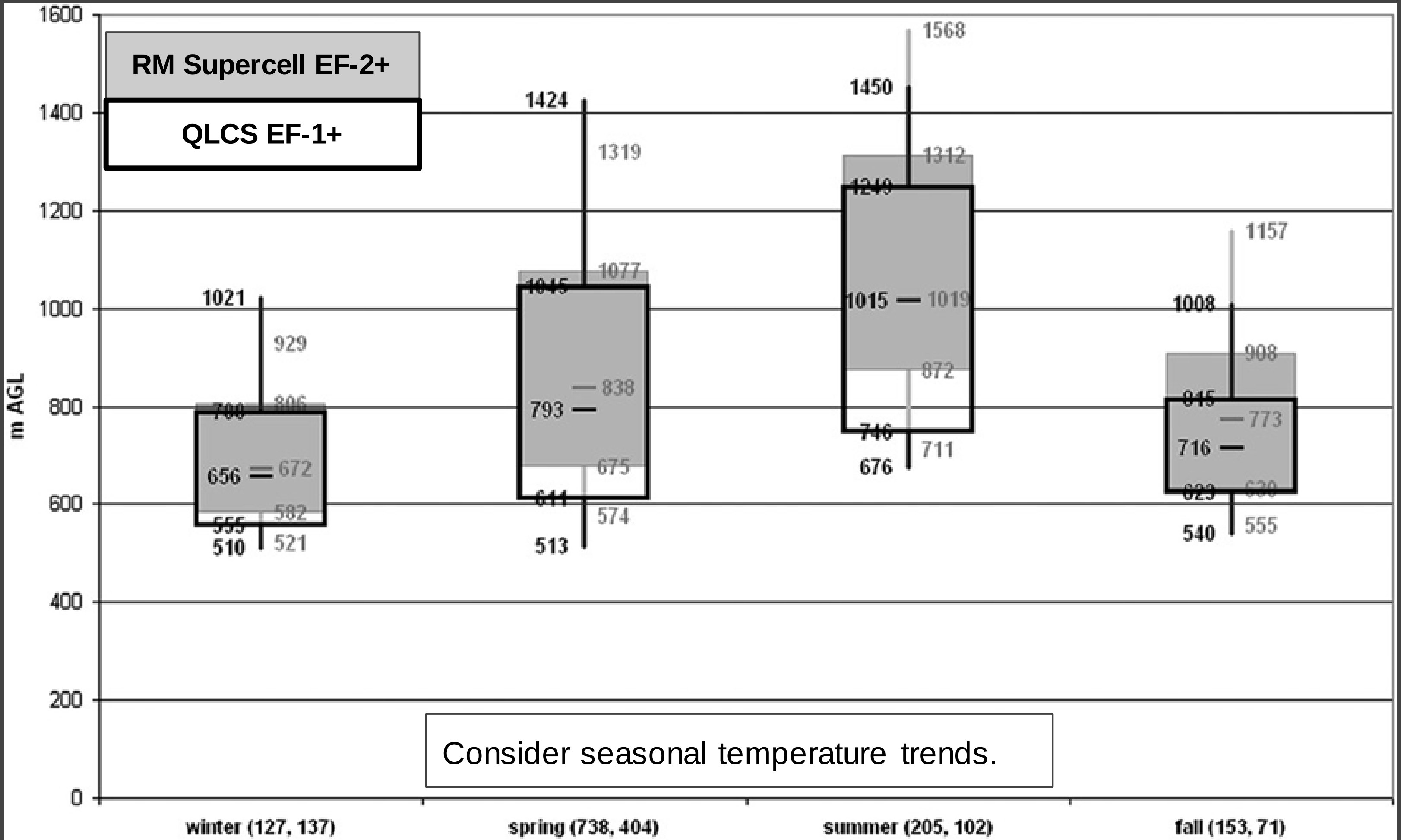

Consider low-level moisture availability in summer vs. winter.
RM Supercell EF-2+
QLCS EF-1+
J kg-1
4000
3750
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
1343
1056
773
672
440
370
224
153
72
6
3136
2433
2120
1501
1354
825
603
392
263
55
3918
3148
3058
2252
2201
1533
1281
799
759
391
1877
1272
1082
855
699
430
375
150
151
93
winter (127, 137)
spring (738, 404)
summer (205, 102)
fall (153, 71)

MLCIN



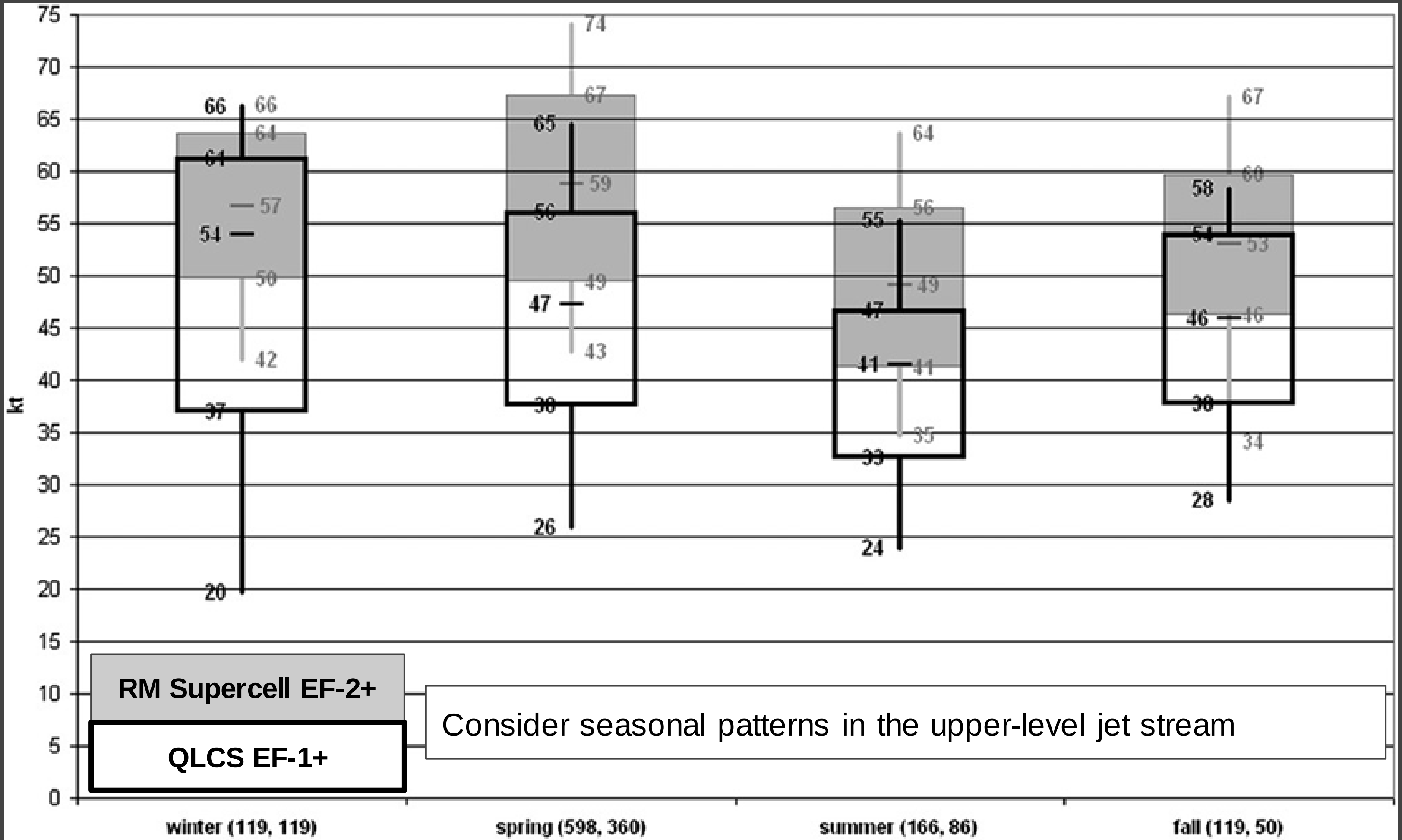
RM Supercell EF-2+
QLCS EF-1+
J kg-1
225
200
175
150
125
100
75
50
25
0
133
84
87
53
49
23
20
11
8
2
209
128
114
71
52
36
22
13
6
3
193
121
104
65
62
30
28
14
13
4
108
92
72
57
38
35
23
14
9
6
winter (126, 124)
spring (733, 389)
summer (204, 100)
fall (151, 68)

MLLCL

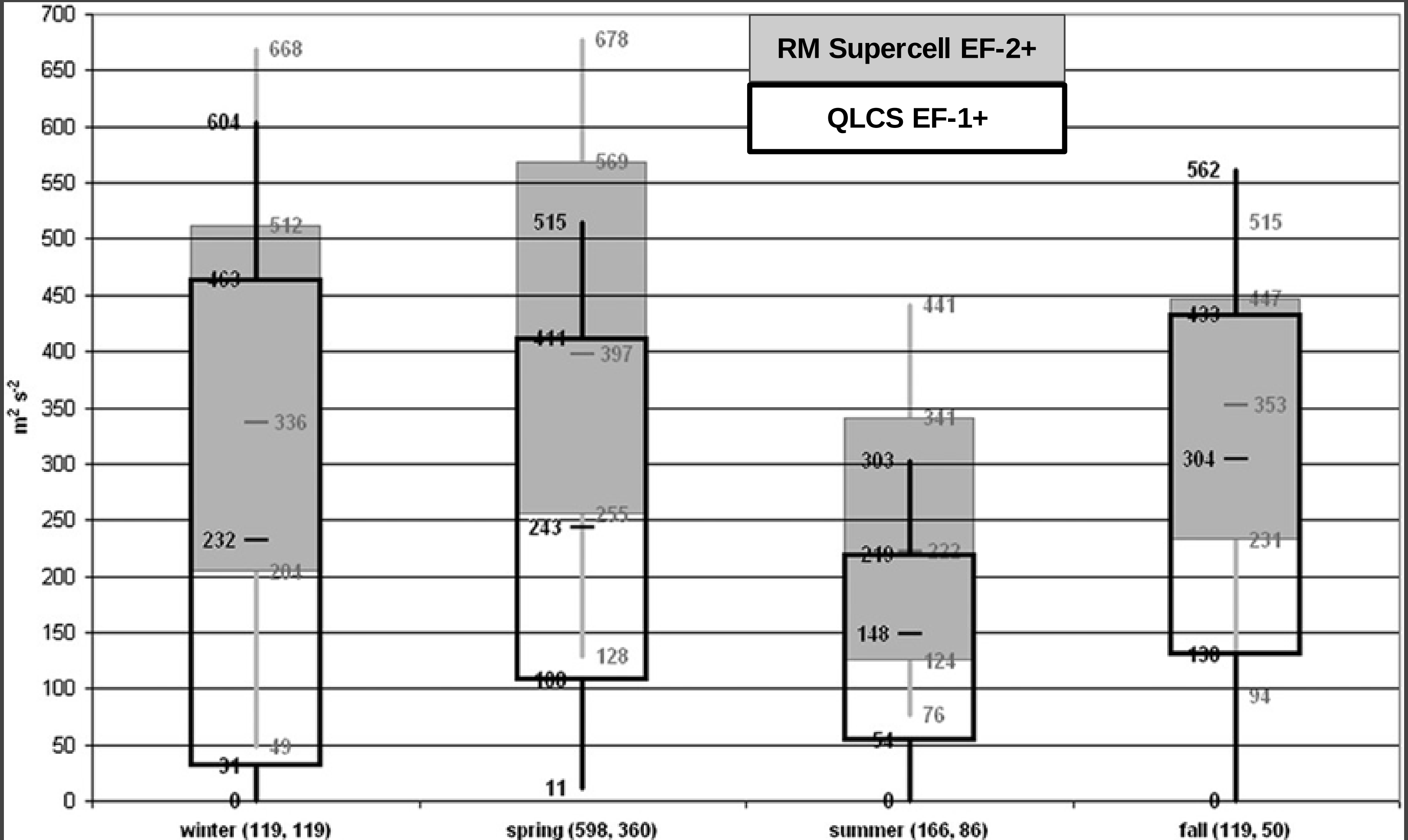


RM Supercell EF-2+
QLCS EF-1+
m AGL
1600
1400
1200
1000
800
600
400
200
0
1021
929
806
790
656
672
582
555
510
521
1424
1319
1077
1045
838
793
675
611
574
513
1568
1450
1312
1249
1015
1019
872
746
711
676
1157
1008
908
815
773
716
629
623
555
540
Consider seasonal temperature trends.
winter (127, 137)
spring (738, 404)
summer (205, 102)
fall (153, 71)

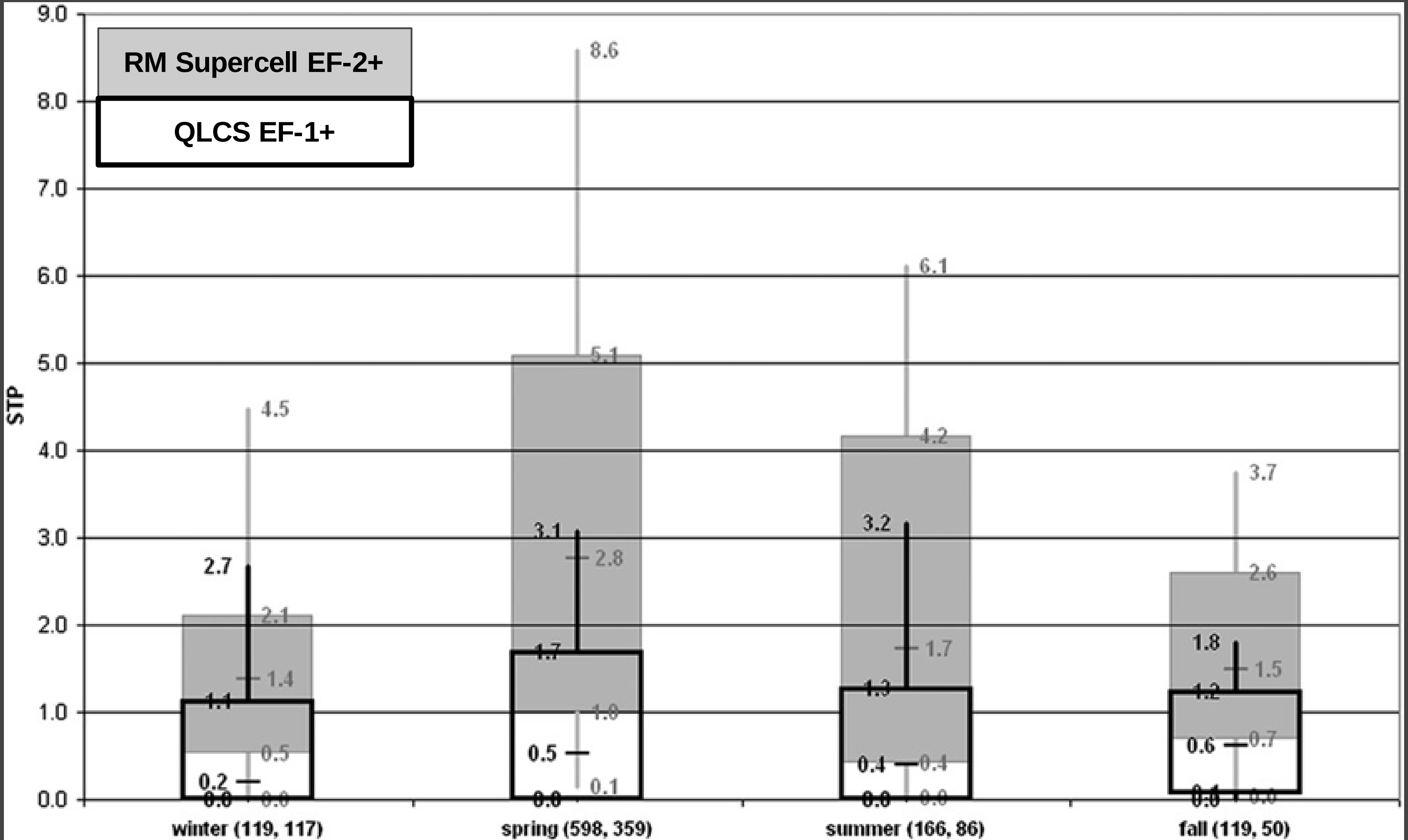
Eff. Bulk Wind Difference



Eff. SRH


RM Supercell EF-2+
QLCS EF-1+
m² s⁻²
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
668
604
512
463
336
232
204
49
31
0
678
569
515
411
397
255
243
128
108
11
441
341
303
222
219
148
124
76
54
0
562
515
447
433
353
304
231
130
94
0
winter (119, 119)
spring (598, 360)
summer (166, 86)
fall (119, 50)

Eff. STP



RM Supercell EF-2+
QLCS EF-1+
STP
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
8.6
5.1
4.5
2.1
1.4
0.5
0.0
2.7
1.1
0.2
3.1
2.8
1.7
1.0
0.5
0.1
6.1
4.2
3.2
1.7
1.3
0.4
3.7
2.6
1.8
1.5
1.2
0.7
0.6
winter (119, 117)
spring (598, 359)
summer (166, 86)
fall (119, 50)

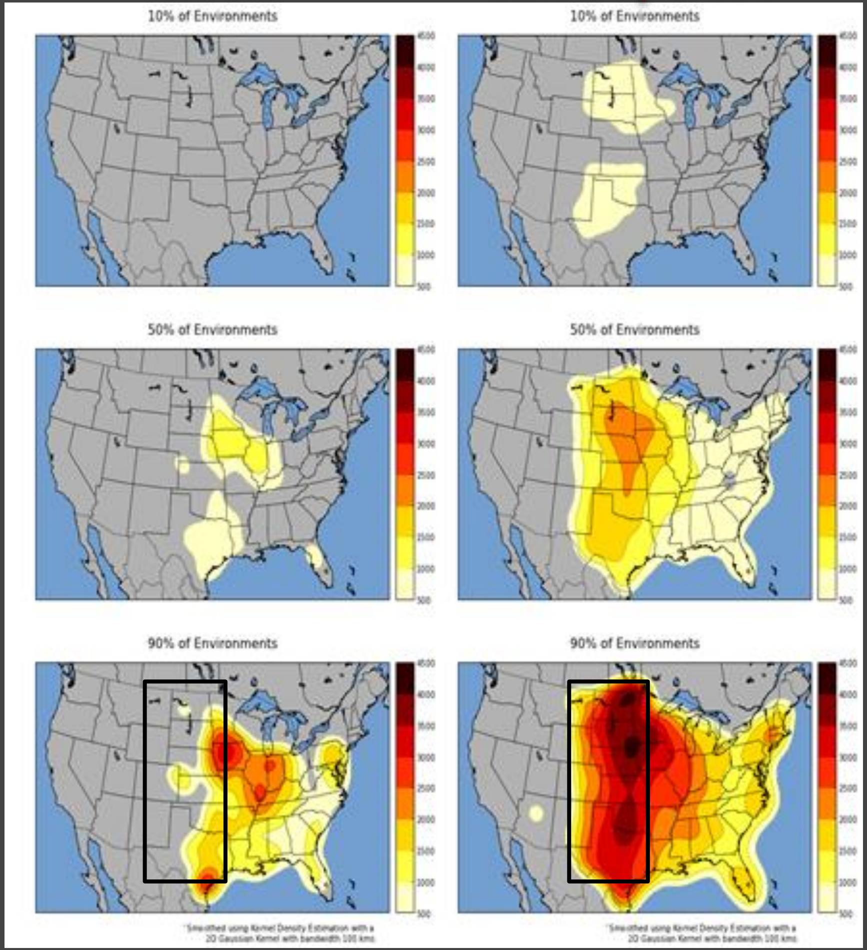
MLCAPE (J/kg)

QLCS RM Supercell

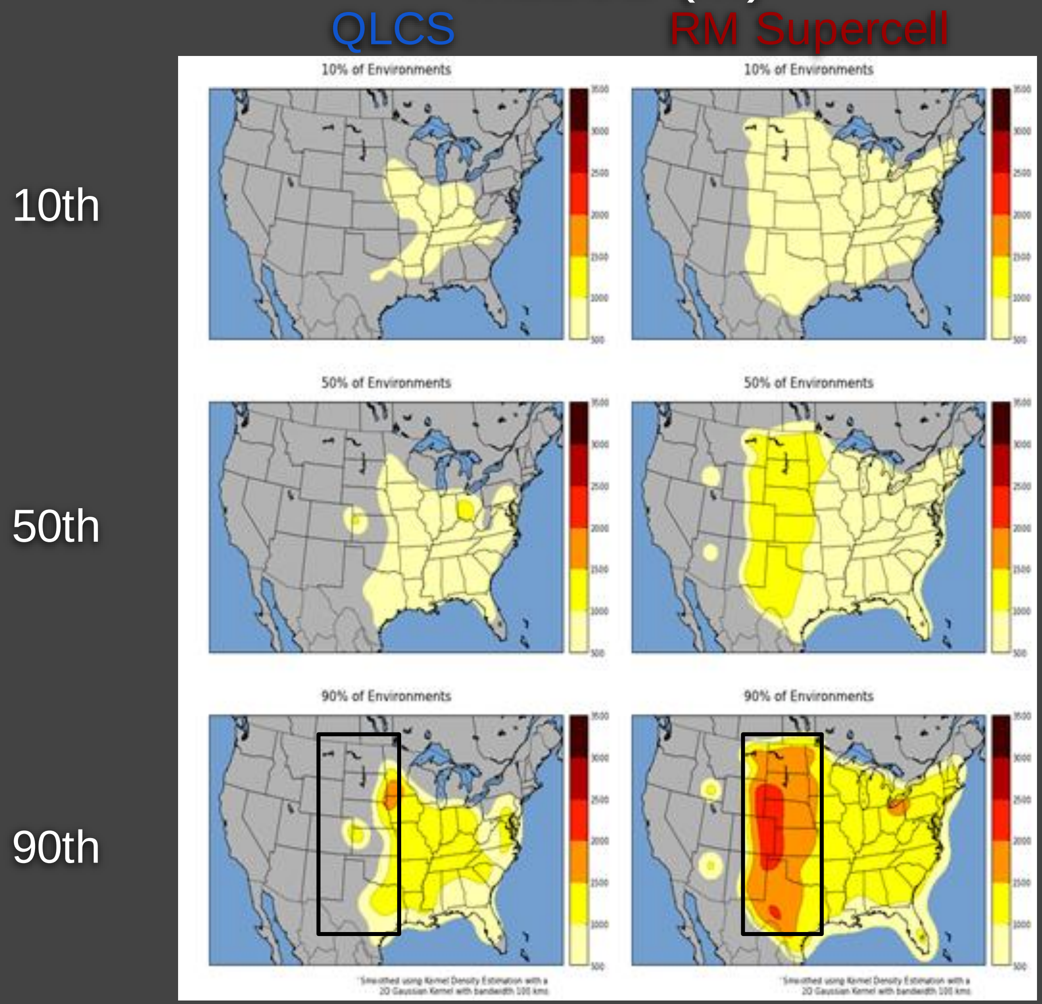
10th

50th

90th



MLLCL (m)


QLCS
RM Supercell
10th
50th
90th
10% of Environments
50% of Environments
90% of Environments

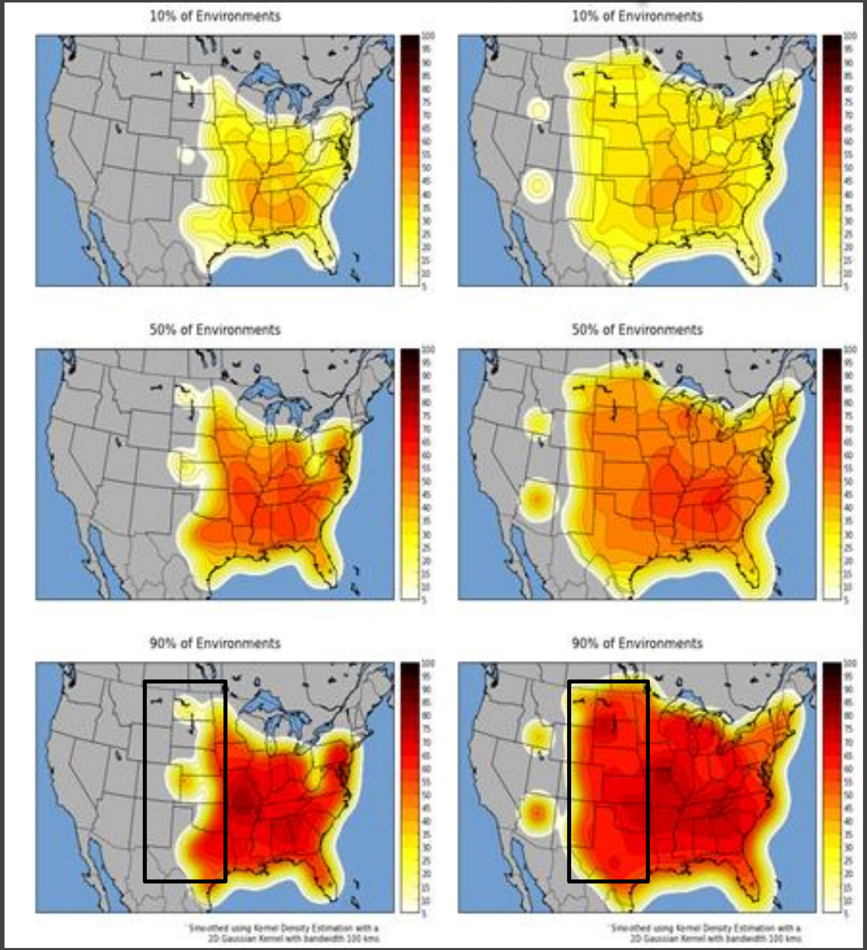
0-6 km Bulk Wind Difference (kt)

QLCS | RM Supercell

10th

50th

90th



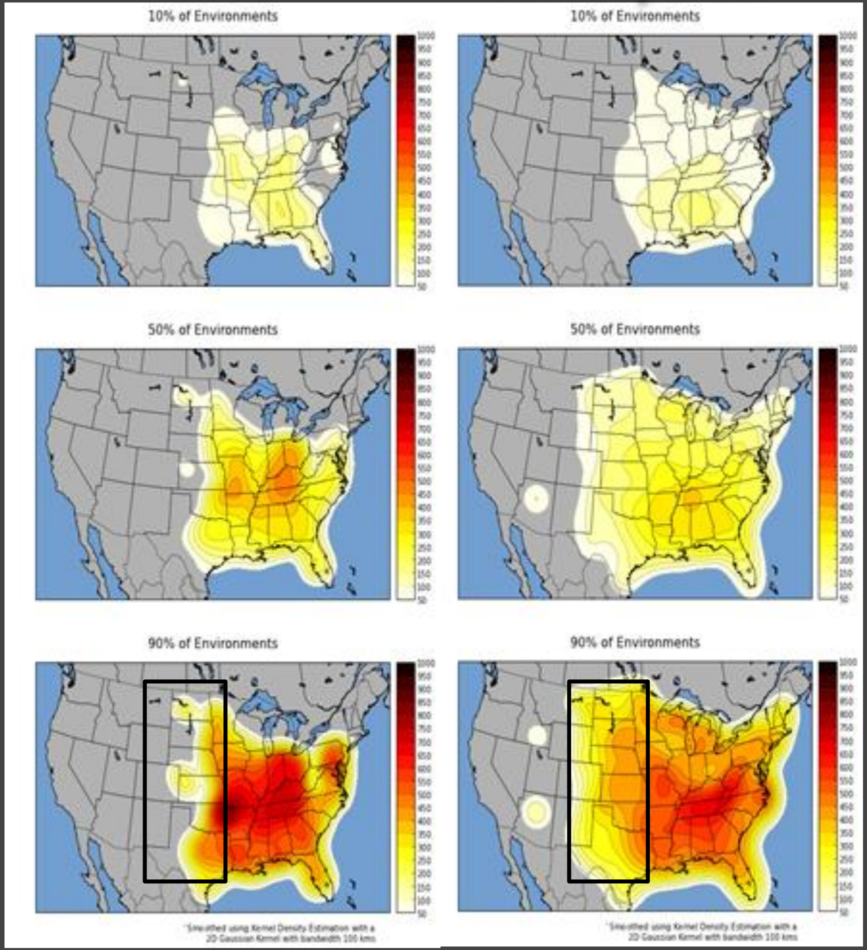
0-1 km SRH (m2/s2)

QLCS | RM Supercell

10th

50th

90th



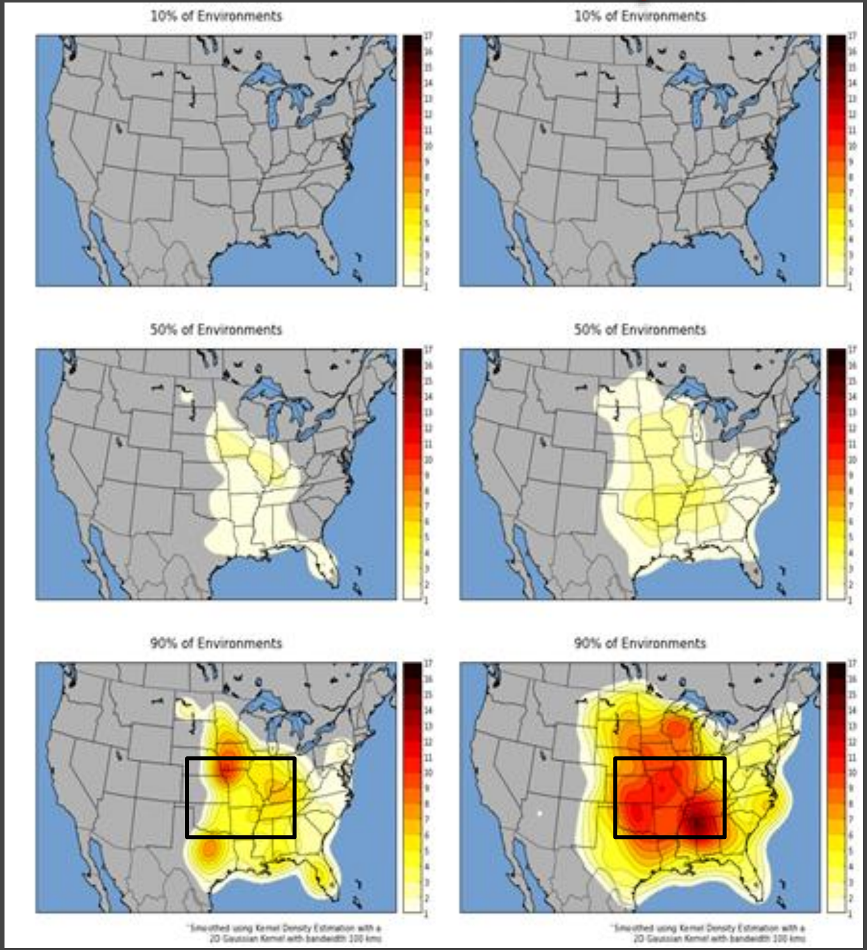
Fixed-Layer STP

QLCS RM Supercell

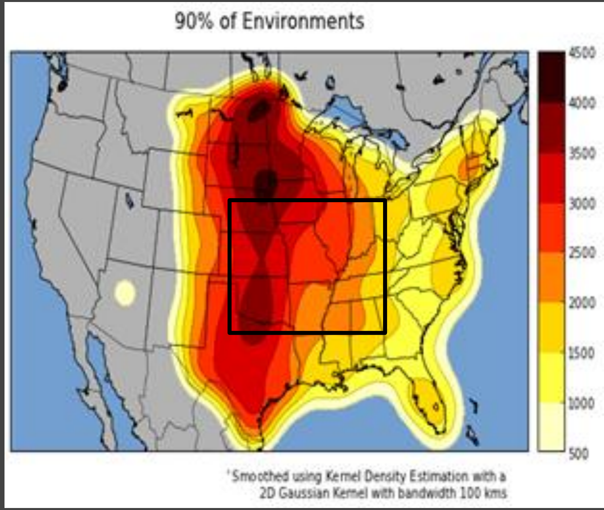
10th

50th

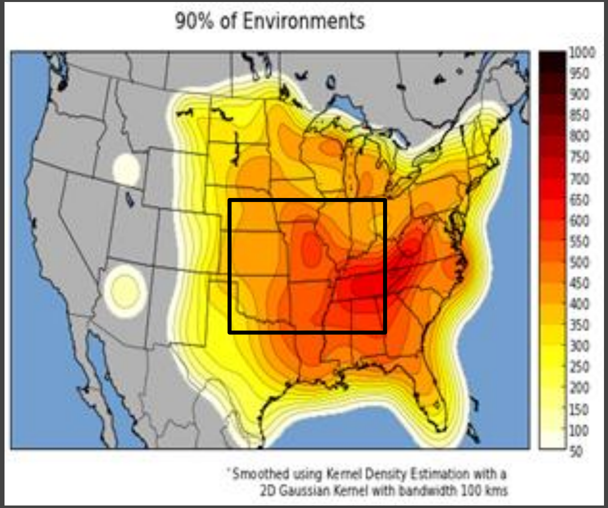
90th



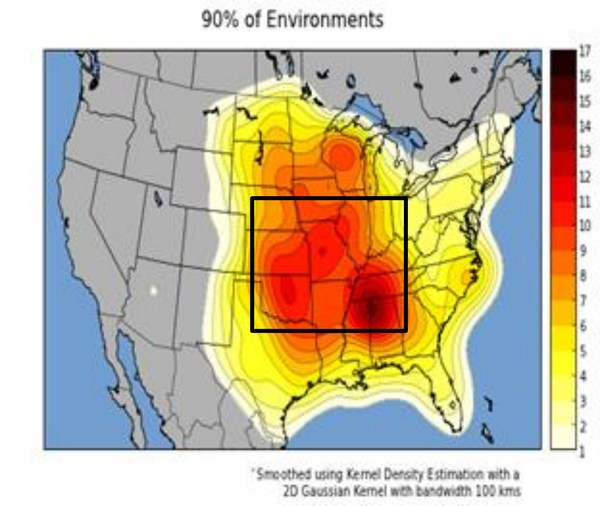
STP distribution is largely driven by the overlap in MLCAPE and 0-1 km SRH



Supercell MLCAPE

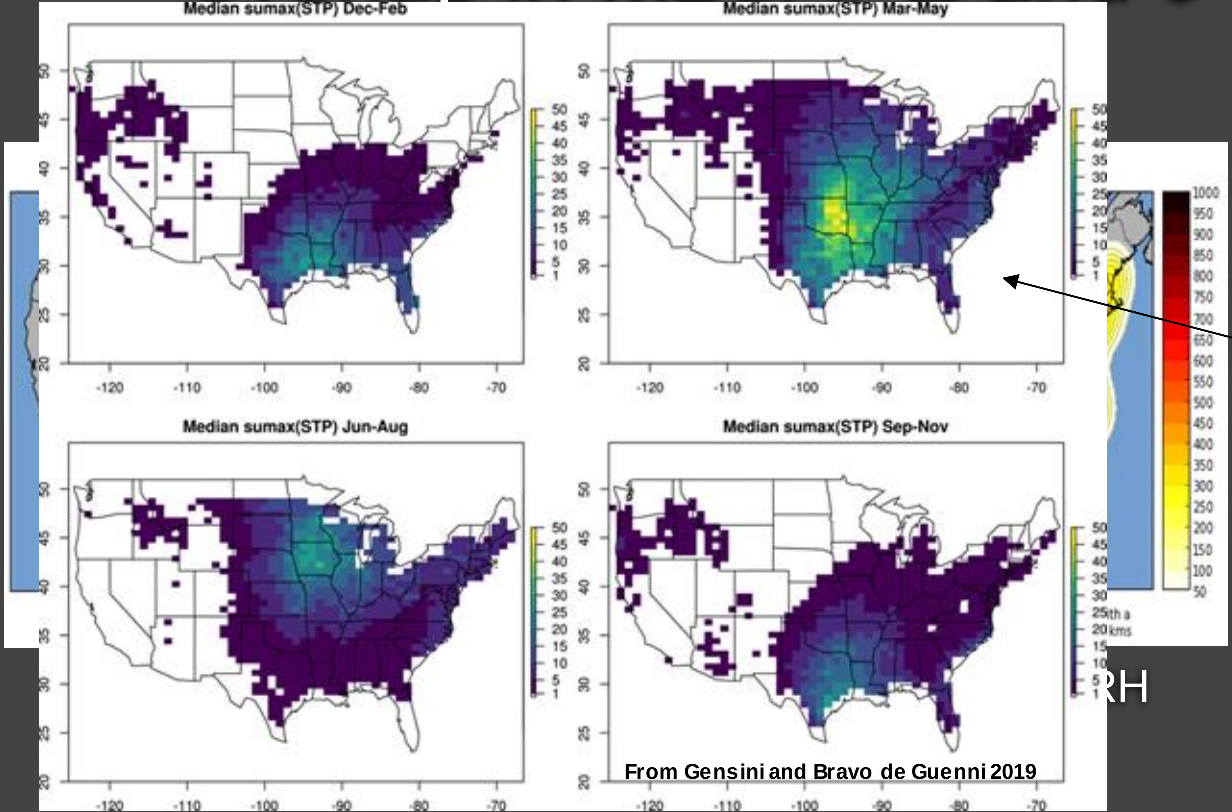


Supercell 0-1 km SRH

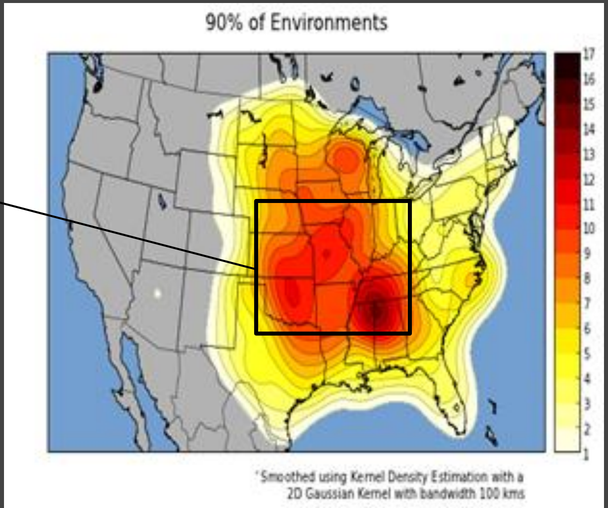


Supercell STP

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

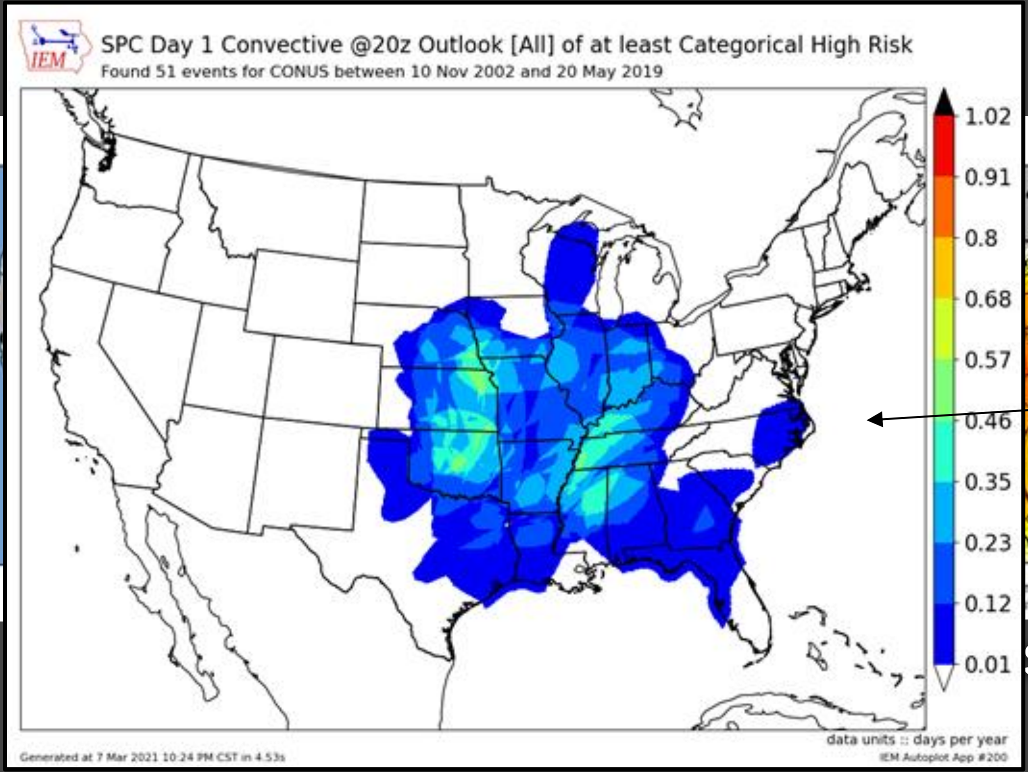


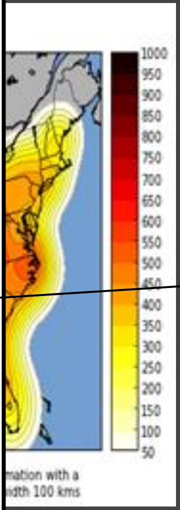
RH



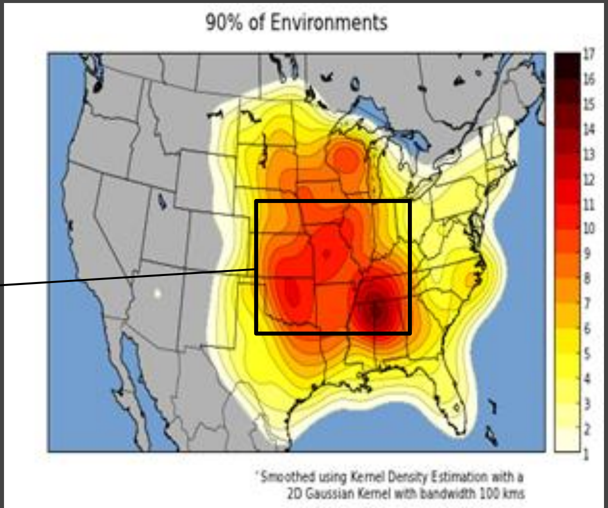
Supercell STP

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





SRH



Supercell STP

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

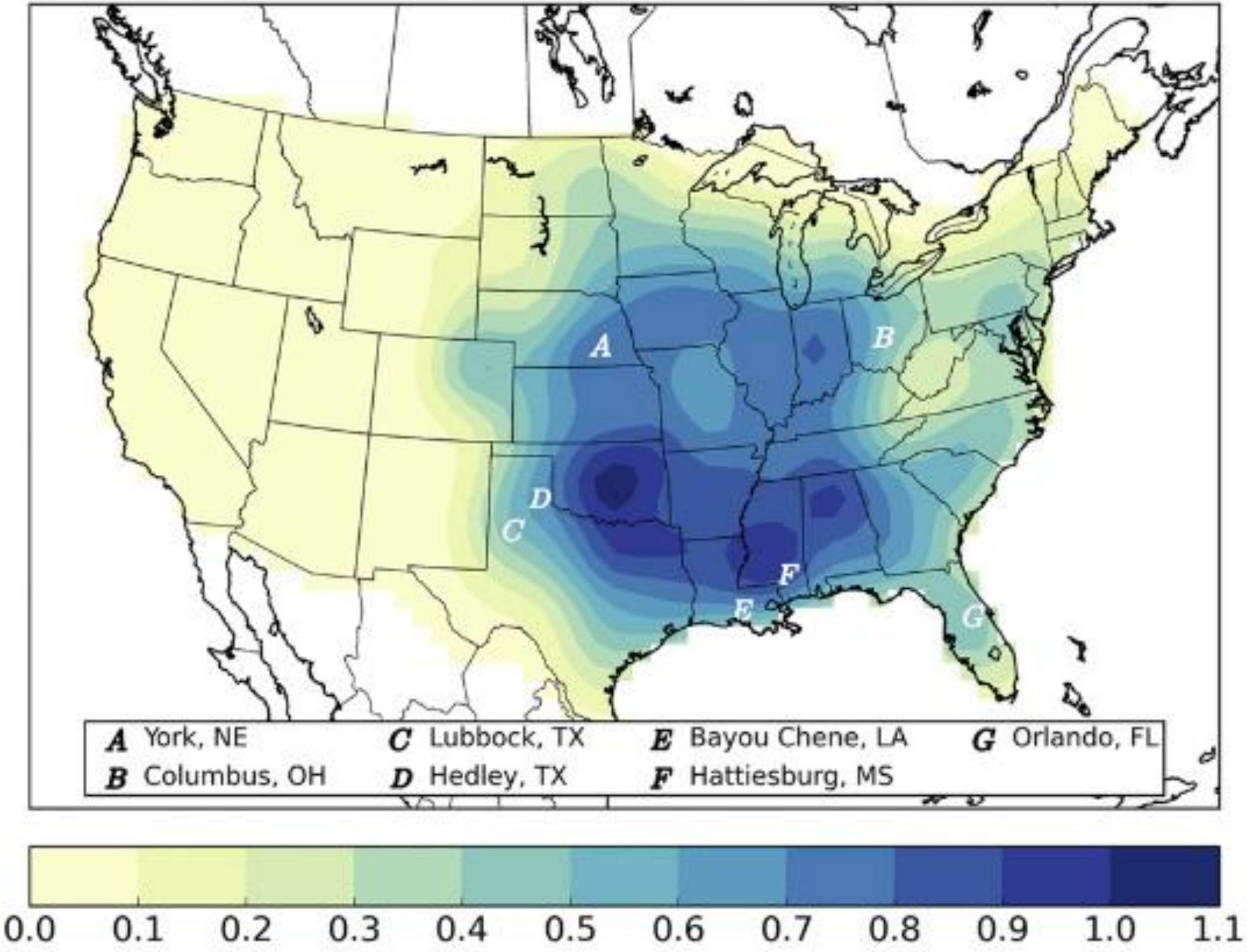


FIG. 3. The total number of tornadoes per year for every grid point across the United States.

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)

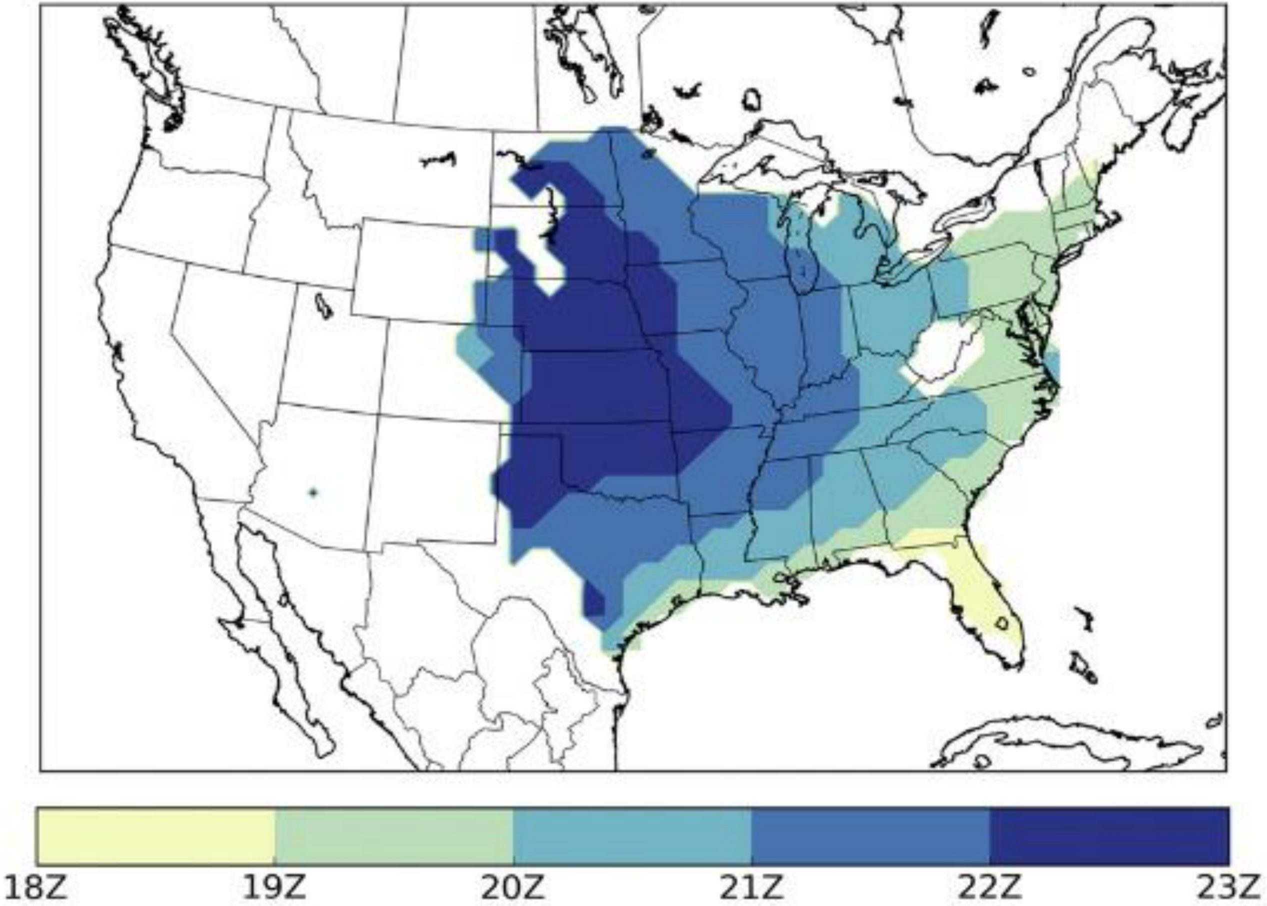
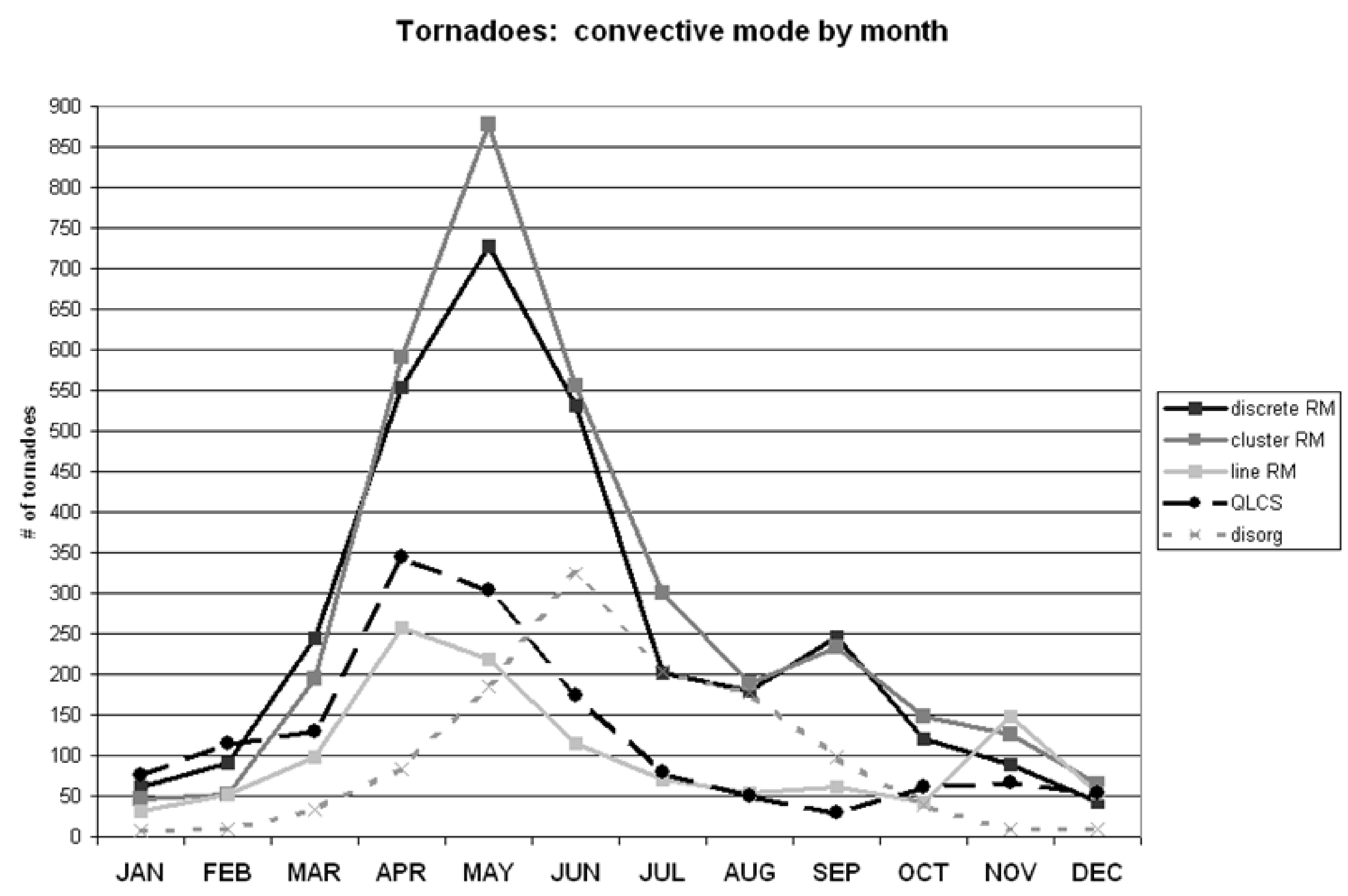
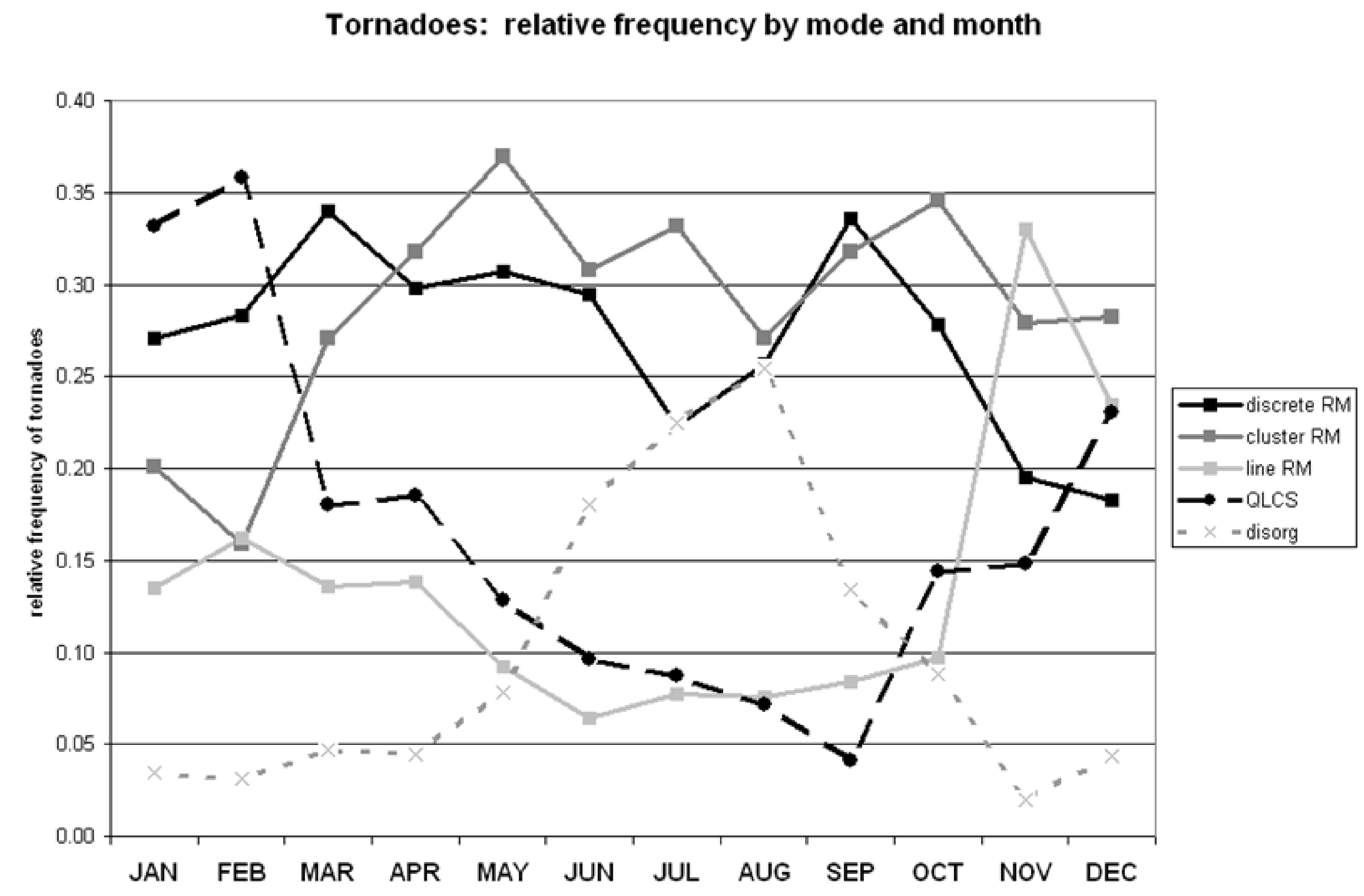


FIG. 7. Start time of the 4-h period that captures the highest fraction of tornado reports for every location across the country. Note the calculation was only done for points with greater than 40 reports over the 1954–2015 period.

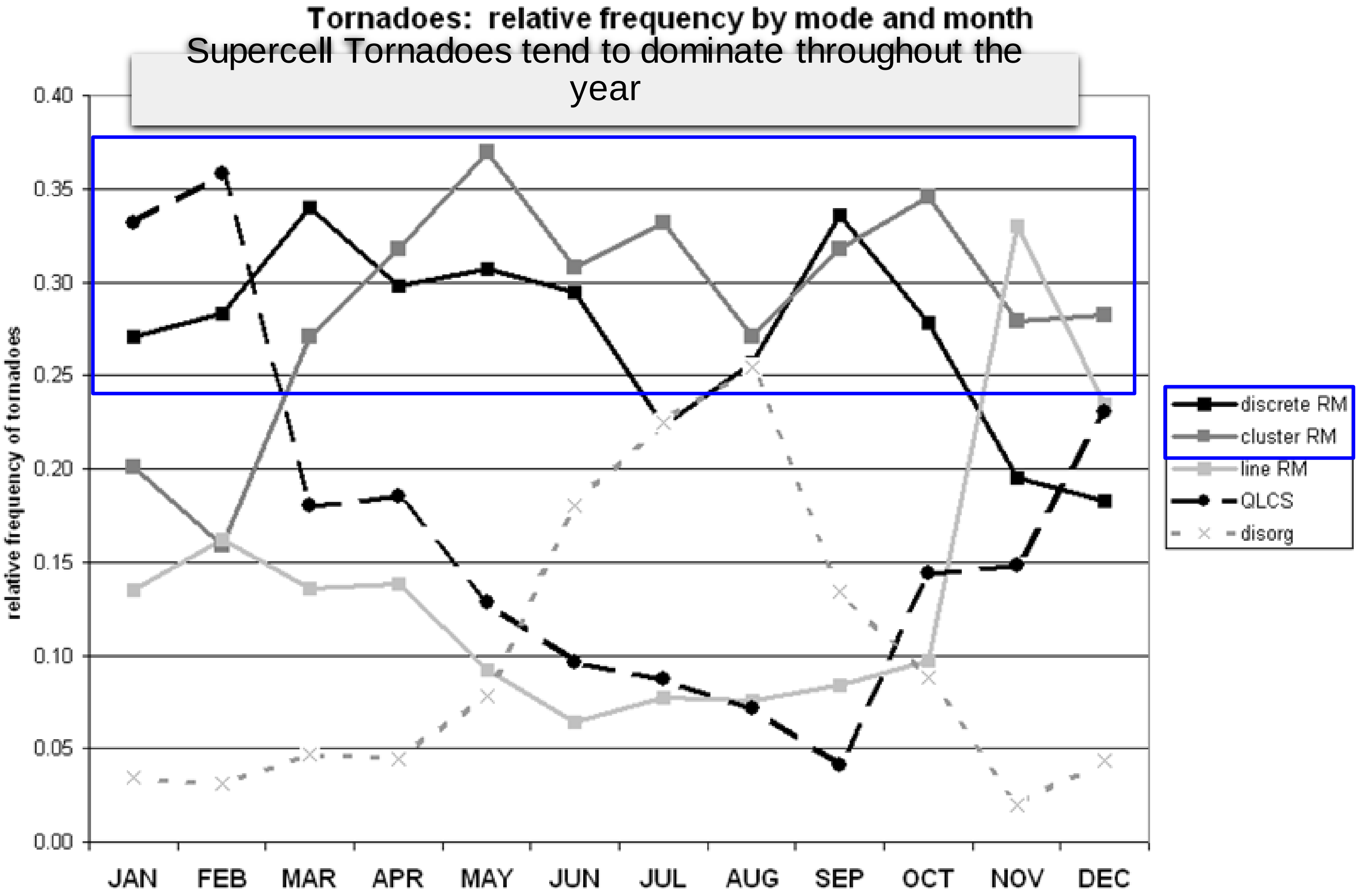


Tornadoes: convective mode by month
# of tornadoes
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
discrete RM
cluster RM
line RM
QLCS
disorg

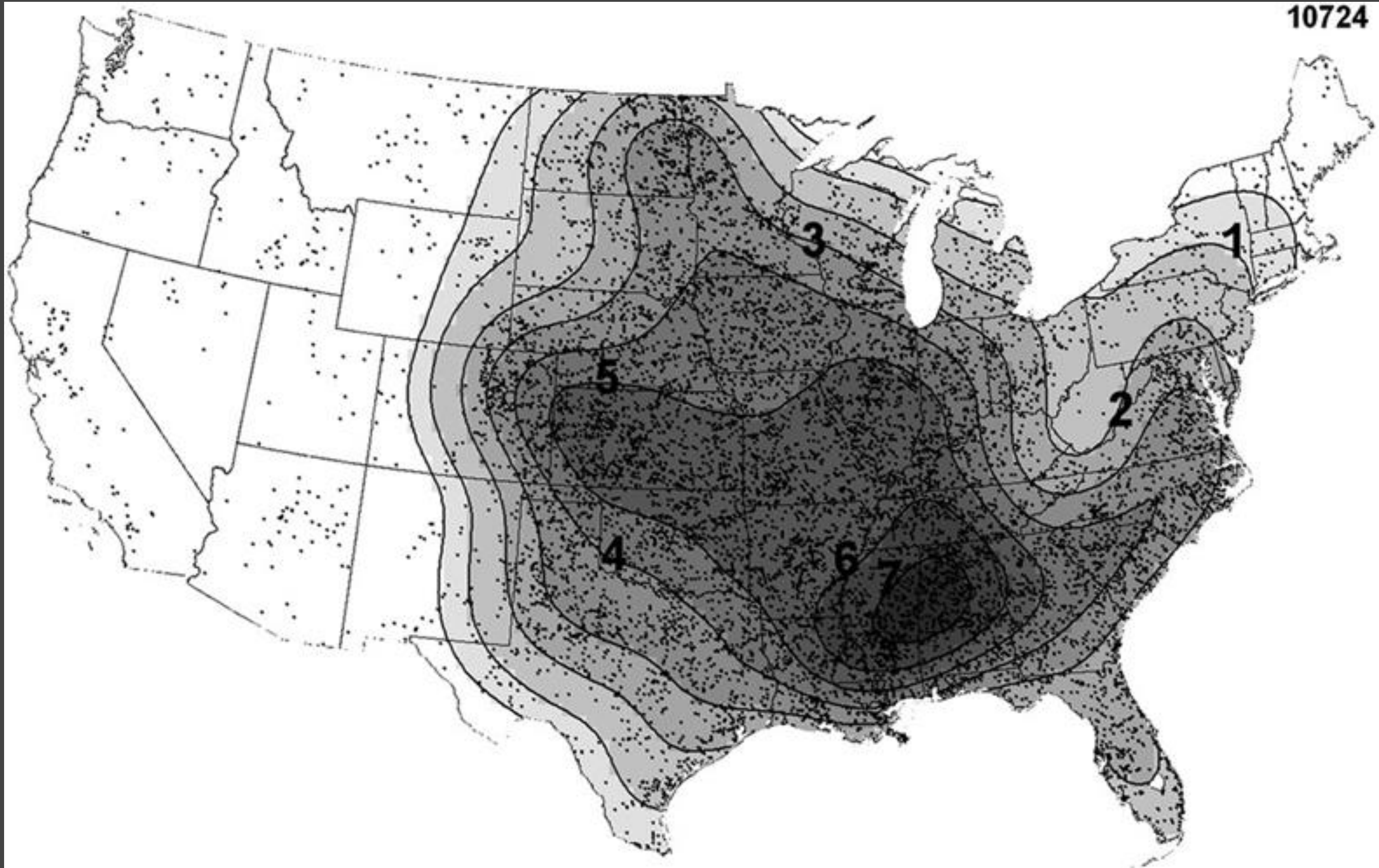


Tornadoes: relative frequency by mode and month
relative frequency of tornadoes
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
discrete RM
cluster RM
line RM
QLCS
disorg

Supercell Tornadoes tend to dominate throughout the year

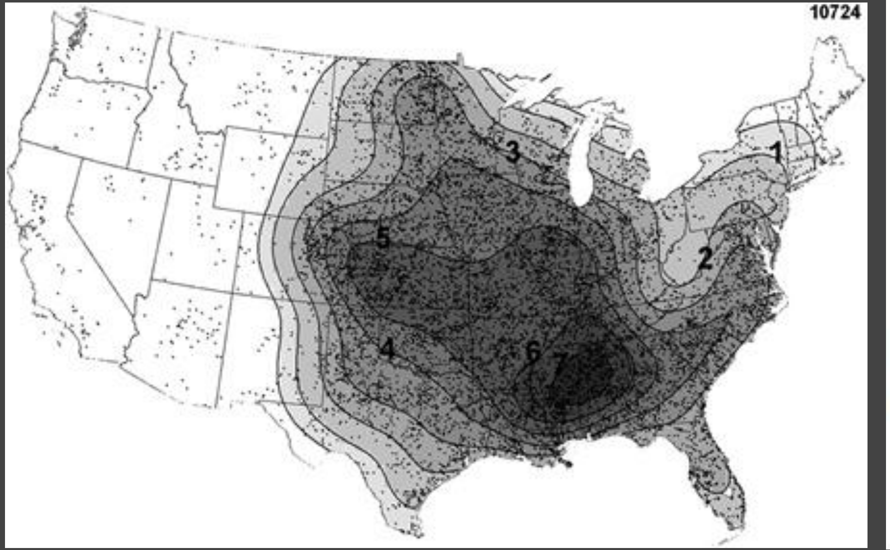


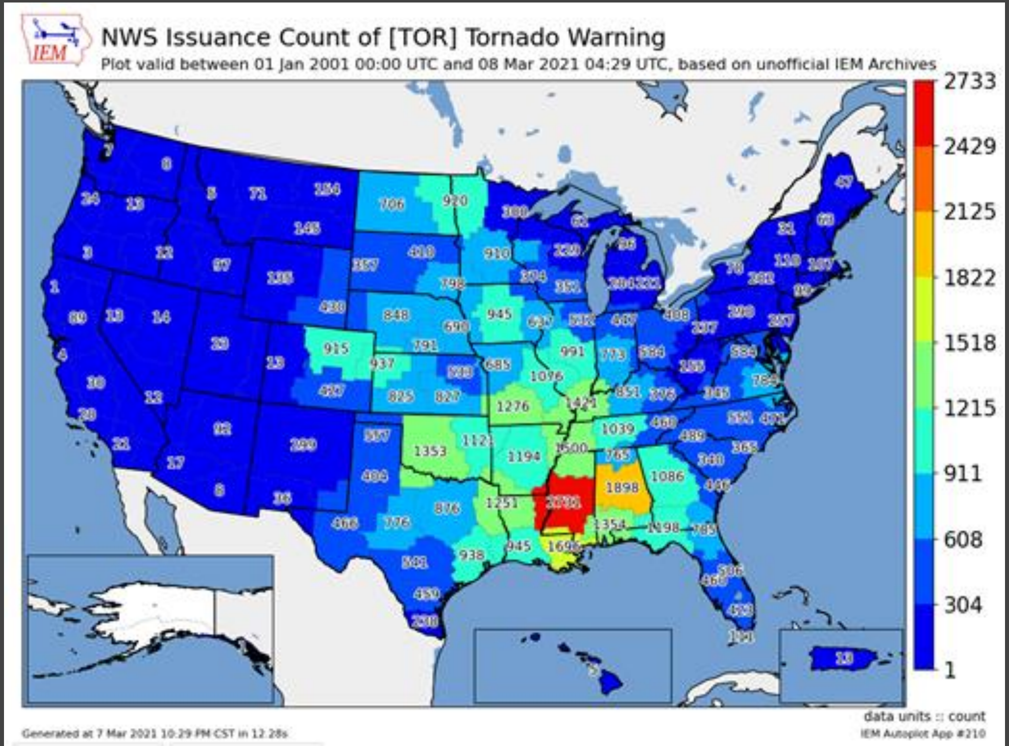
Tornado Events per Decade



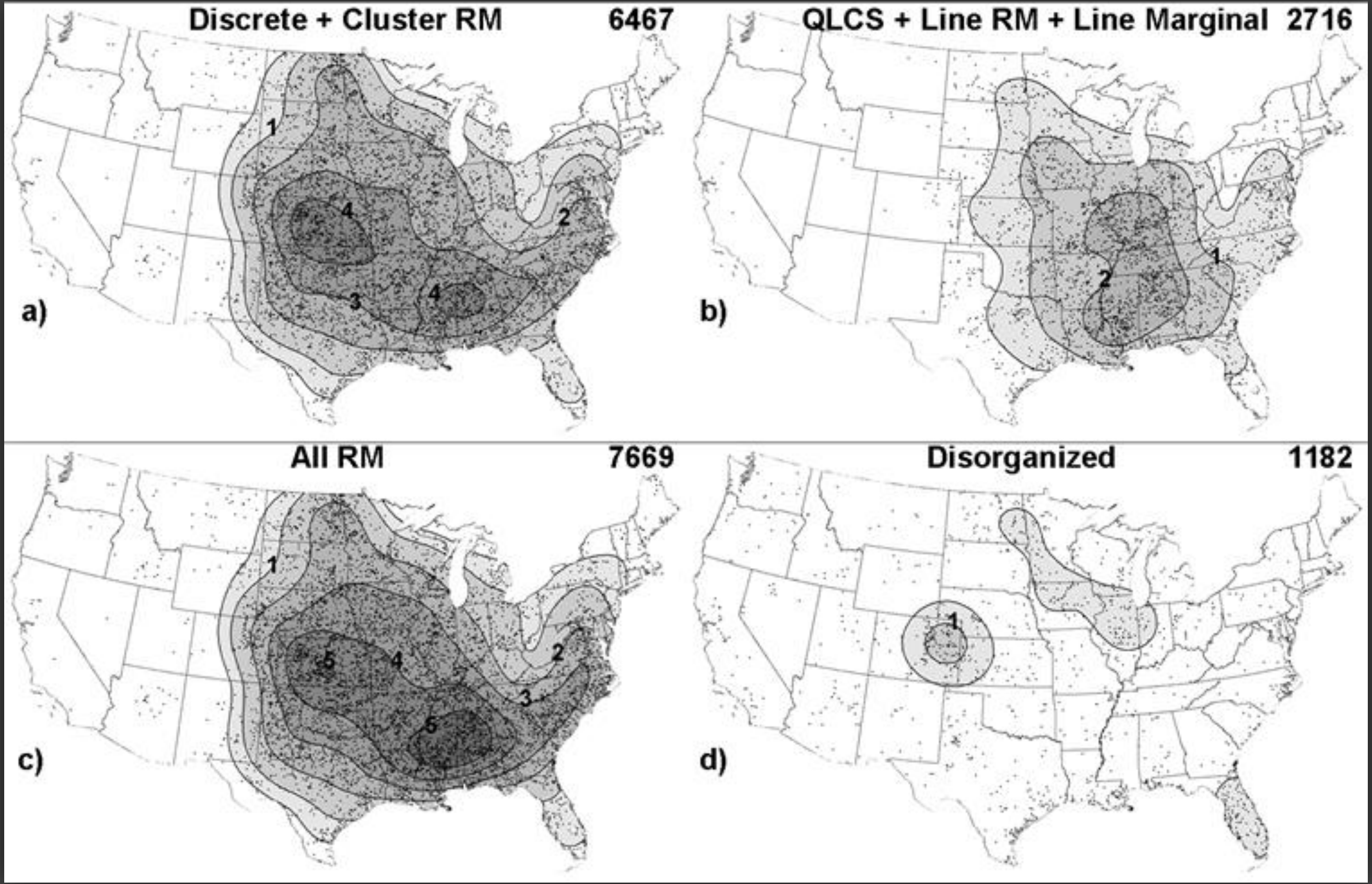
Tornado Events per Decade

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

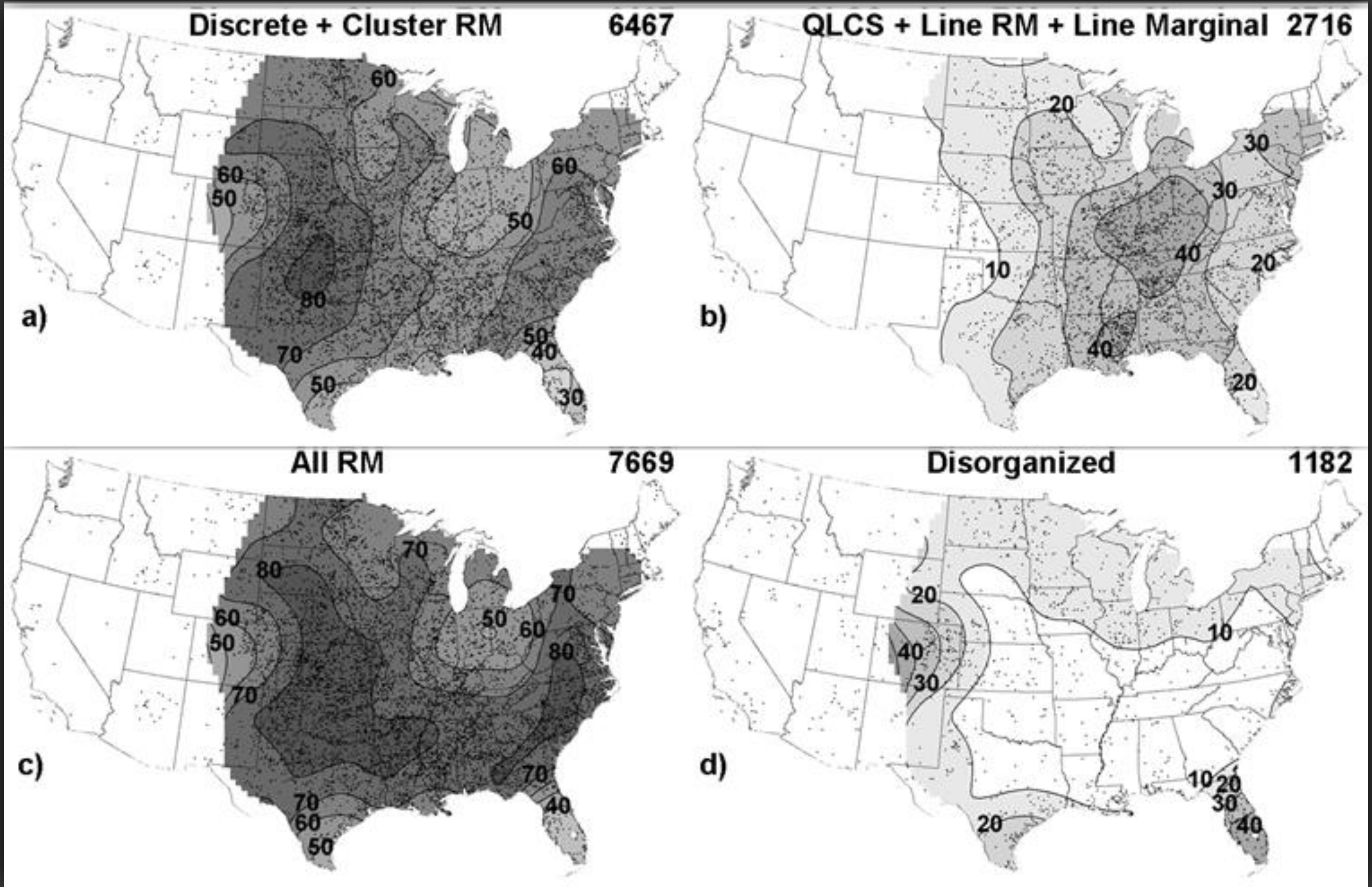




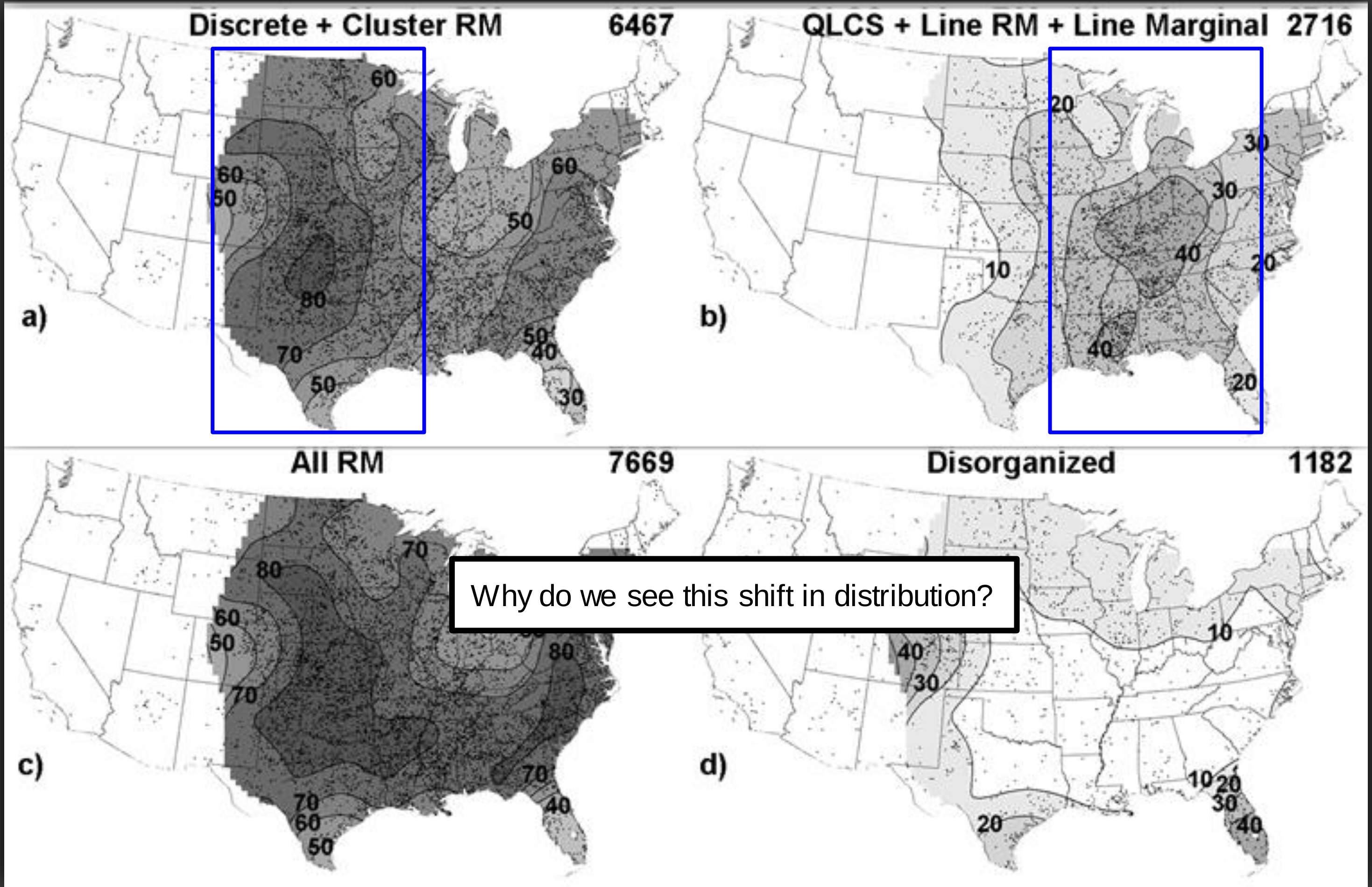
Tornado Events per Decade



Tornado Relative Frequency

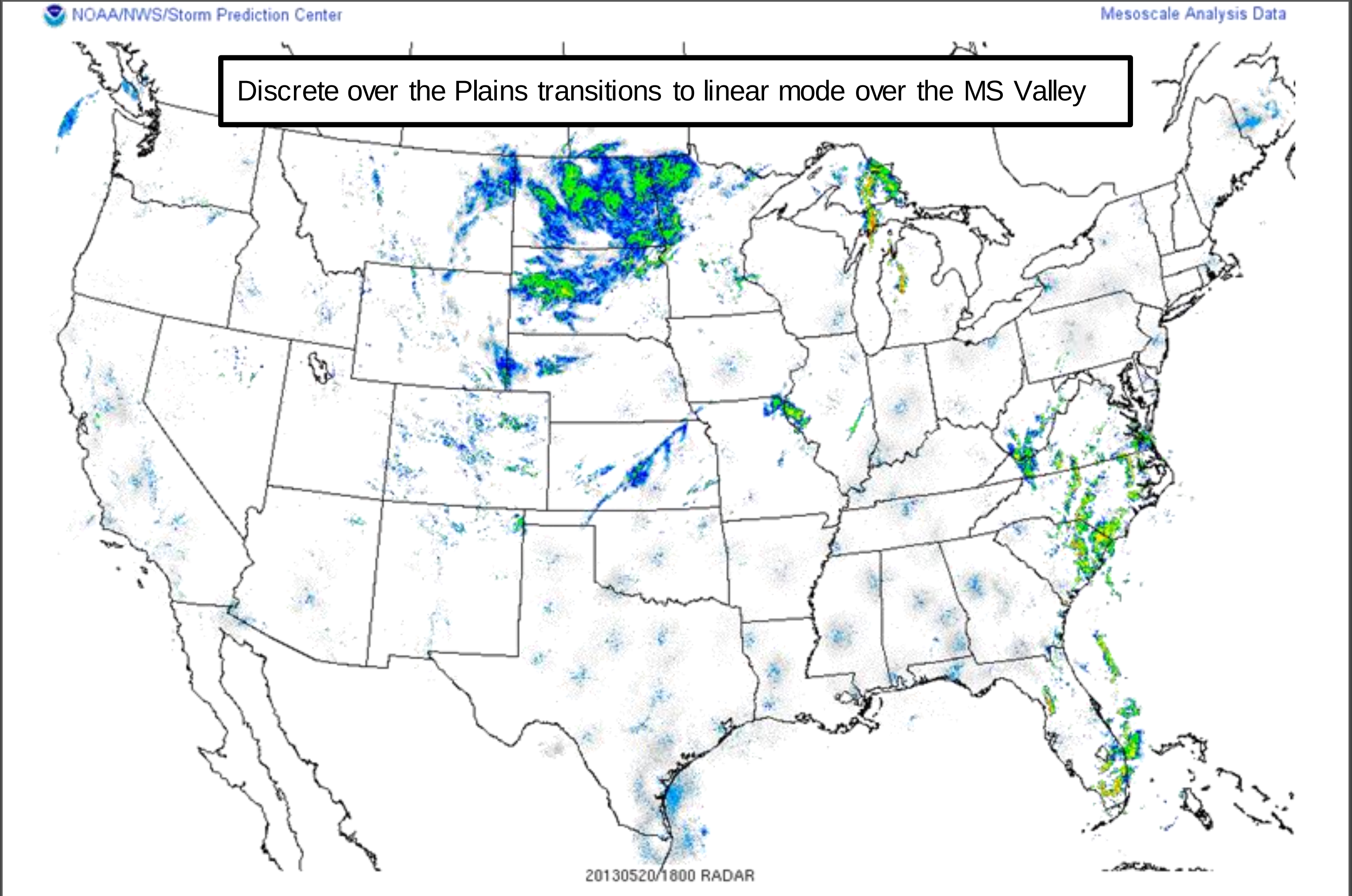


Tornado Relative Frequency

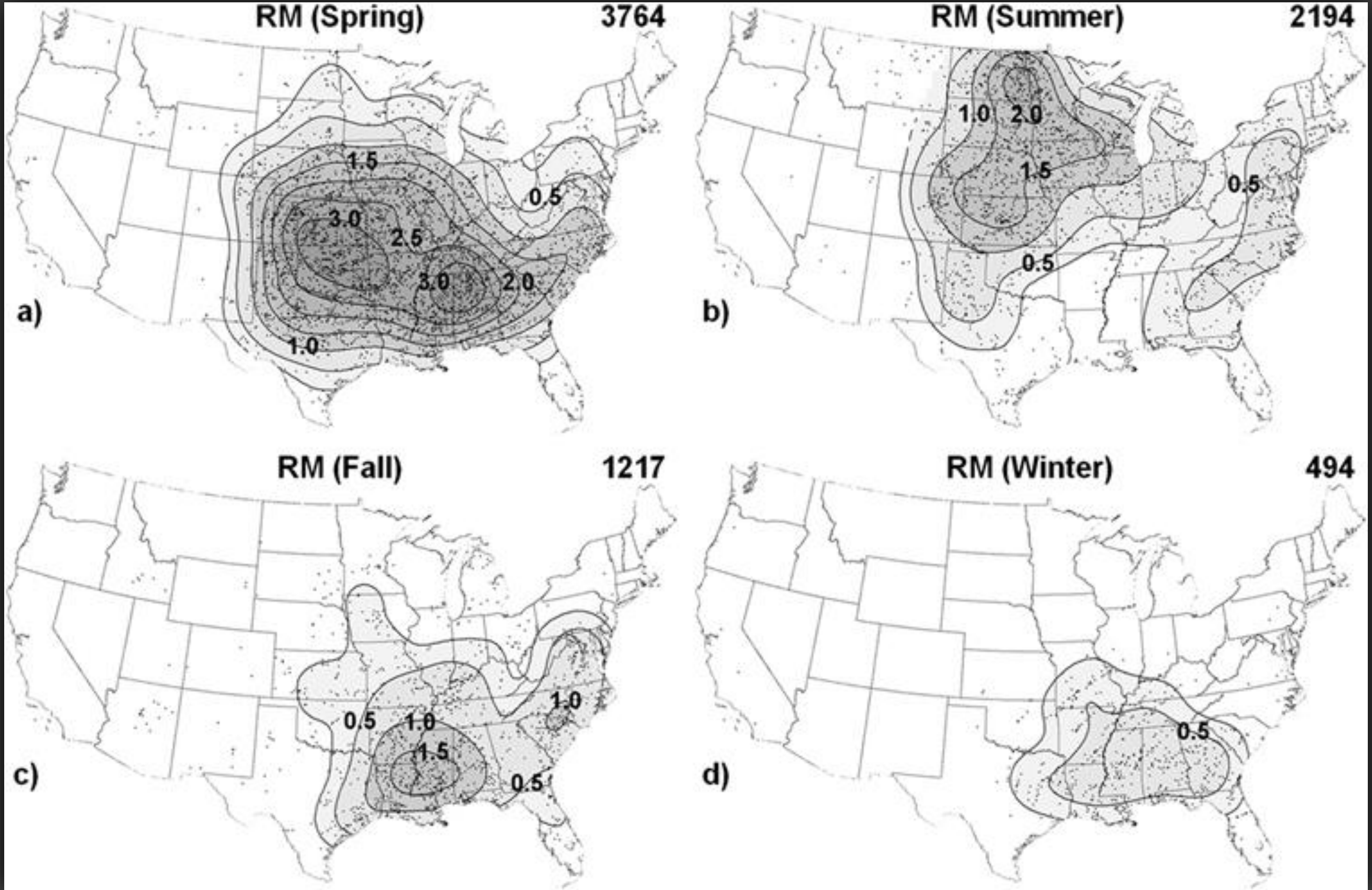


Why do we see this shift in distribution?

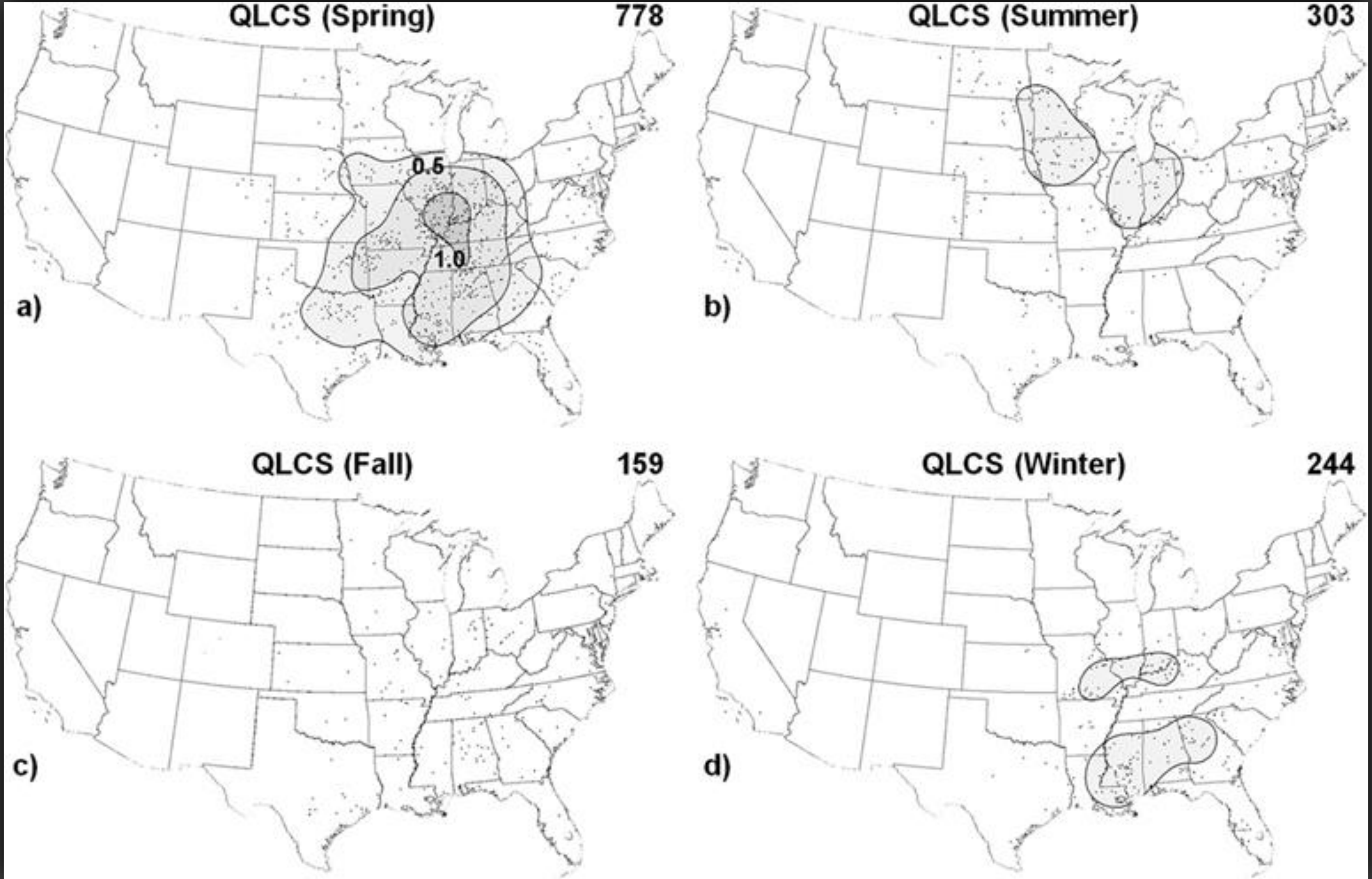
What are some possible reasons for this shift in distribution?


NOAA/NWS/Storm Prediction Center
Mesoscale Analysis Data
Discrete over the Plains transitions to linear mode over the MS Valley
20130520/1800 RADAR

RM Supercell Tornadoes by Season



QLCS Tornadoes by Season

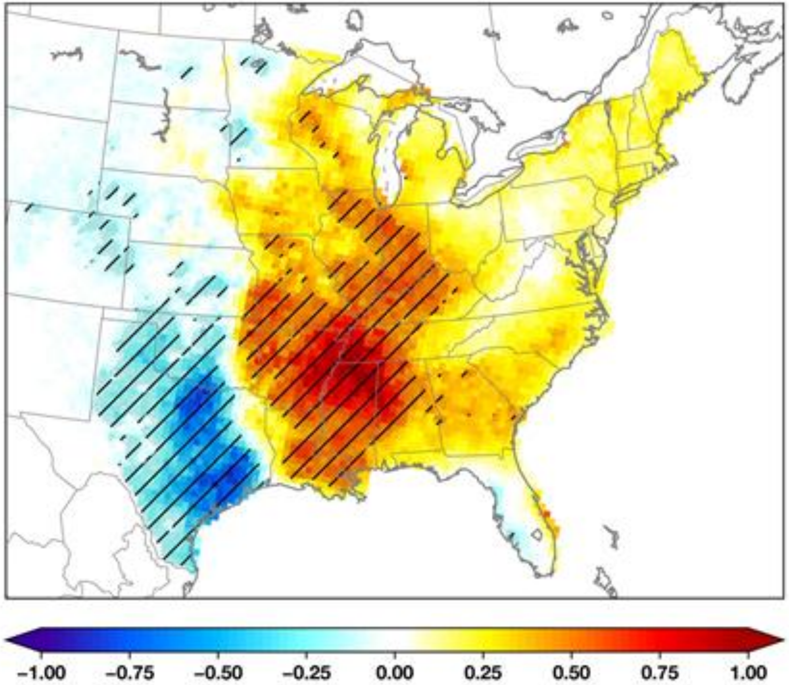


Shifting Tornado Climatology?

Fig. 4

From: Spatial trends in United States tornado frequency

From Gensini and Brooks 2018



Theil-Sen slope analysis of 1979–2017 annual grid-point sum of daily max STP from NARR. p values are hatched at values ≤ 0.05 significance using Kendall's τ statistic. Slope units are sum of daily max STP per year

Recent work by Gensini and Brooks (2018) argues that the frequency of tornadoes may be shifting eastward.

This study used STP (from the NARR) as a proxy for tornado environments and occurrences (recall that even more recent work by Gensini and Bravo de Guenni showed STP was a strong covariate for tornado frequency).

They noted that the annual “accumulation” of STP was decreasing across the southern Plains and increasing across the Midwest/Southeast.

The cause? Unknown at this point!

Still lots of room for research!

A Few Notes on Tornado Intensity Estimation

EF4-rated damage from the Rolling Fork, MS, tornado on 24 March 2023.

The Fujita Scale was developed in 1971 to quickly estimate tornado intensity from damage surveys.

Ratings with wind speed ranges were developed so that a reasonable range of possible wind speeds could be estimated without the need for detailed forensic engineering studies of structures.

Engineers quickly raised concerns that wind speeds for the higher damage ratings were overestimates of the wind speeds necessary to cause the associated damage.

The Enhanced Fujita Scale was debuted in 2007 to provide more damage indicators to estimate tornado intensity and to lower the wind speed ranges for the higher ratings (EF2–EF5).

A Few Notes on Tornado Intensity Estimation

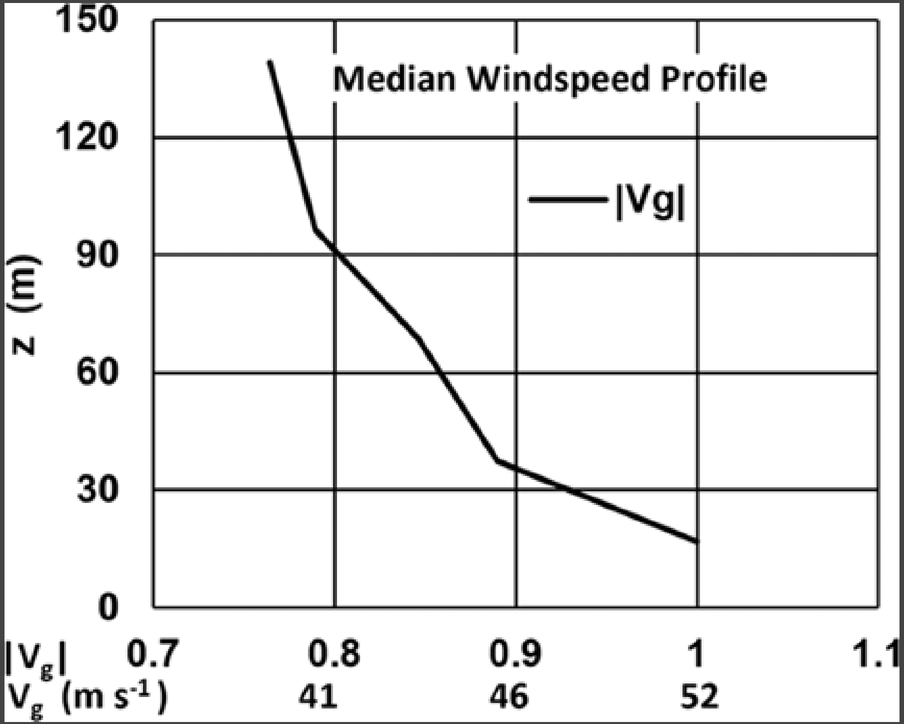


Fig. 4 from Kosiba and Wurman (2023).

The American Society of Civil Engineers (ASCE) has formed a Wind Speed Estimation Standard Committee (WSEC) to develop a standard for estimating tornado wind speeds.

The WSEC is working on a revised EF scale, as well as standard methods for tornado wind speed estimation using radar, forensic engineering, tree fall pattern analysis, in-situ observations, and satellite and UAS remote sensing.

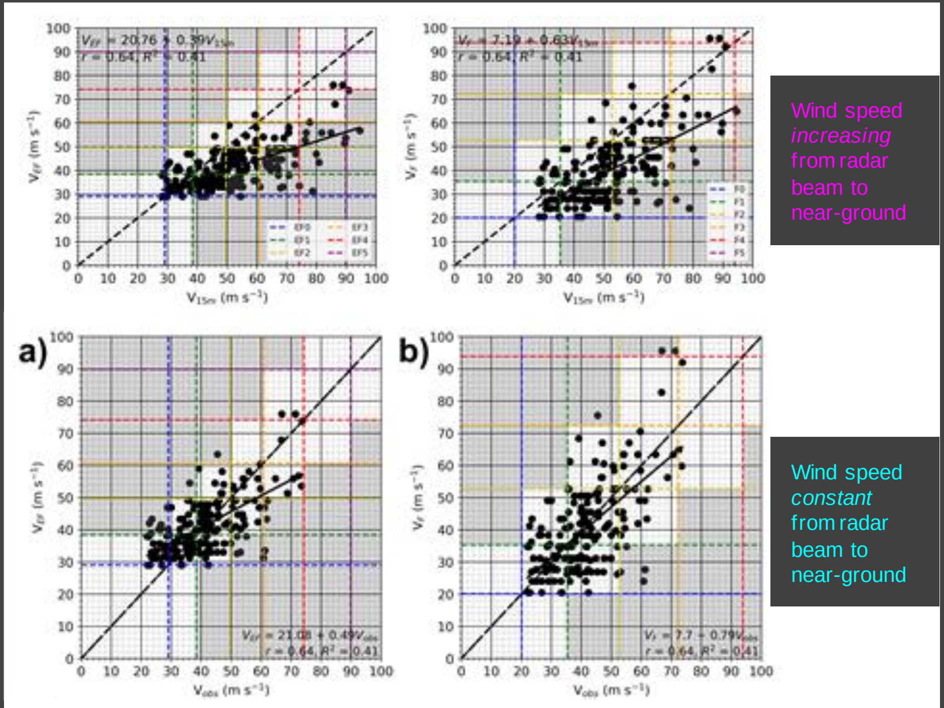
Radar estimation of tornado wind speeds is of particular interest since radar has a unique ability to detect wind components throughout the entire vortex at relatively high-resolution.

Work by Kosiba and Wurman (2023) used a radar climatology of tornadoes sampled with Doppler on Wheels (DOWs) to illustrate that tornado winds may be strongest near the ground (consistent with past modeling studies).

A Few Notes on Tornado Intensity Estimation

EF-Scale Wind Speed Estimate from Damage

F-Scale Wind Speed Estimate from Damage



Adapted from Figs. 6, 12, and 17 of Lyza et al. (2024; MWR)

Lyza et al. (2024) gathered 194 observations from 105 different tornadoes that had observations from WSR-88D radars 150 m AGL and compared those observations to both EF and F-scale estimates of wind speed from damage.

Applied two different assumptions to estimate winds near the ground: (1) that wind speeds increase along the Kosiba and Wurman (2023) curve and (2) that wind speeds remain constant from radar beam height to the surface.

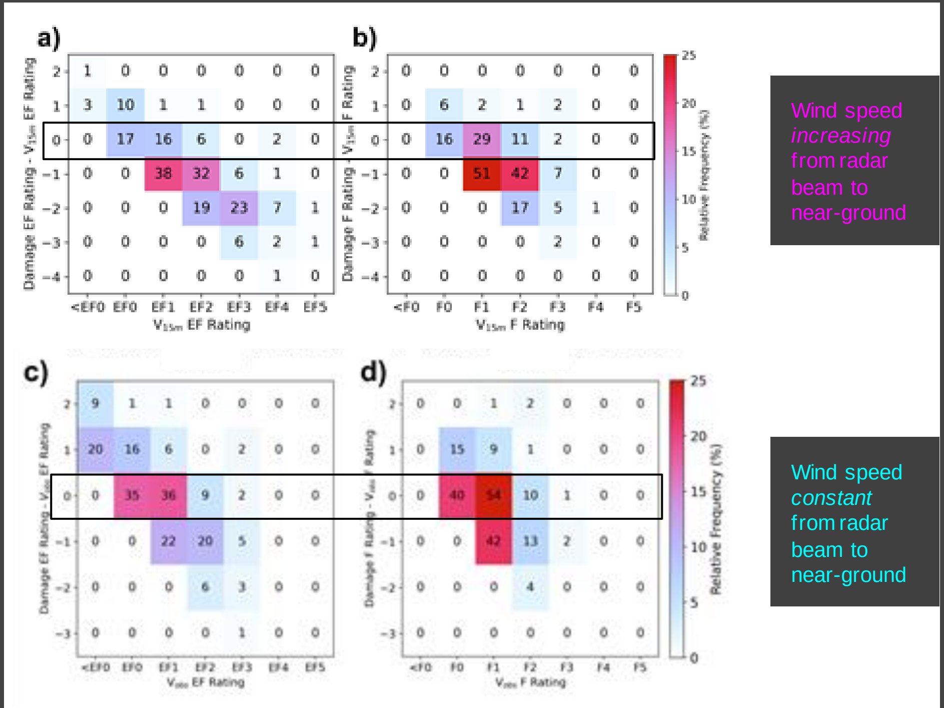
For both assumptions, radar-based intensity estimates of near-ground winds increase more quickly than wind speed estimates from damage from the EF scale as vortex intensity increases.

Damage-based wind speed estimates from EF scale more closely match radar for weak tornadoes, while wind speed estimates from the F scale more closely match radar for strong–violent tornadoes. However…

A Few Notes on Tornado Intensity Estimation

EF-Scale Wind Speed Ranges

F-Scale Wind Speed Ranges



Adapted from Figs. 14 and 17 of Lyza et al. (2024; MWR)

The official tornado climatology is still based on the ratings of tornadoes.

When the radar-based wind speed estimates and damage-based wind speed estimates are both binned into their respective EF and F scale ratings, the F scale yields **less rating error** than the EF scale across the entire range of tornado intensities.

Key Takeaway: Tornado intensity estimation is still a very difficult task, and damage-based estimates of tornado intensity can still contain a lot of error. *Estimates of tornado intensity from the EF scale likely yield lower-bound estimations of actual tornado intensity in many cases, especially for stronger tornadoes.*

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

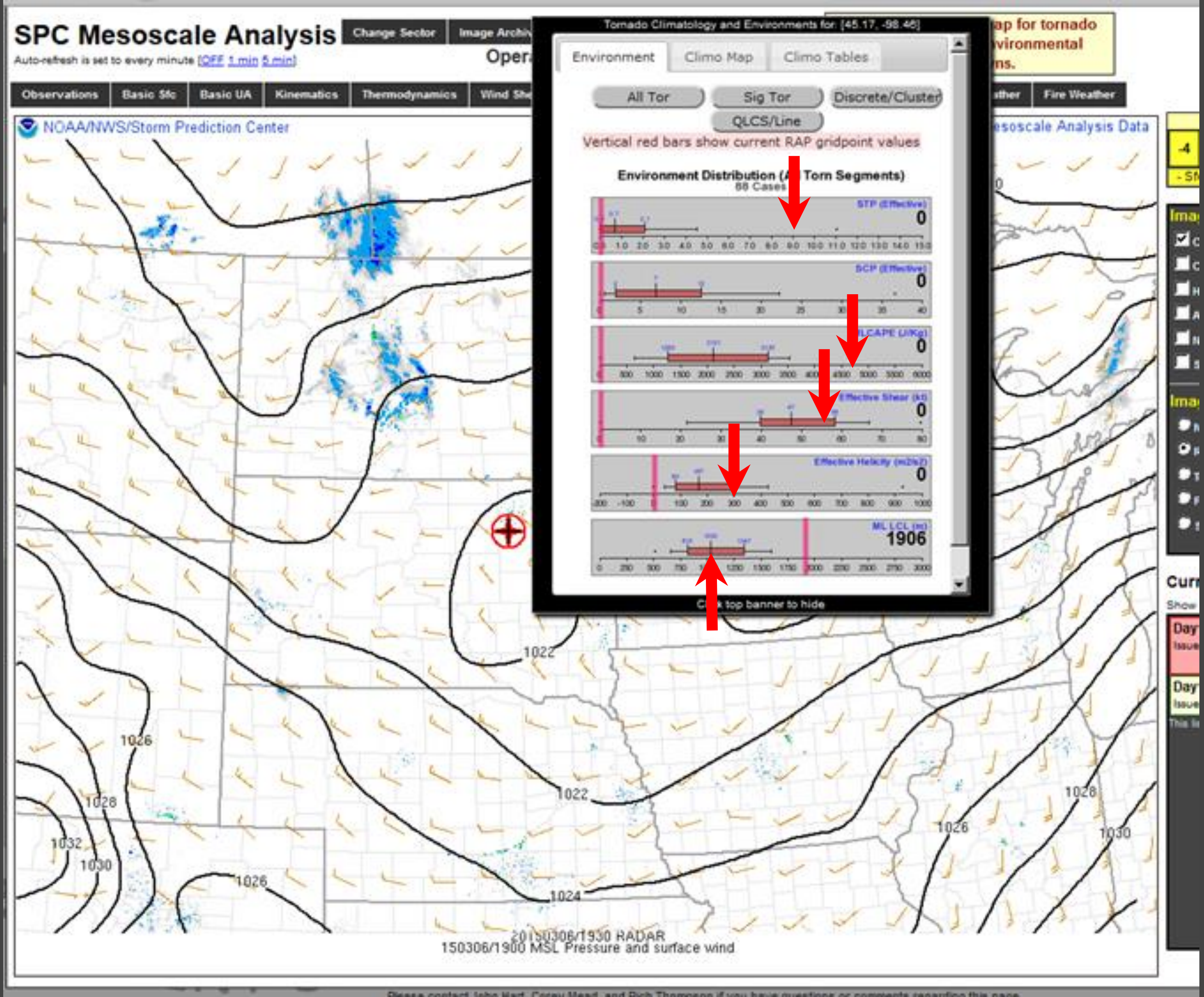
- QLCS tornadoes are also most common in the spring with a minimum in the fall.
  - However, these can also occur throughout the year.
  - Tornado maxima over the OH/MS River Valleys may be related to upscale growth from the west

- Tornado intensity estimation is still a work in progress!

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.


SPC Mesoscale Analysis
Change Sector
Auto-refresh is set to every minute [OFF 1 min 5 min]
Observations
Basic Sfc
Basic UA
Kinematics
Thermodynamics
Fire Weather
NOAA/NWS/Storm Prediction Center
Tornado Climatology and Environments for: [45.17, -98.46]
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Climo Tables
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Discrete/Cluster
QLCS/Line
Vertical red bars show current RAP gridpoint values
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SCP (Effective)
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Effective Shear (kt)
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Effective Helicity (m2/s2)
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ML LCL (m)
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top banner to hide
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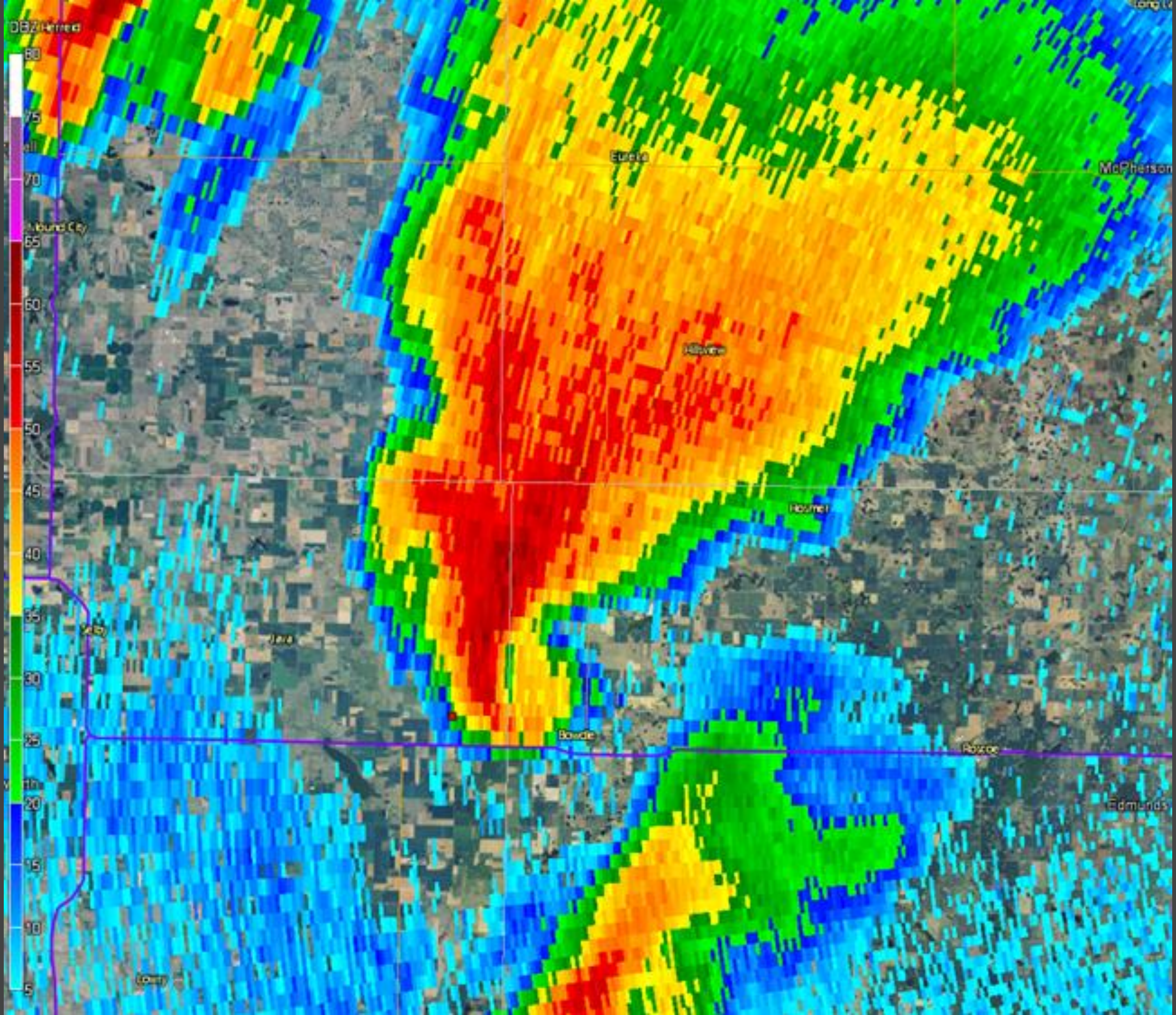
1024
20150306/1930 RADAR
150306/1900 MSL Pressure and surface wind

How would you compare this environment compared to climatology?

- Anomalously unfavorable
- Typical of climatology
- Anomalously favorable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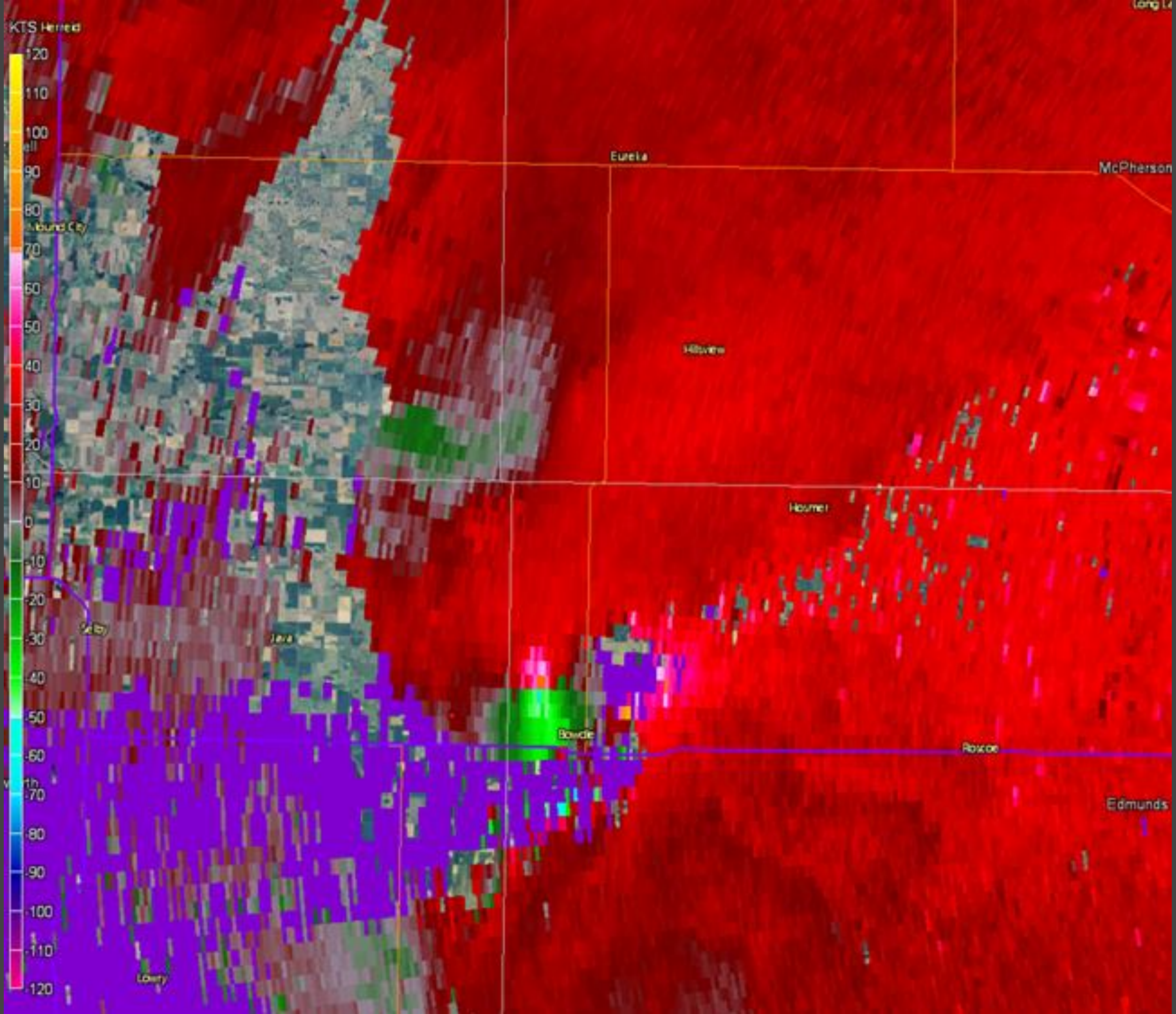
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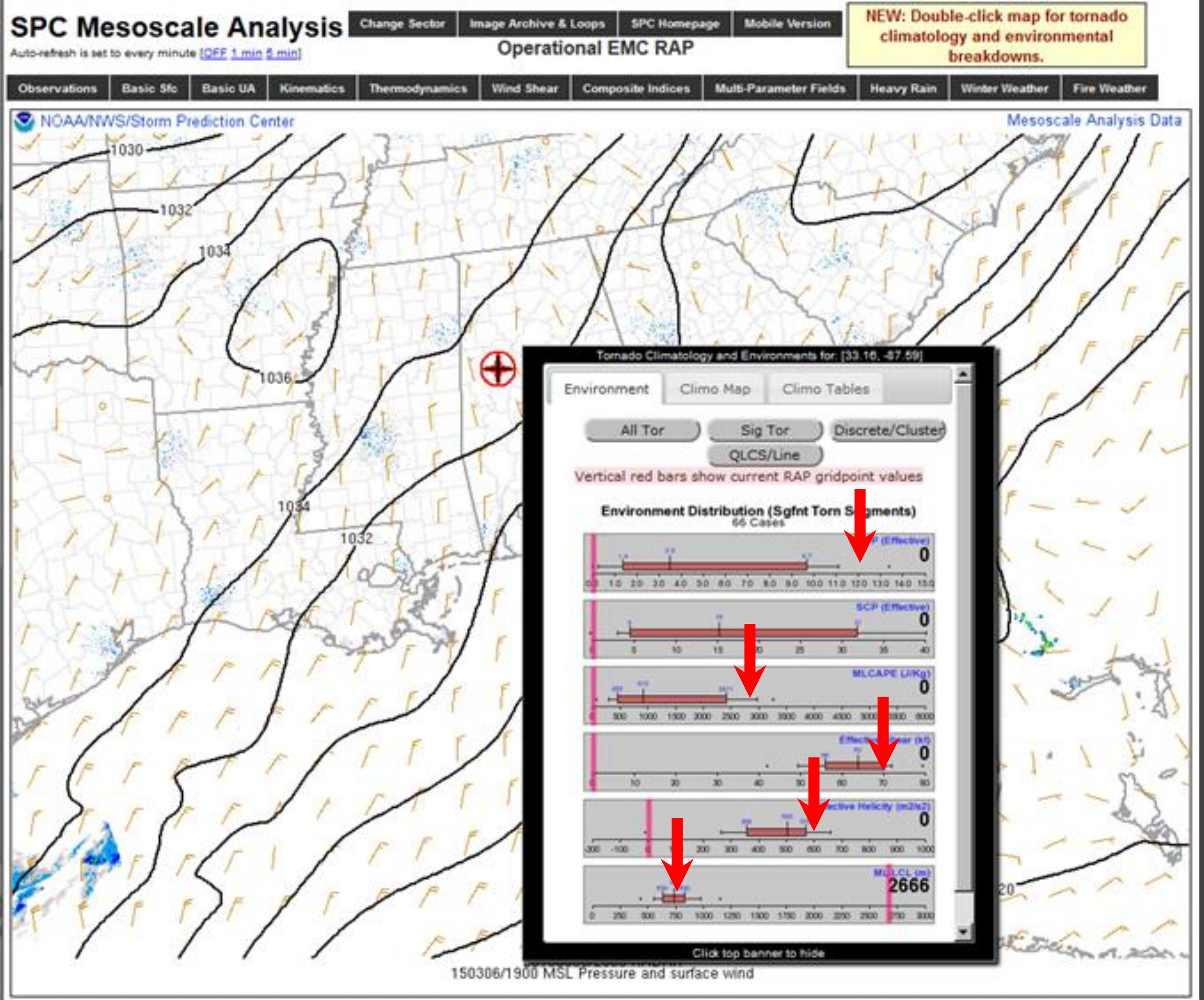
May 22, 2010 Bowdle, SD EF-4


SPC Mesoscale Analysis
Change Sector
Image Archive & Loops
SPC Homepage
Mobile Version
NEW: Double-click map for tornado climatology and environmental breakdowns.
Operational EMC RAP
Observations
Basic Sfc
Basic UA
Kinematics
Thermodynamics
Wind Shear
Composite Indices
Multi-Parameter Fields
Heavy Rain
Winter Weather
Fire Weather
NOAA/NWS/Storm Prediction Center
Mesoscale Analysis Data
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Climo Map
Climo Tables
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Sig Tor
Discrete/Cluster
QLCS/Line
Vertical red bars show current RAP gridpoint values
Environment Distribution (Sgfnt Torn Segments)
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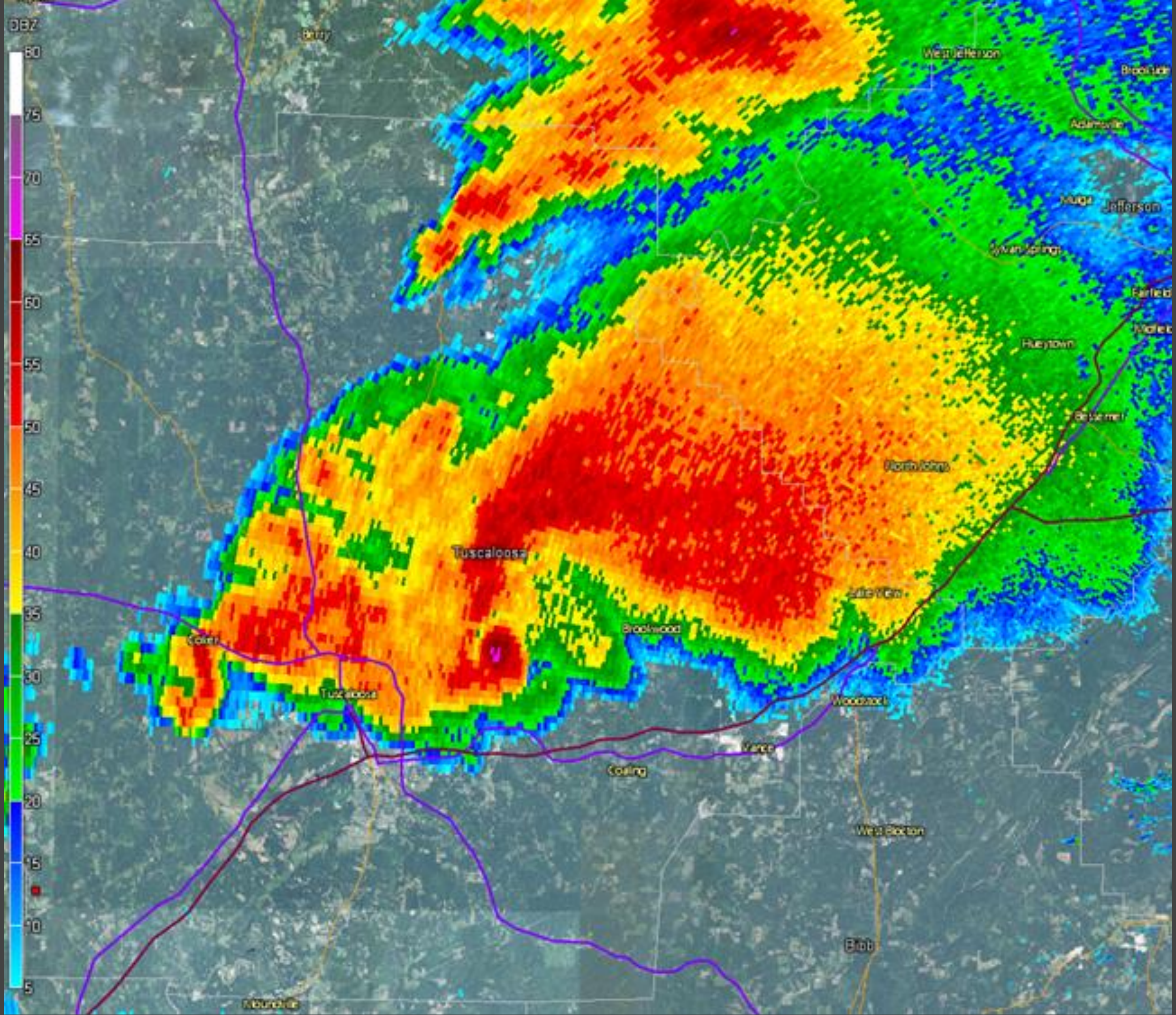
SCP (Effective)
MLCAPE (J/Kg)
MLLCL (m)
2666
Click top banner to hide
150306/1900 MSL Pressure and surface wind

How would you compare this environment compared to climatology?

- Anomalously unfavorable
- Typical of climatology
- Anomalously favorable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Bessemer
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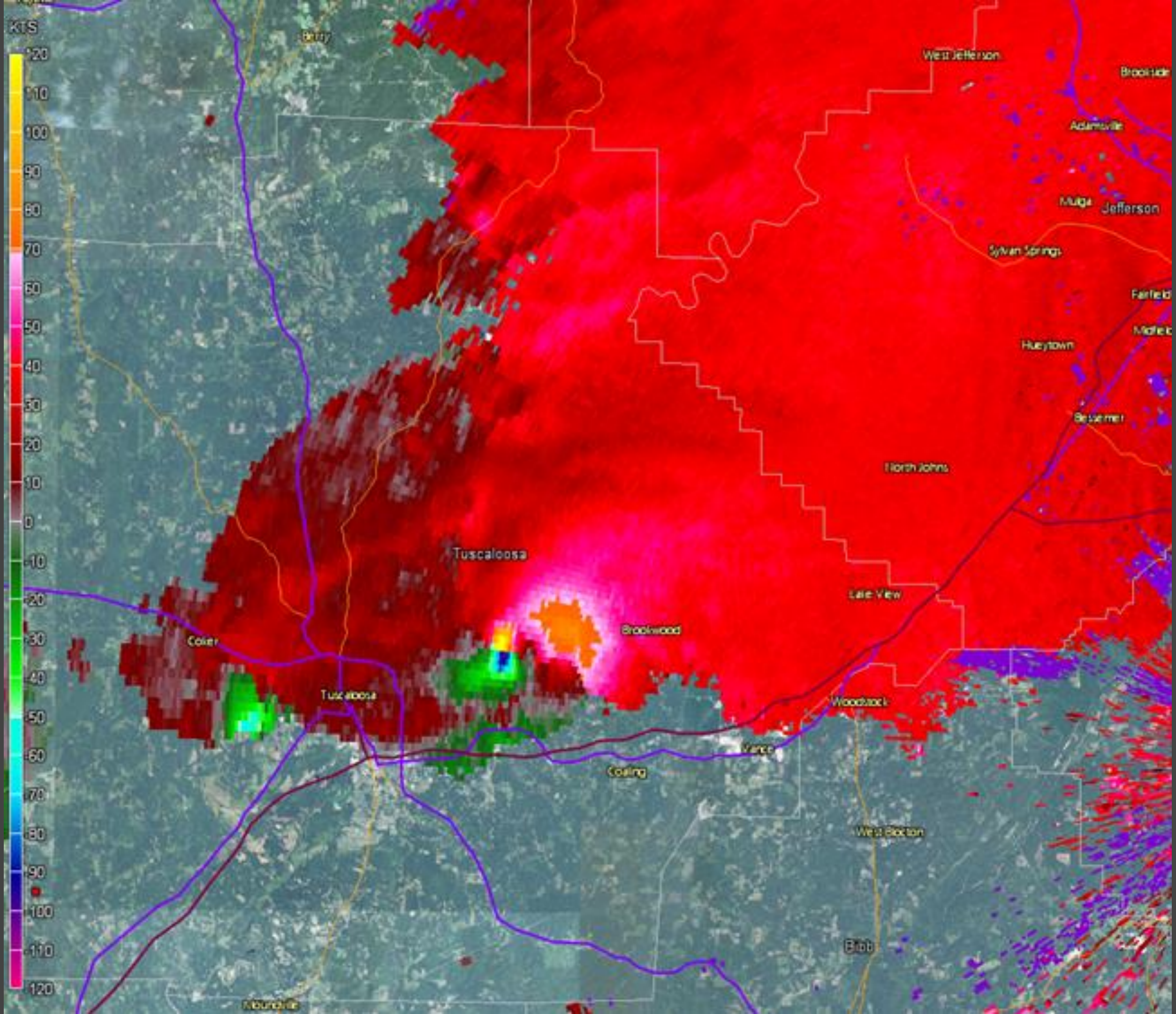
Vance
Coaling
West Blocton
Bibb
Moundville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Adamsville
Mulga
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Sylvan Springs
Fairfield
Hueytown
Bessemer
North Johns
Tuscaloosa
Lake View
Brookwood
Coker
Tuscaloosa
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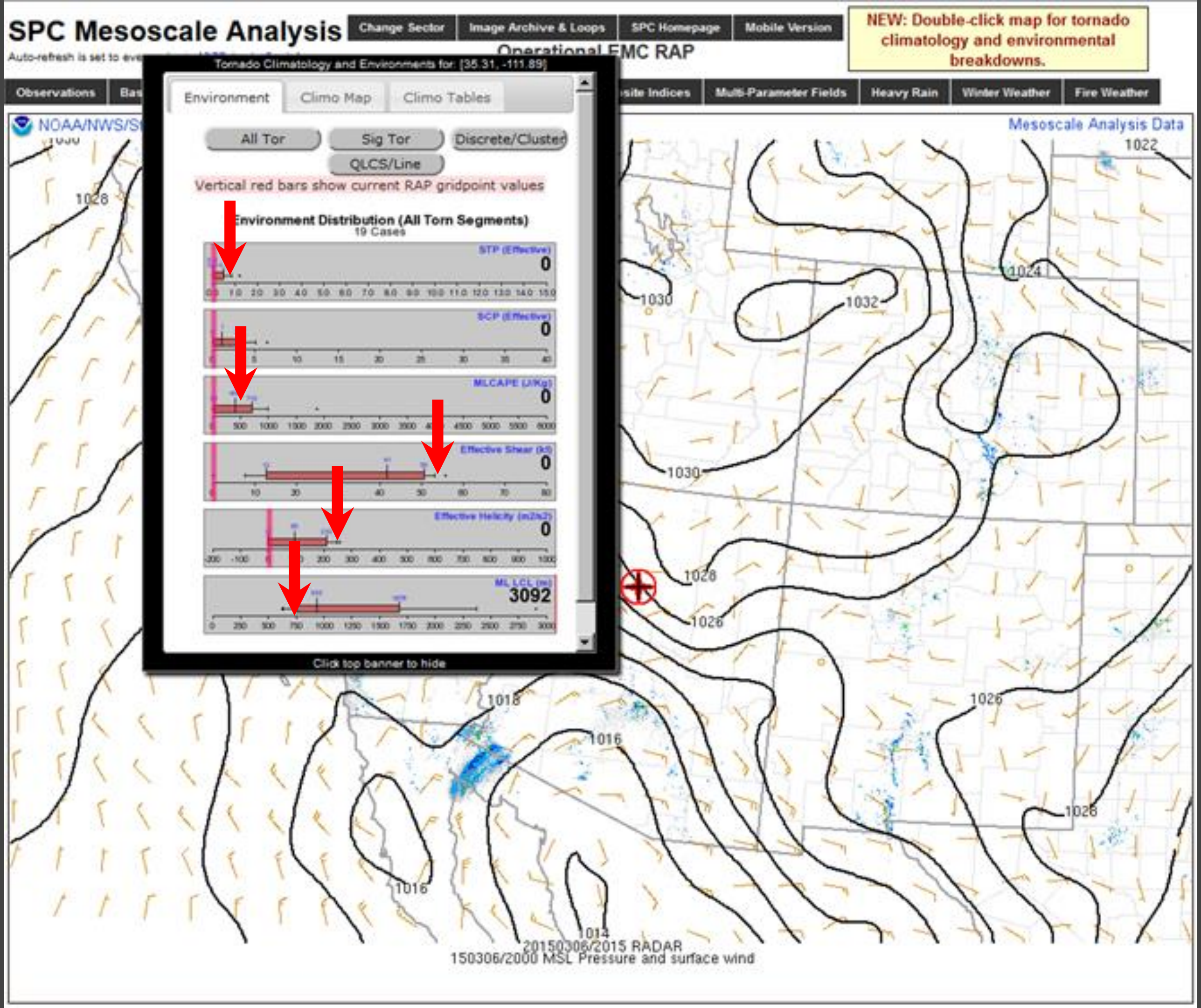
Coaling
West Blocton
Bibb
Moundville

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.
Operational EMC RAP
Tornado Climatology and Environments for: [35.31, -111.89]
Observations
Multi-Parameter Fields
Heavy Rain
Winter Weather
Fire Weather
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)
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MLCAPE (J/Kg)
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Effective Shear (kt)
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Effective Helicity (m2/s2)
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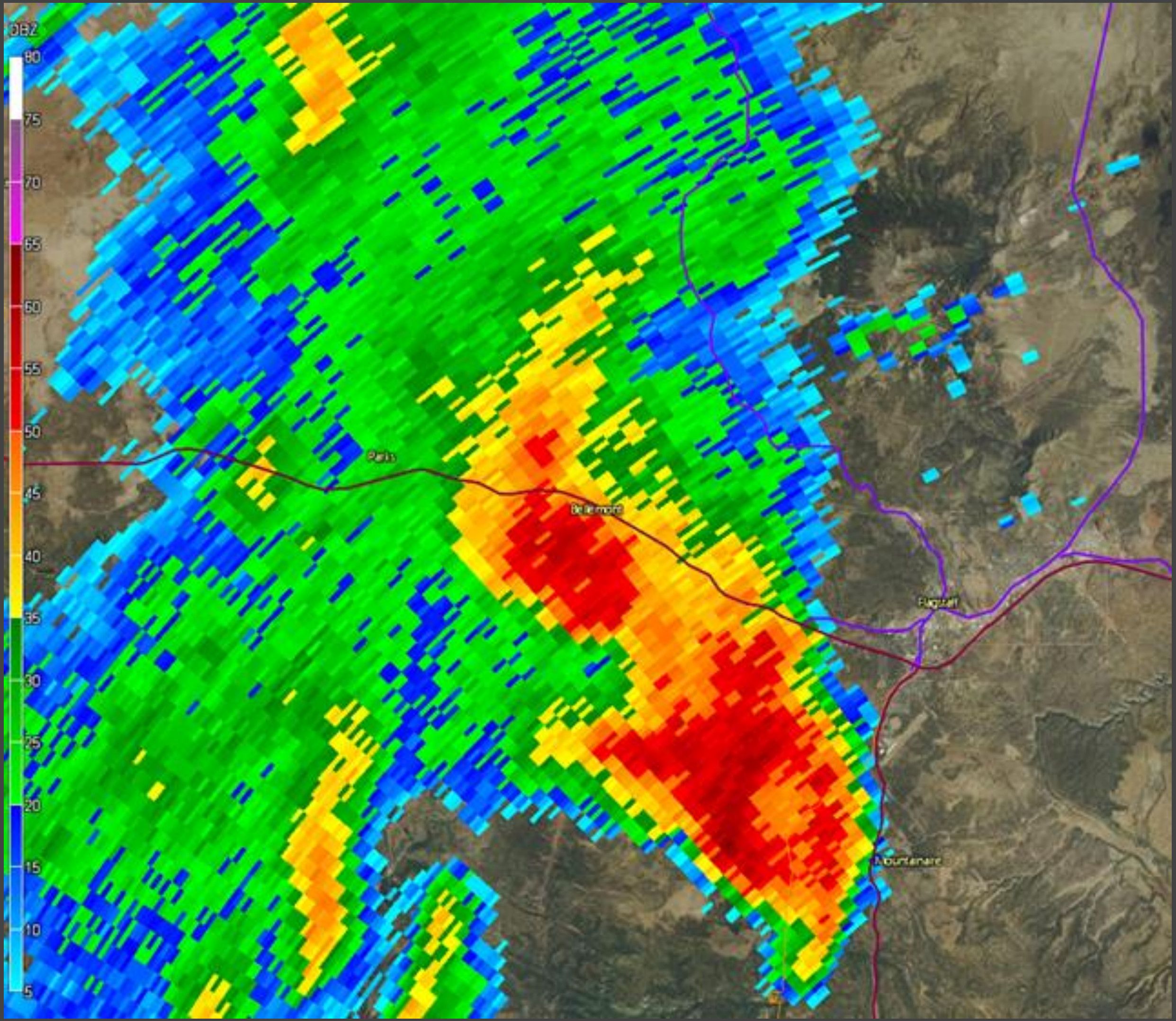
ML LCL (m)
3092
Click top banner to hide
Mesoscale Analysis Data
20150306/2015 RADAR
150306/2000 MSL Pressure and surface wind

How would you compare this environment compared to climatology?

Anomalously unfavorable

Typical of climatology

Anomalously favorable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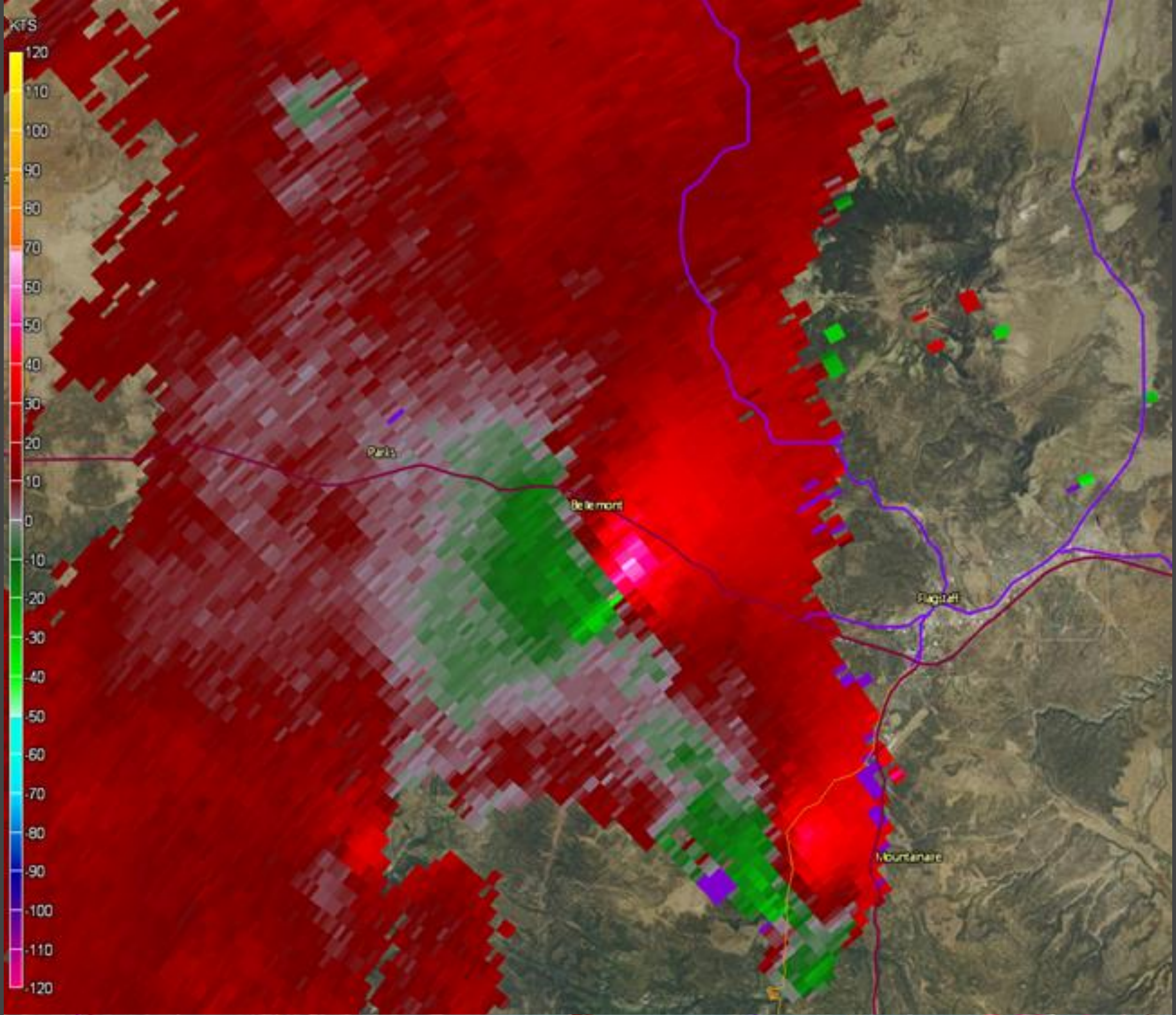

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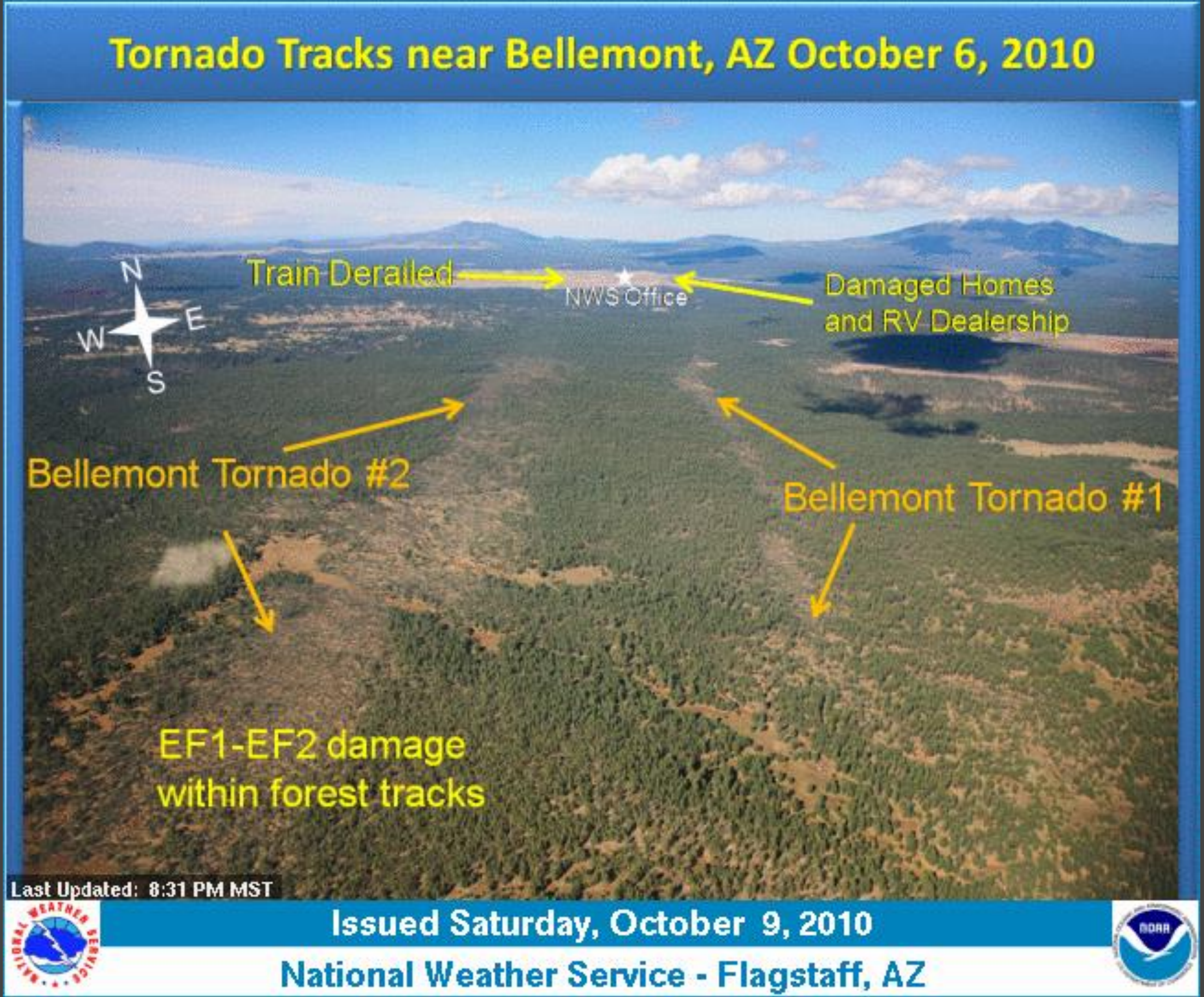
Parks
Bellemont
Flagstaff
Mountainaire

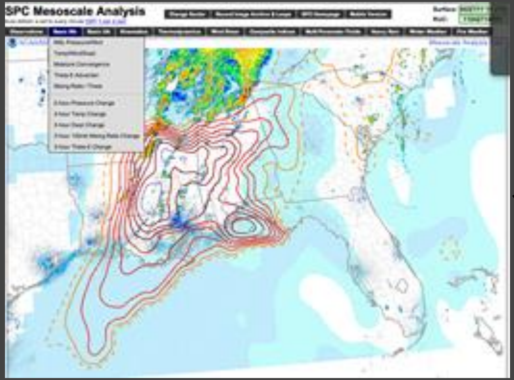


Bellemont, AZ
EF-2

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

Convective parameter magnatudes 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

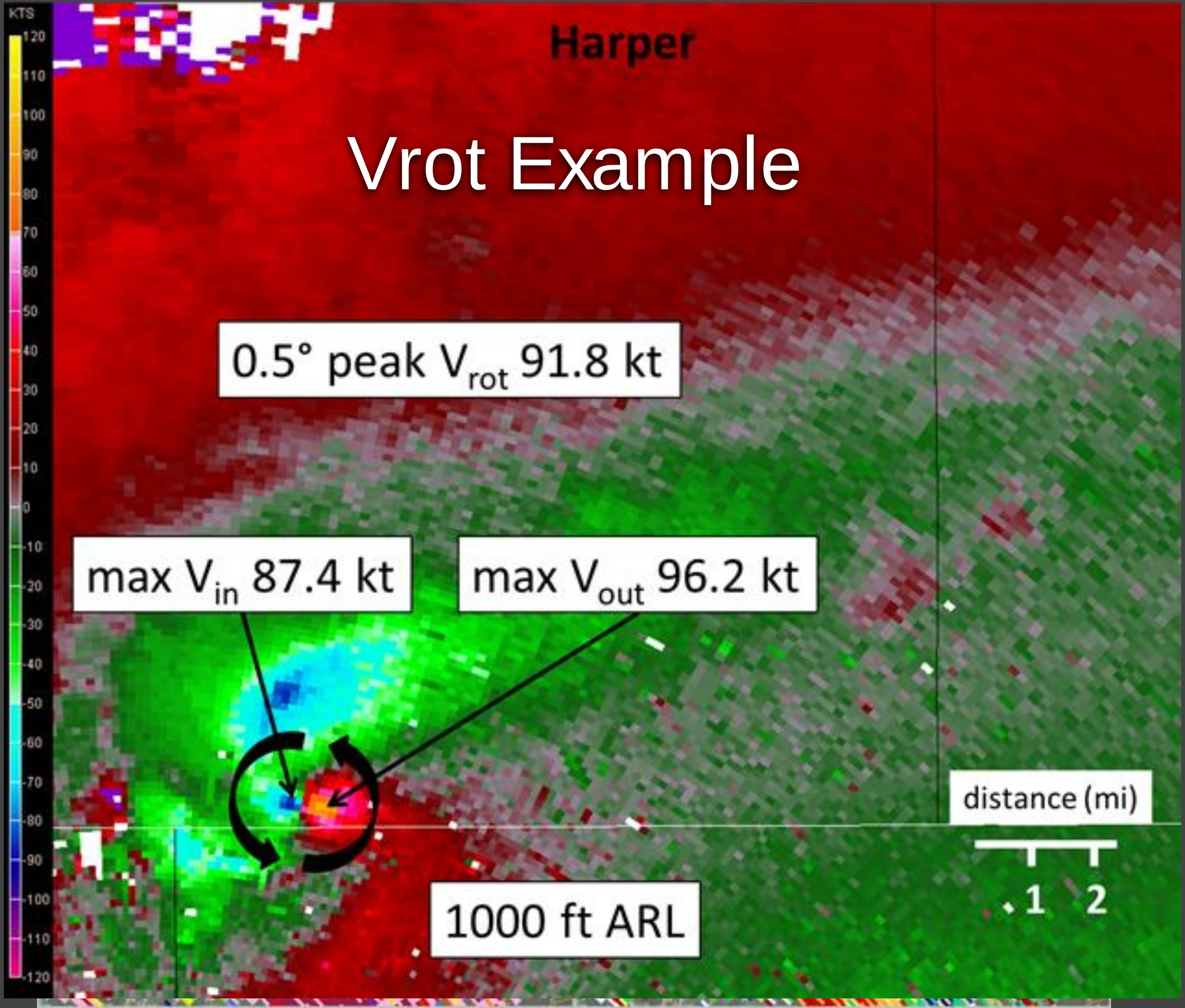
- Used 2009-2014 tornadoes to create conditional probabilities by EF scale

- Used 2014-2015 tornadoes and severe events to create unconditional probabilities by EF scale.

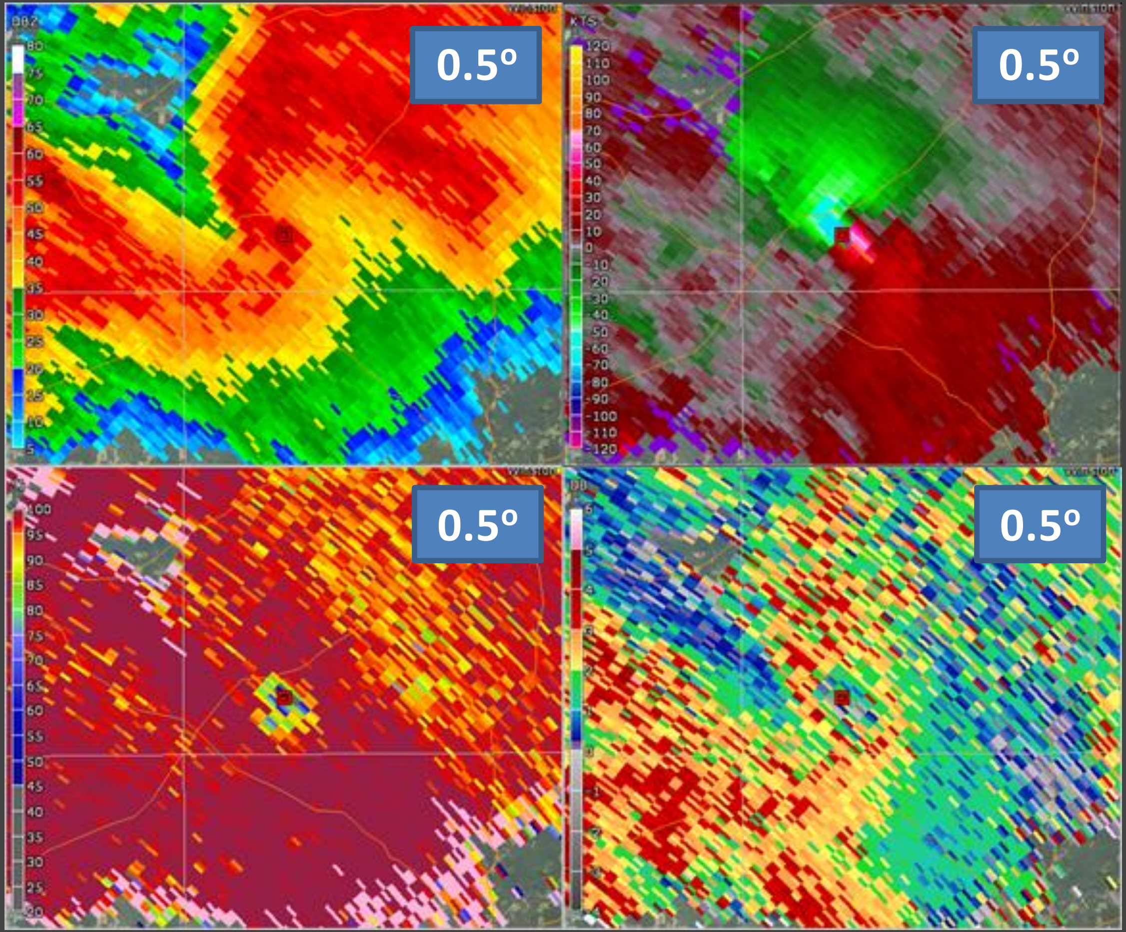
Tornado Detection Via WSR-88D

- Combined radar attributes (same place and time)
  - Storm-relative velocity (V_{rot} > ~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

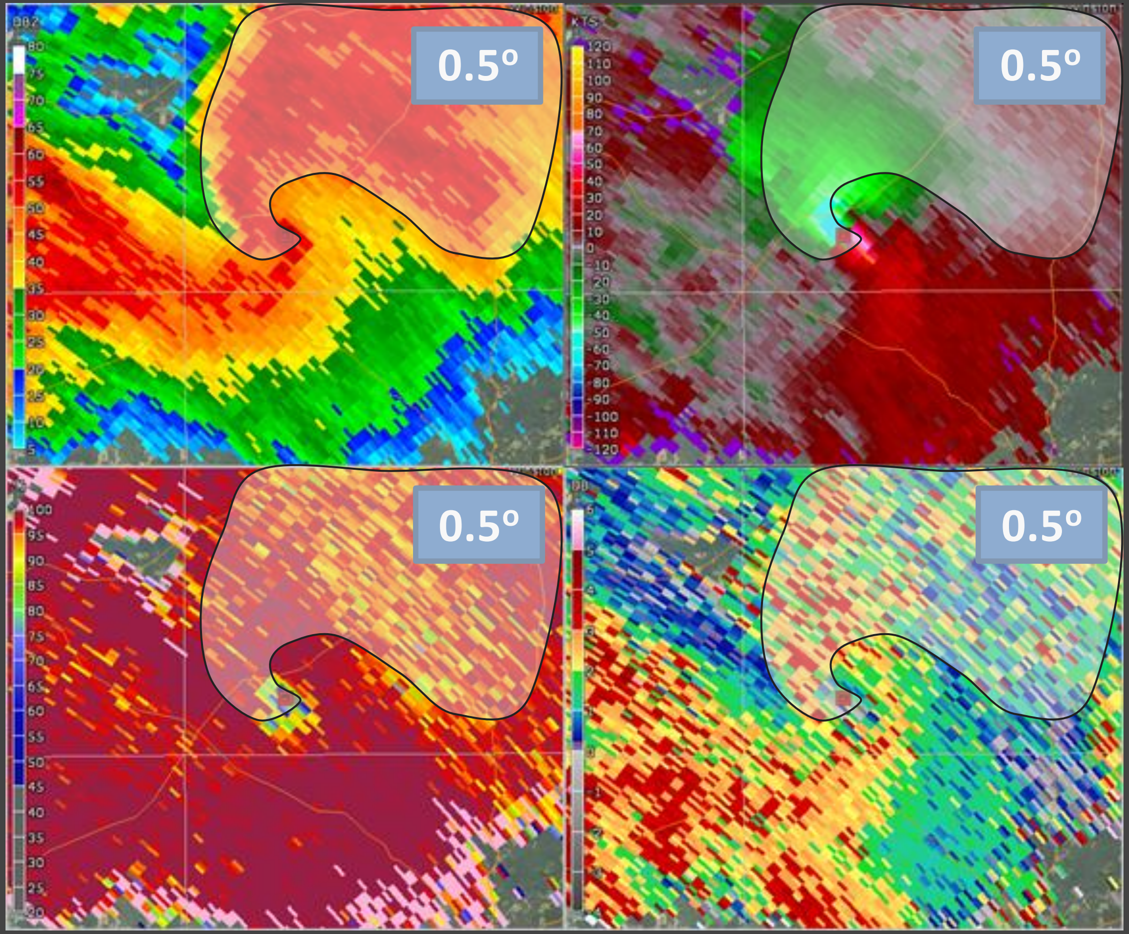
Vrot Example



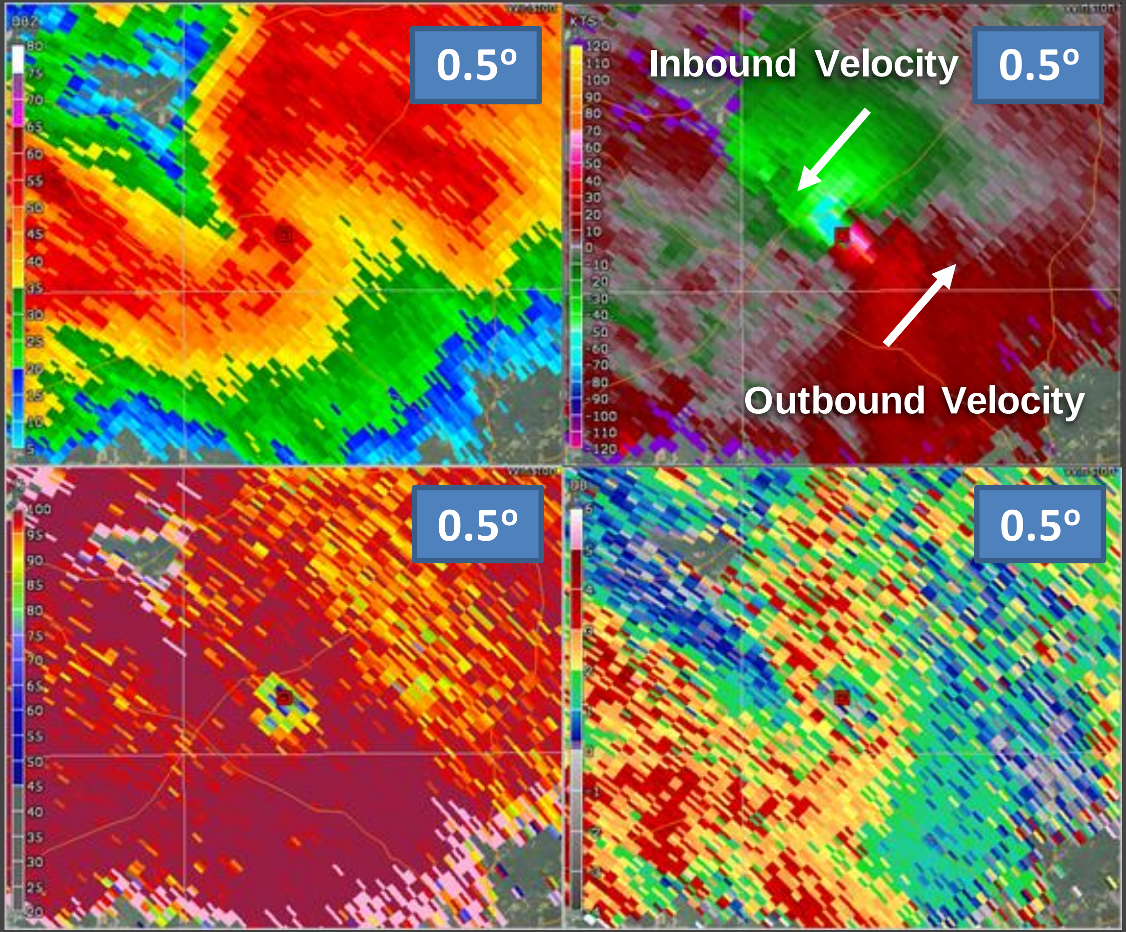
A Quick Note on WSR-88D Tornado Signatures



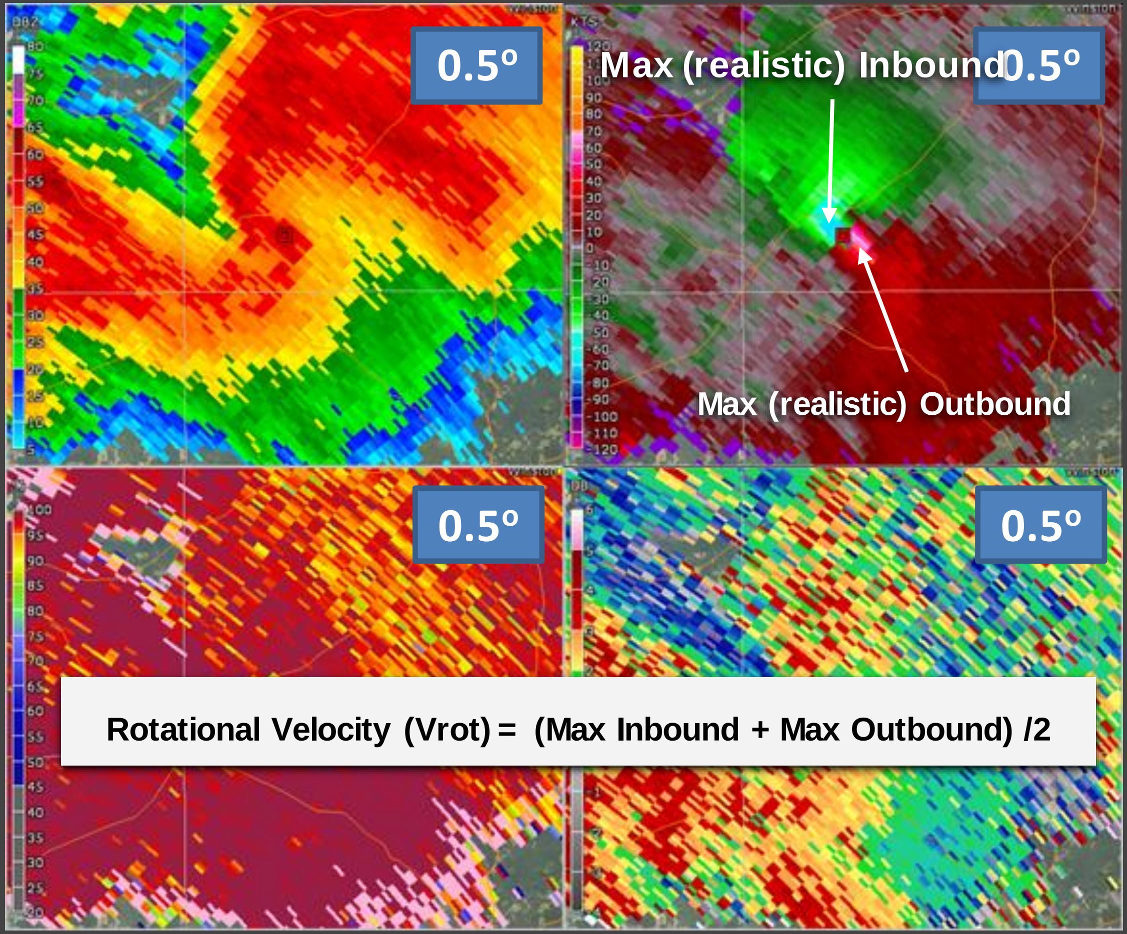
A Quick Note on WSR-88D Tornado Signatures



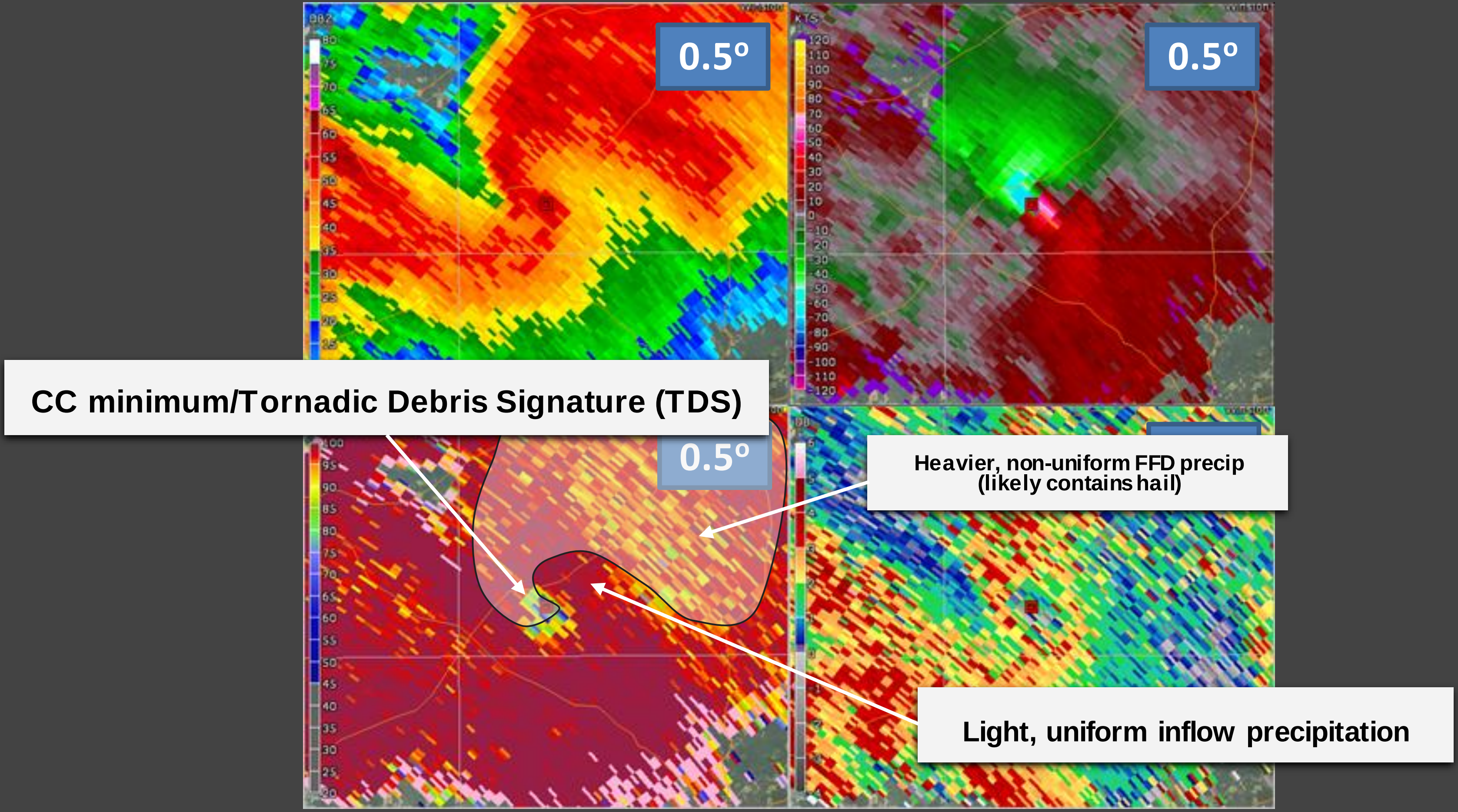
A Quick Note on WSR-88D Tornado Signatures



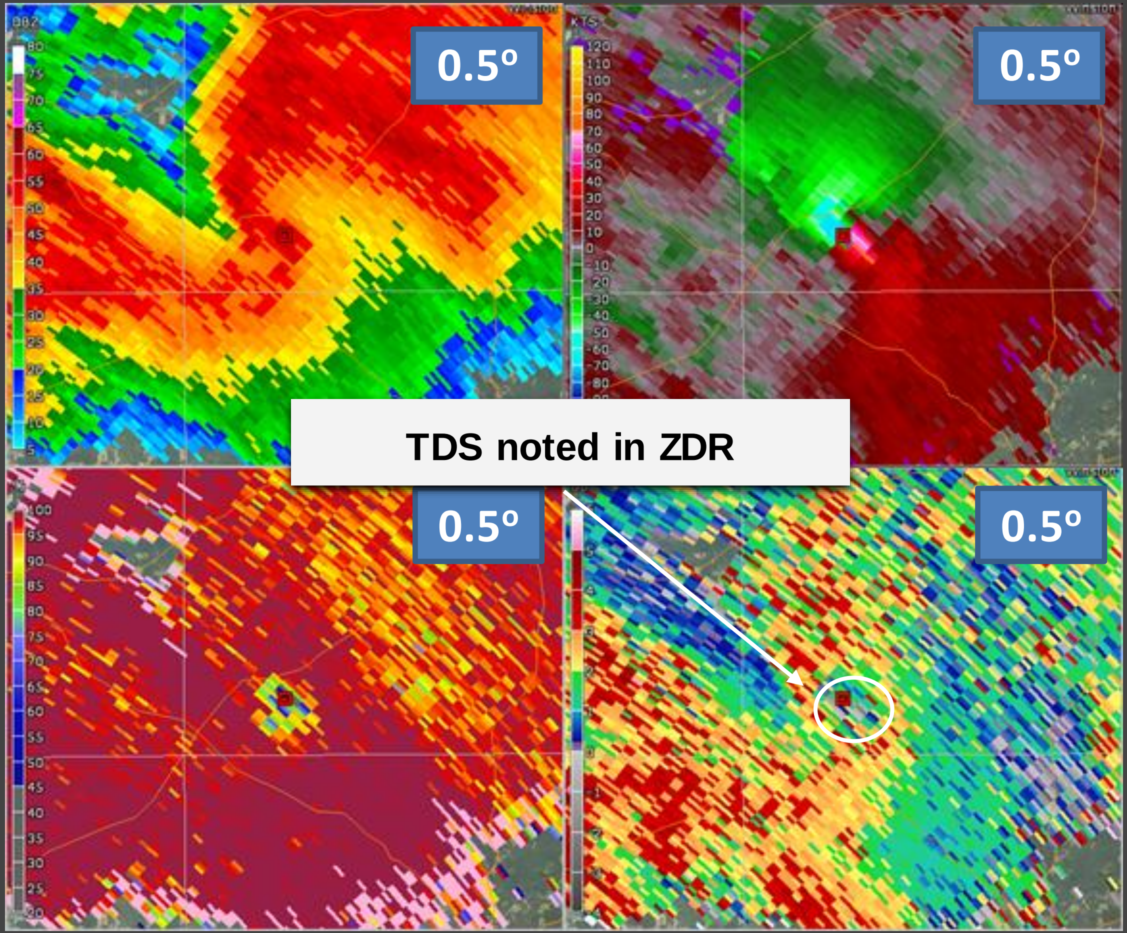
A Quick Note on WSR-88D Tornado Signatures



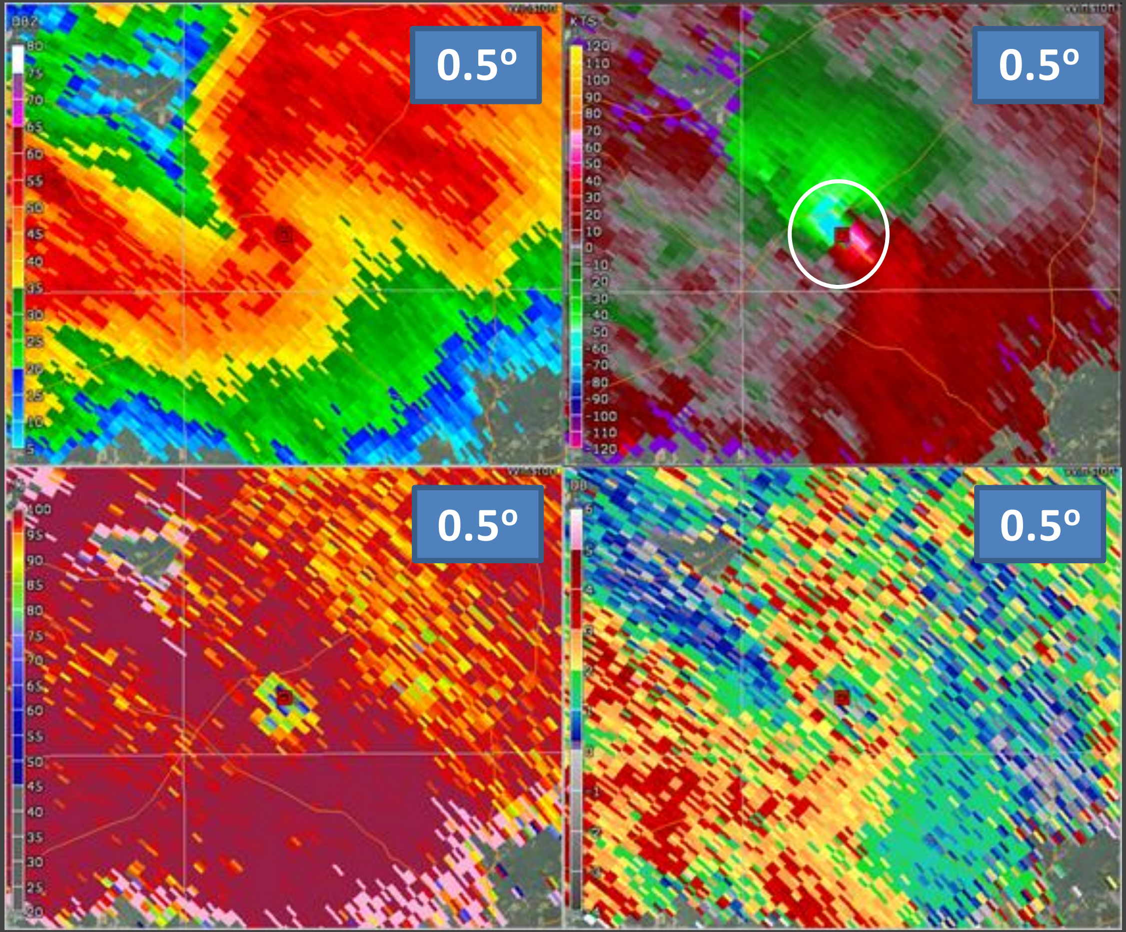
A Quick Note on WSR-88D Tornado Signatures



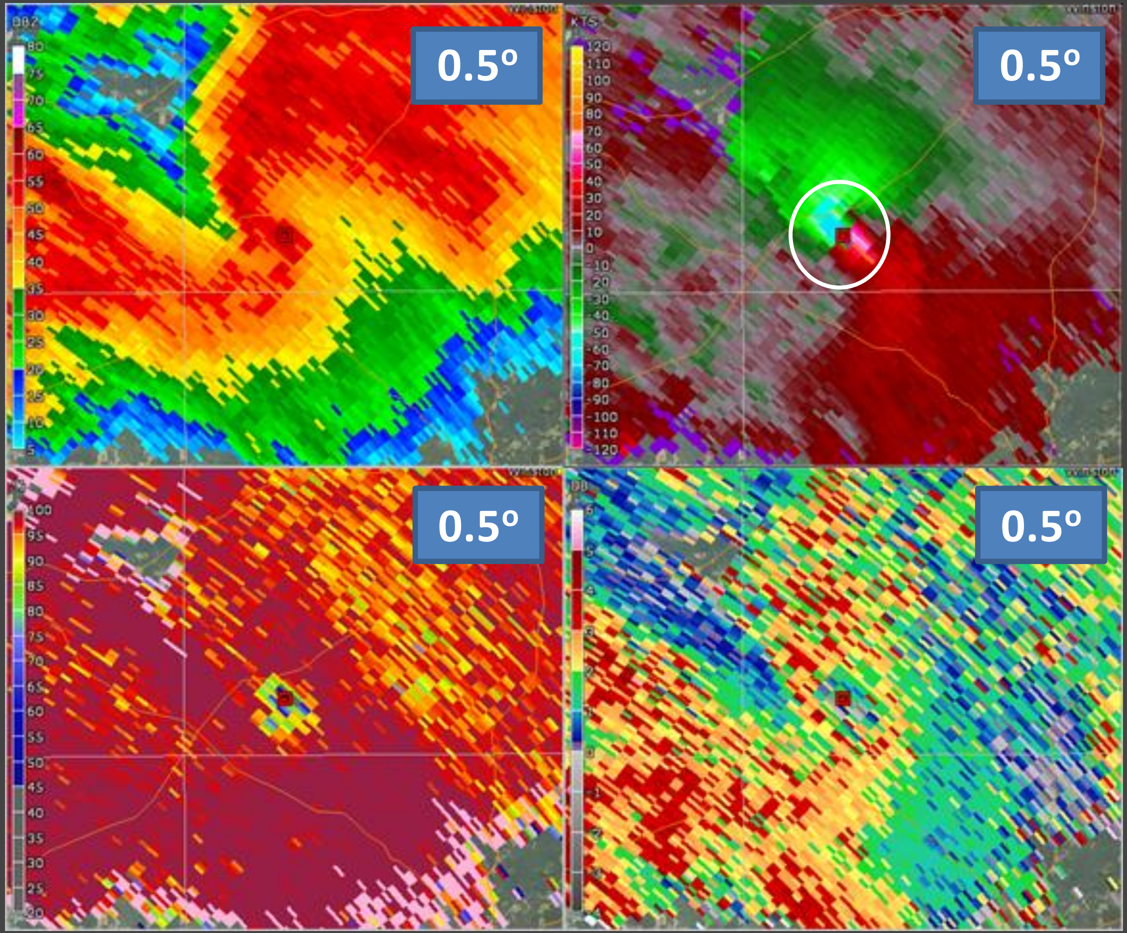
A Quick Note on WSR-88D Tornado Signatures



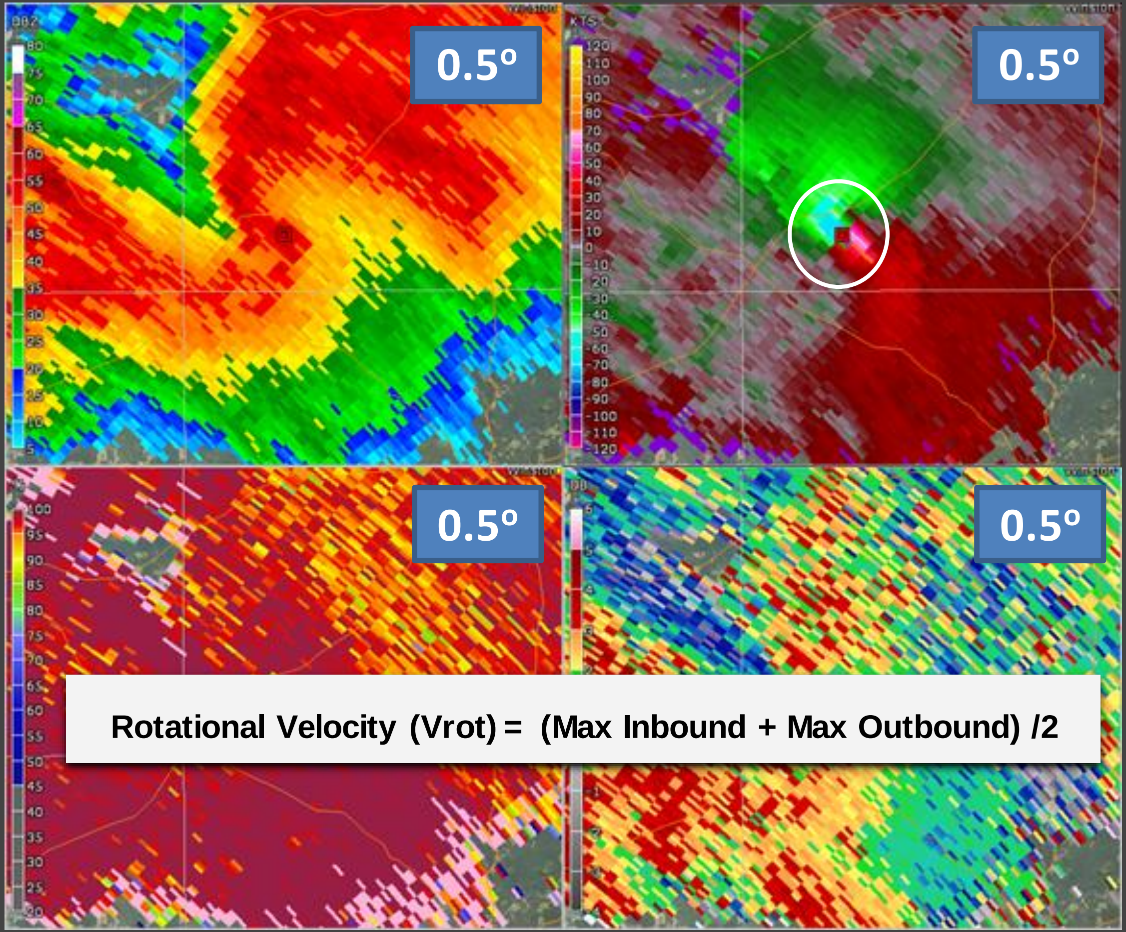
Step 1: Identify a velocity couplet



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

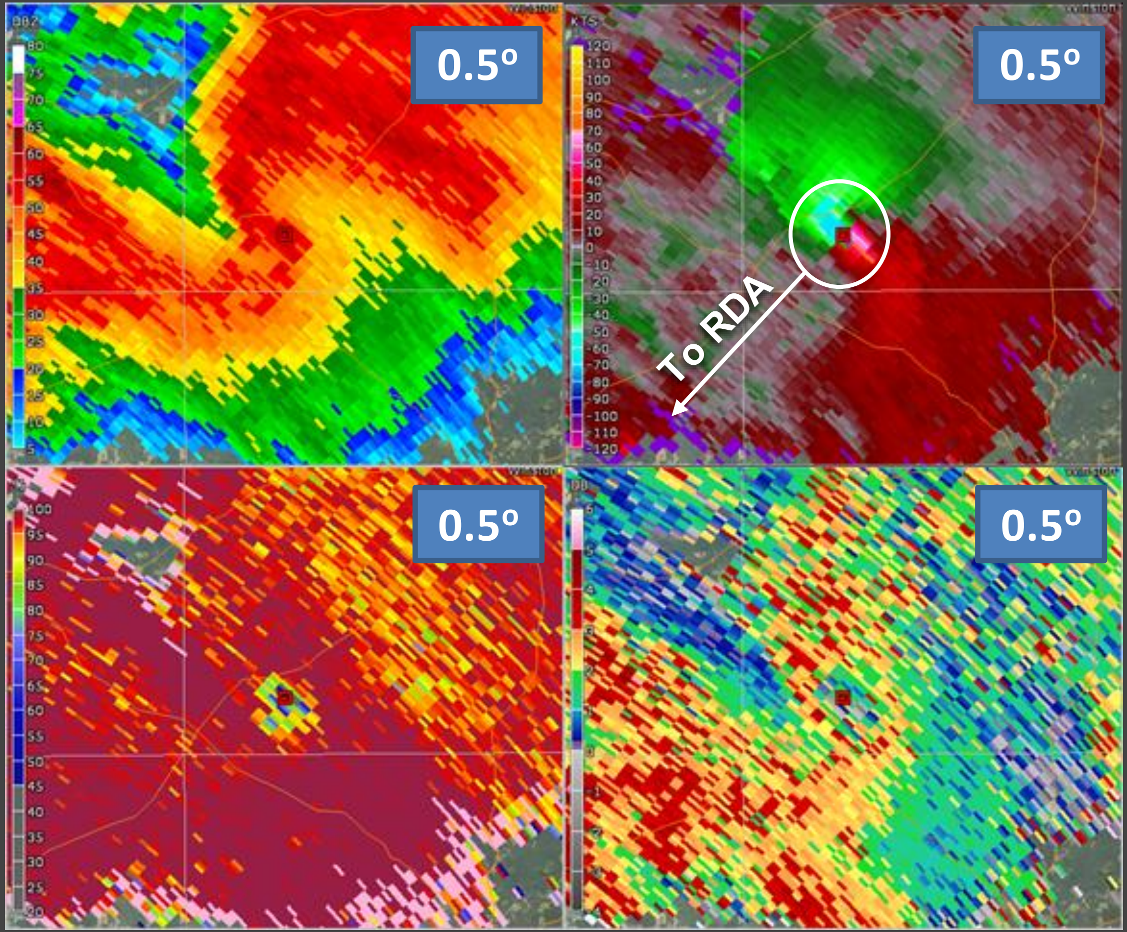


Step 3: Find Vrot

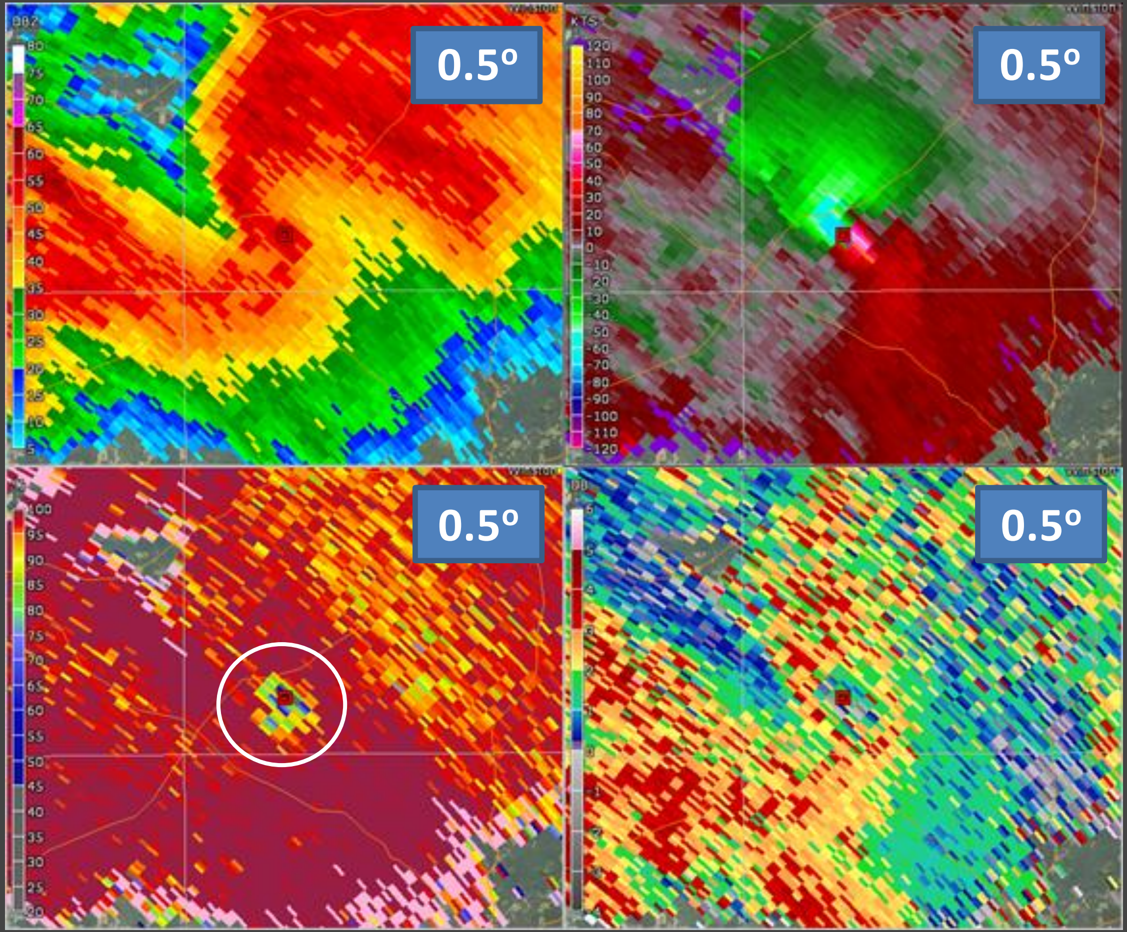


Rotational Velocity (Vrot) = (Max Inbound + Max Outbound) /2

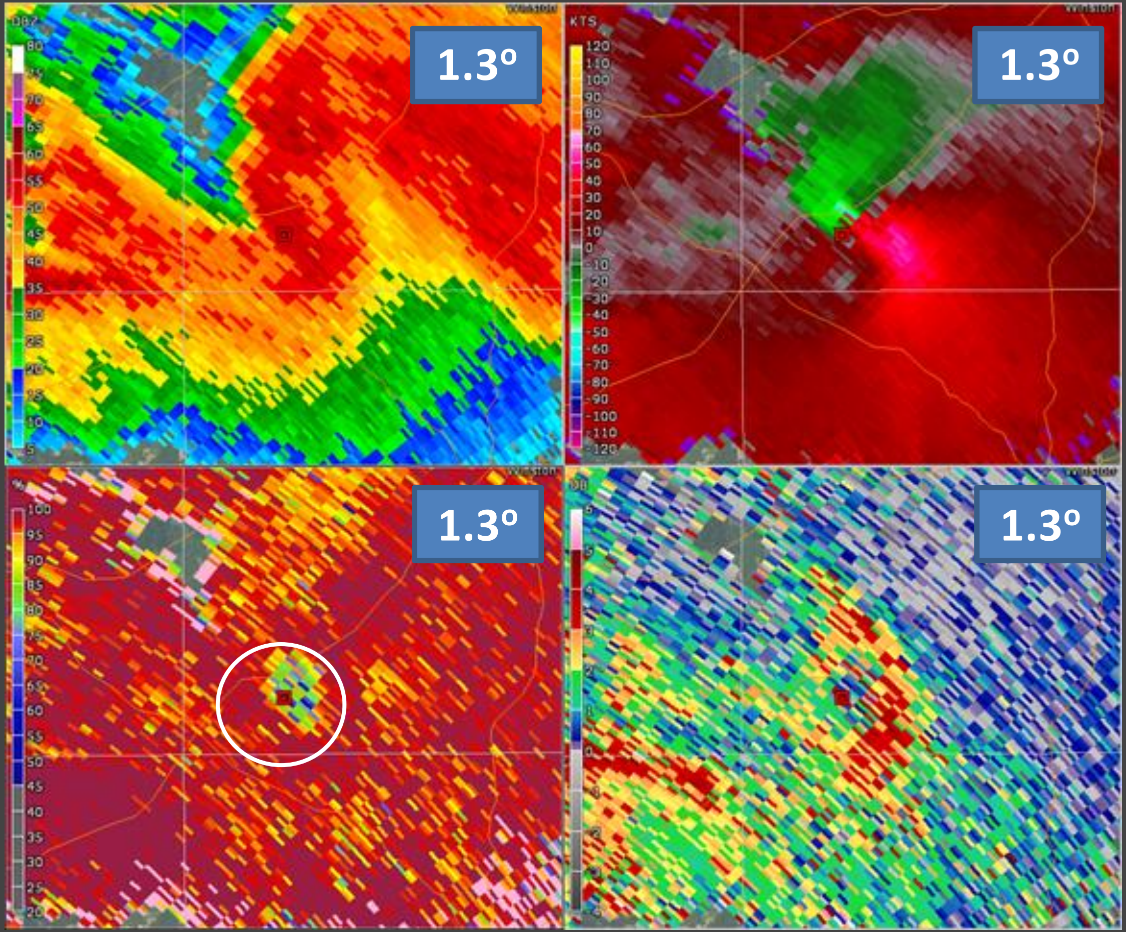
Step 4: Note beam height/distance from radar



Step 5: Check for TDS



Step 6: Check TDS Height

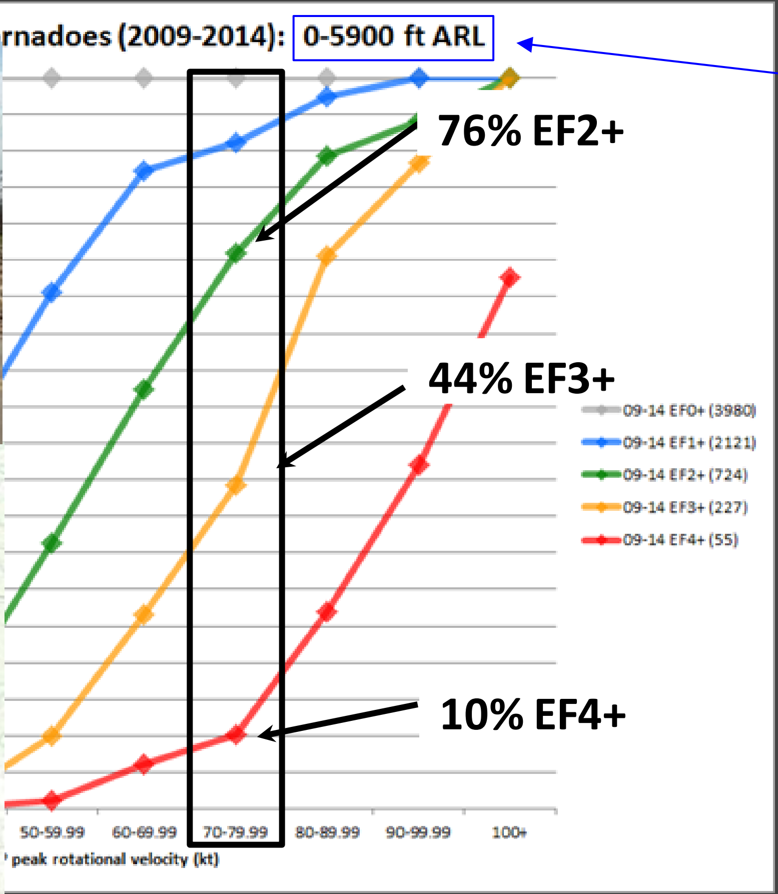


Step 7: Check Conditional Tornado Probs

These are conditional probabilities

You *know* tornado is occurring (TDS)

Louisville, MS EF4
28 April 2014
10 fatalities



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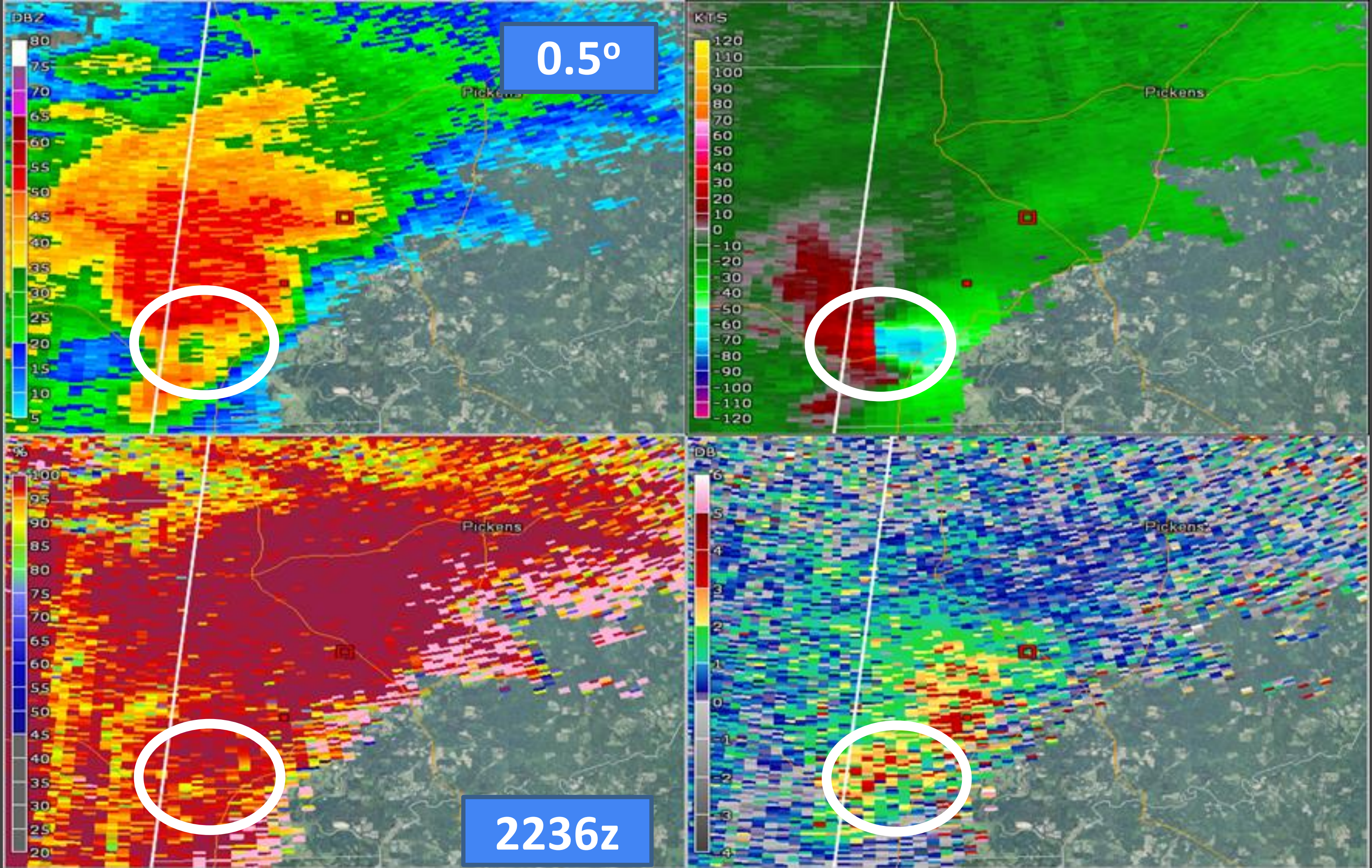
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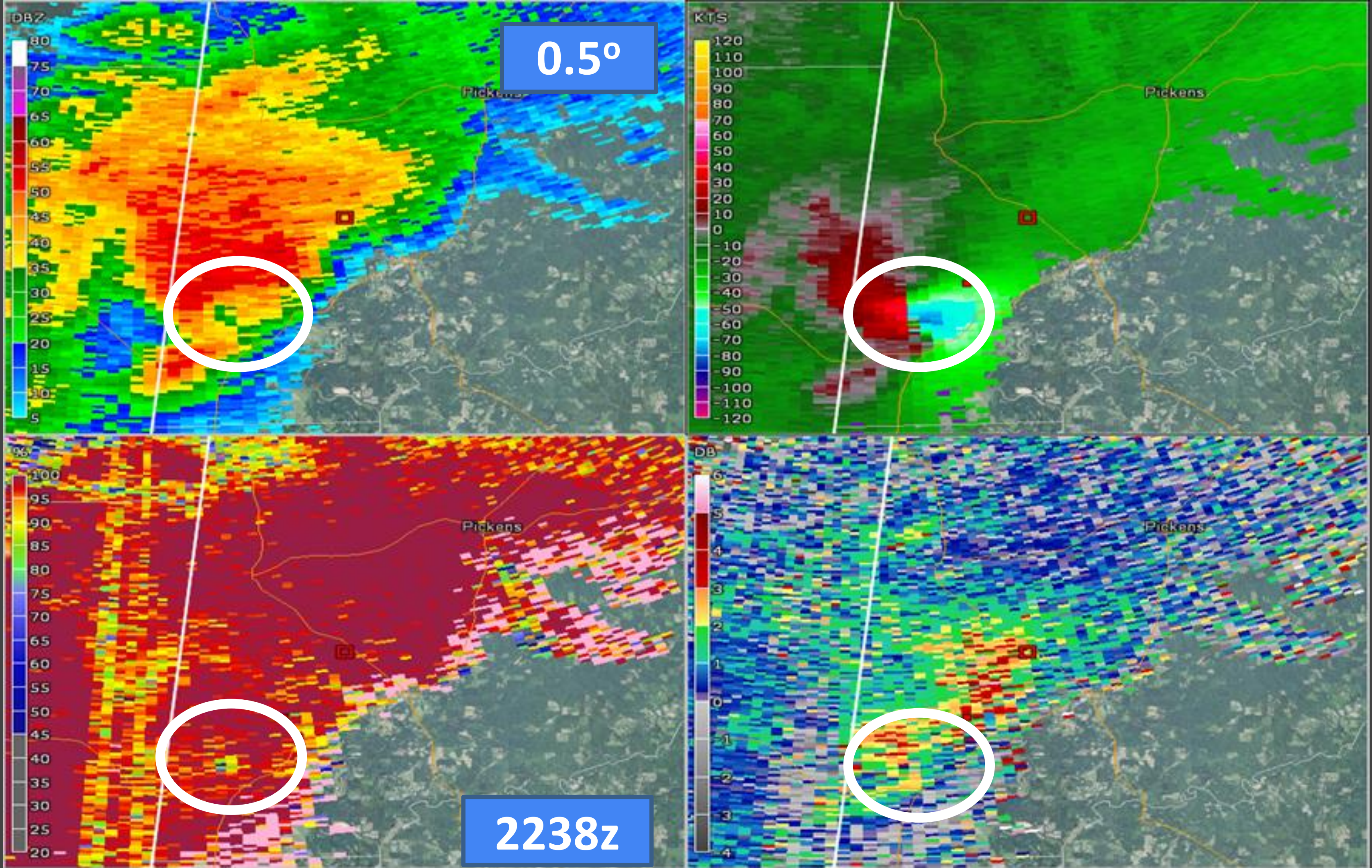

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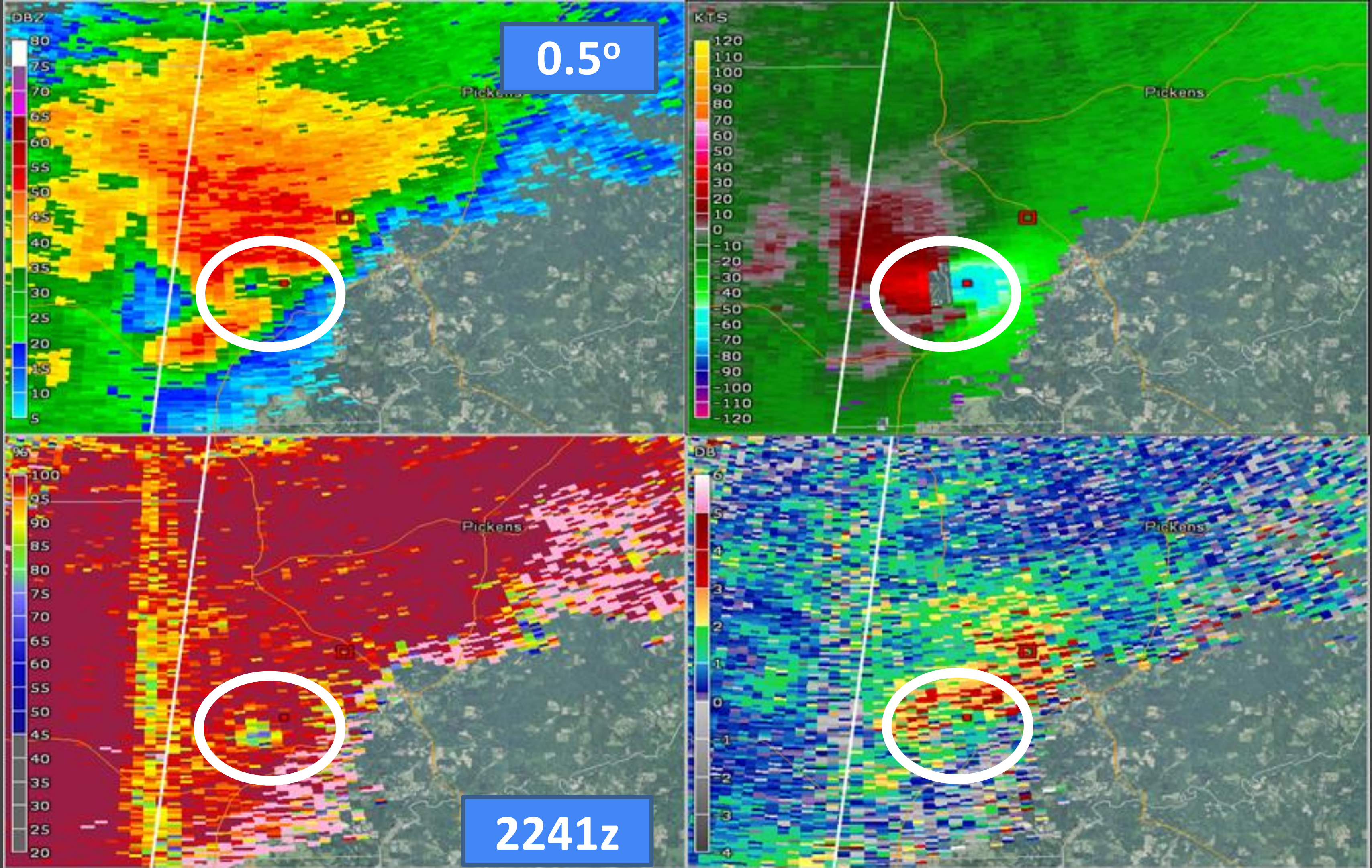

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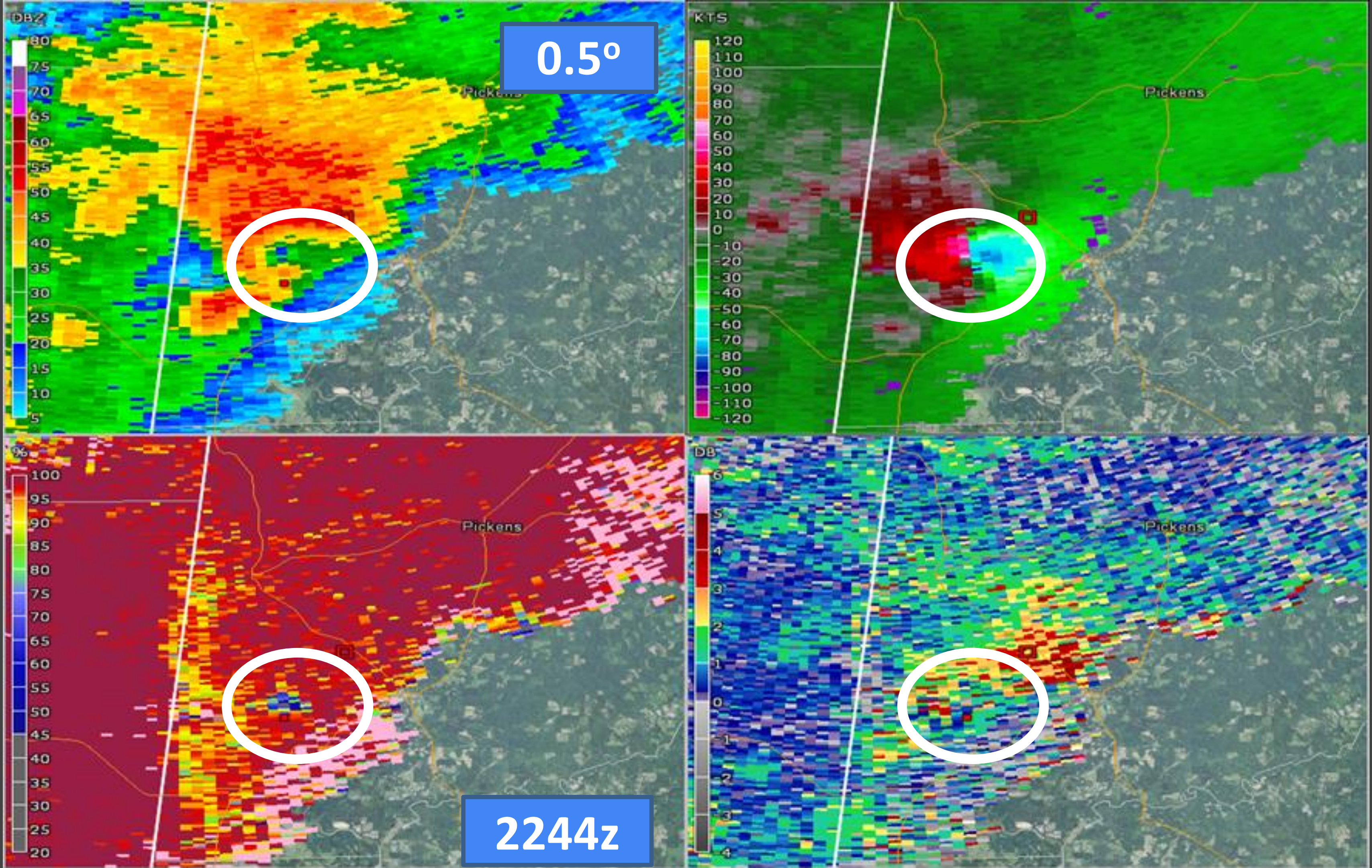
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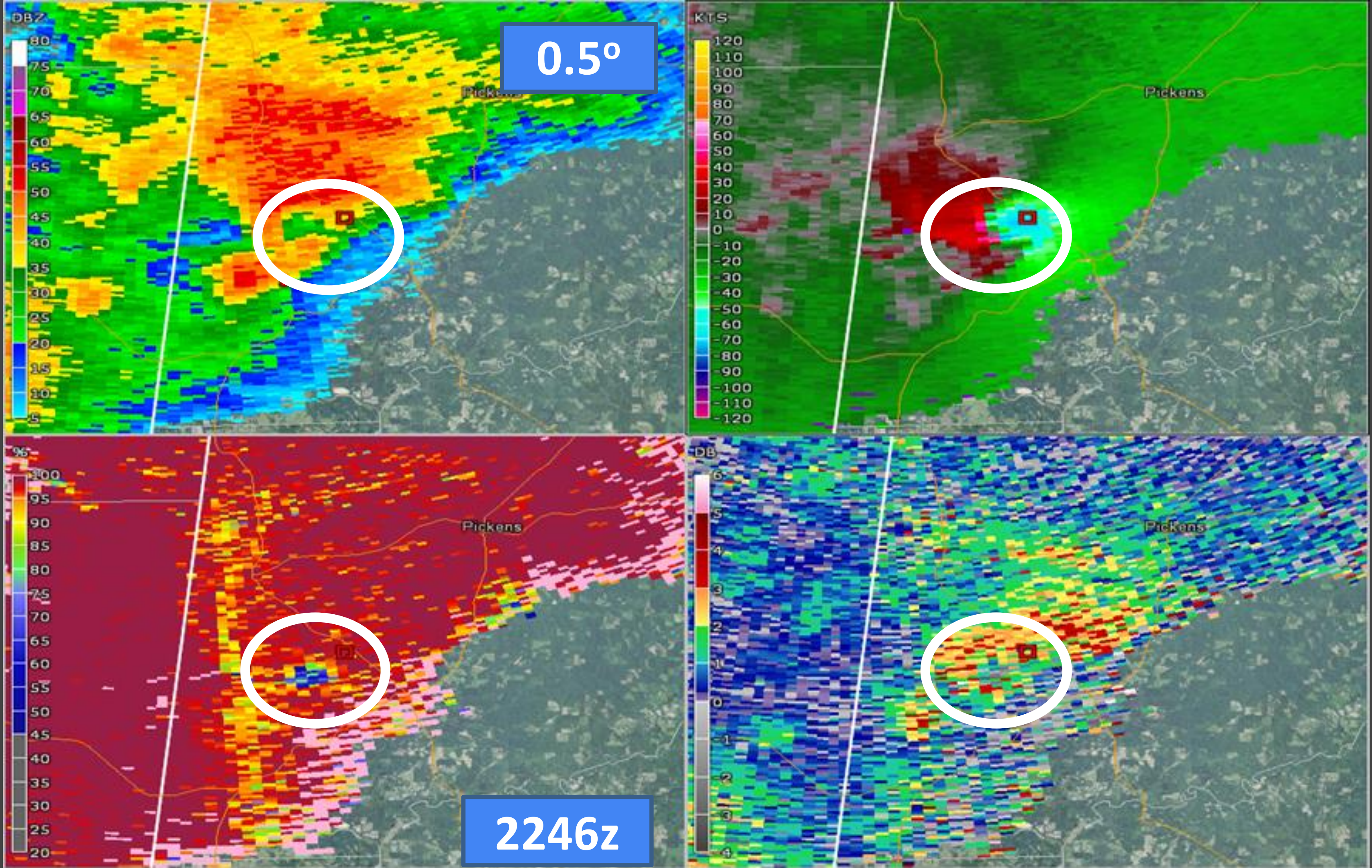

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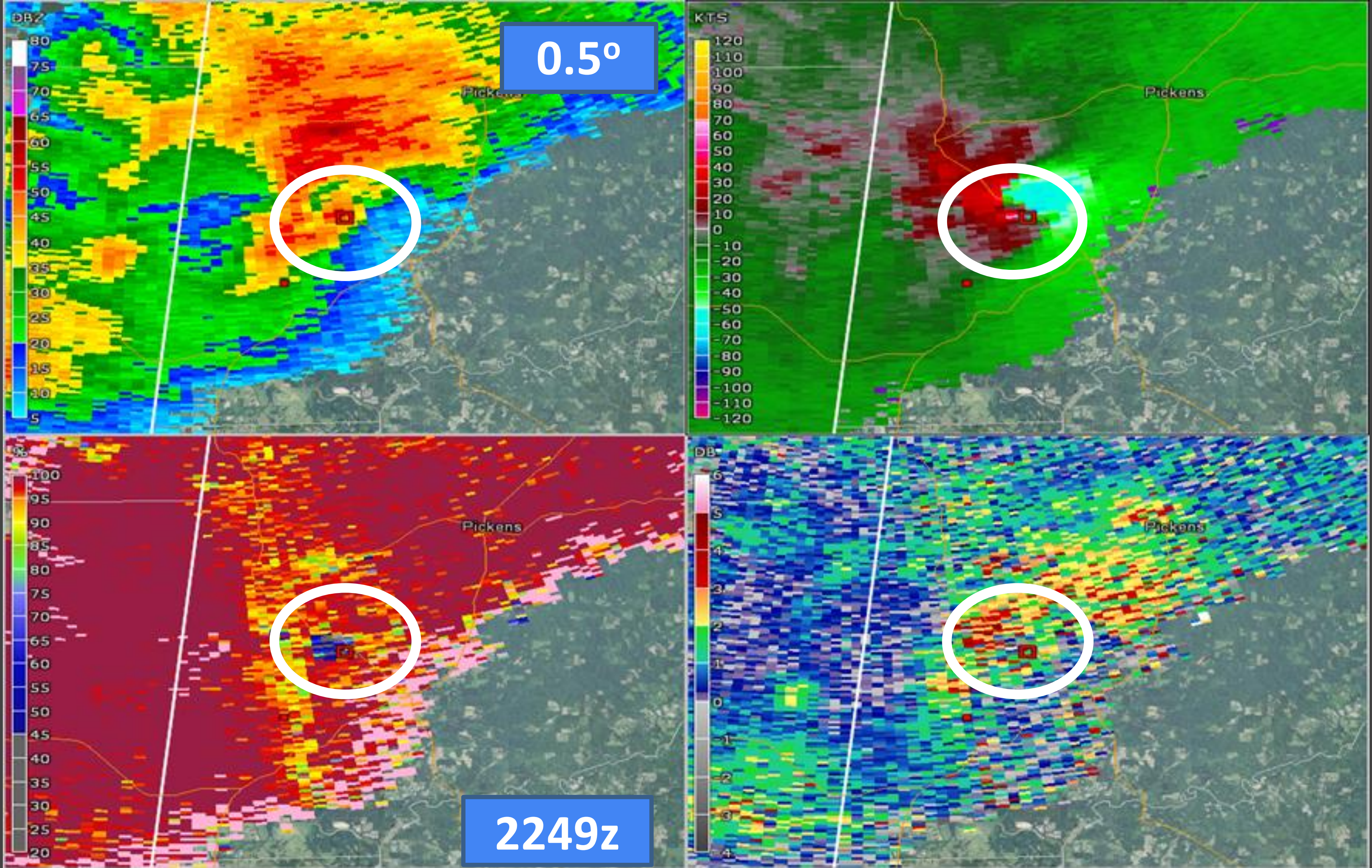

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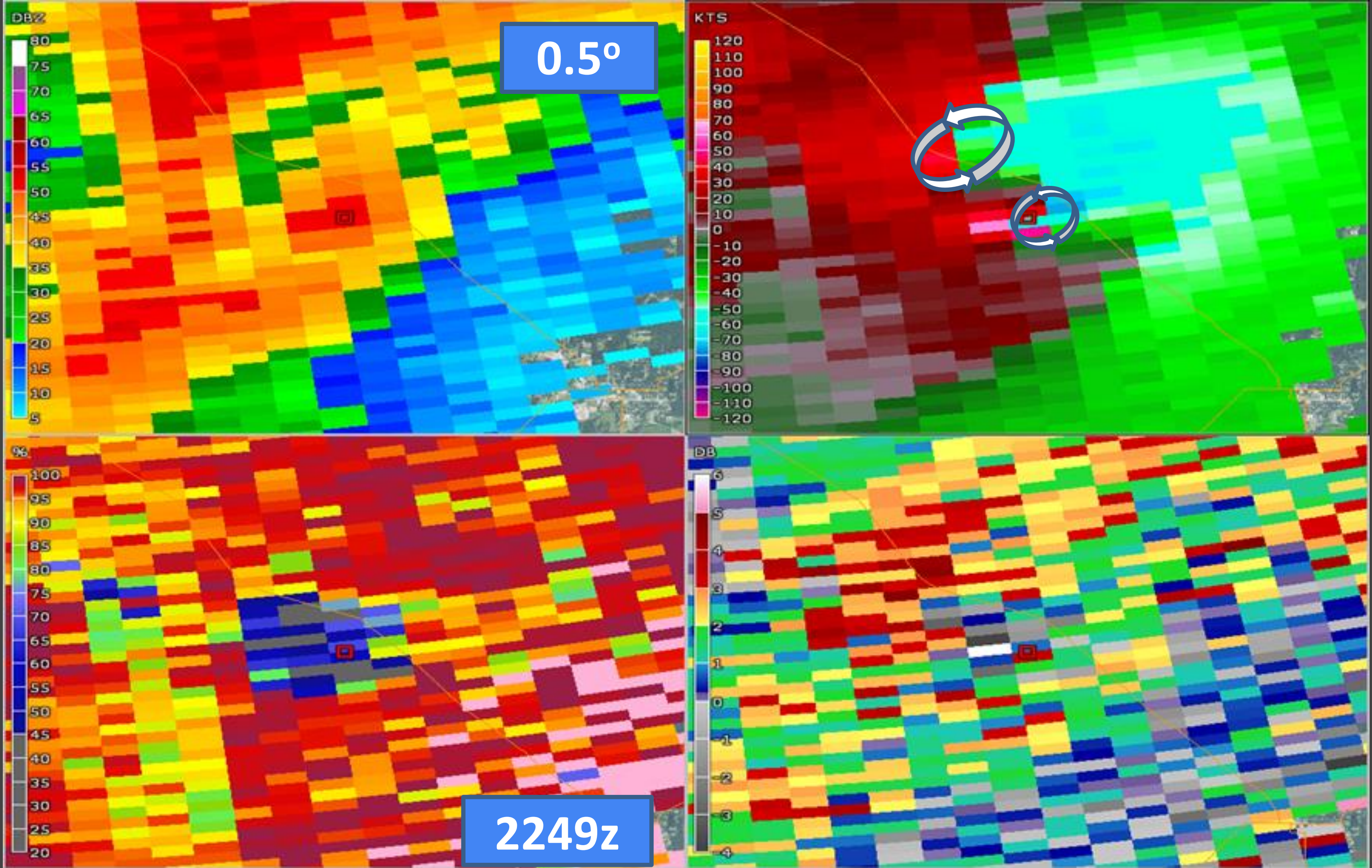
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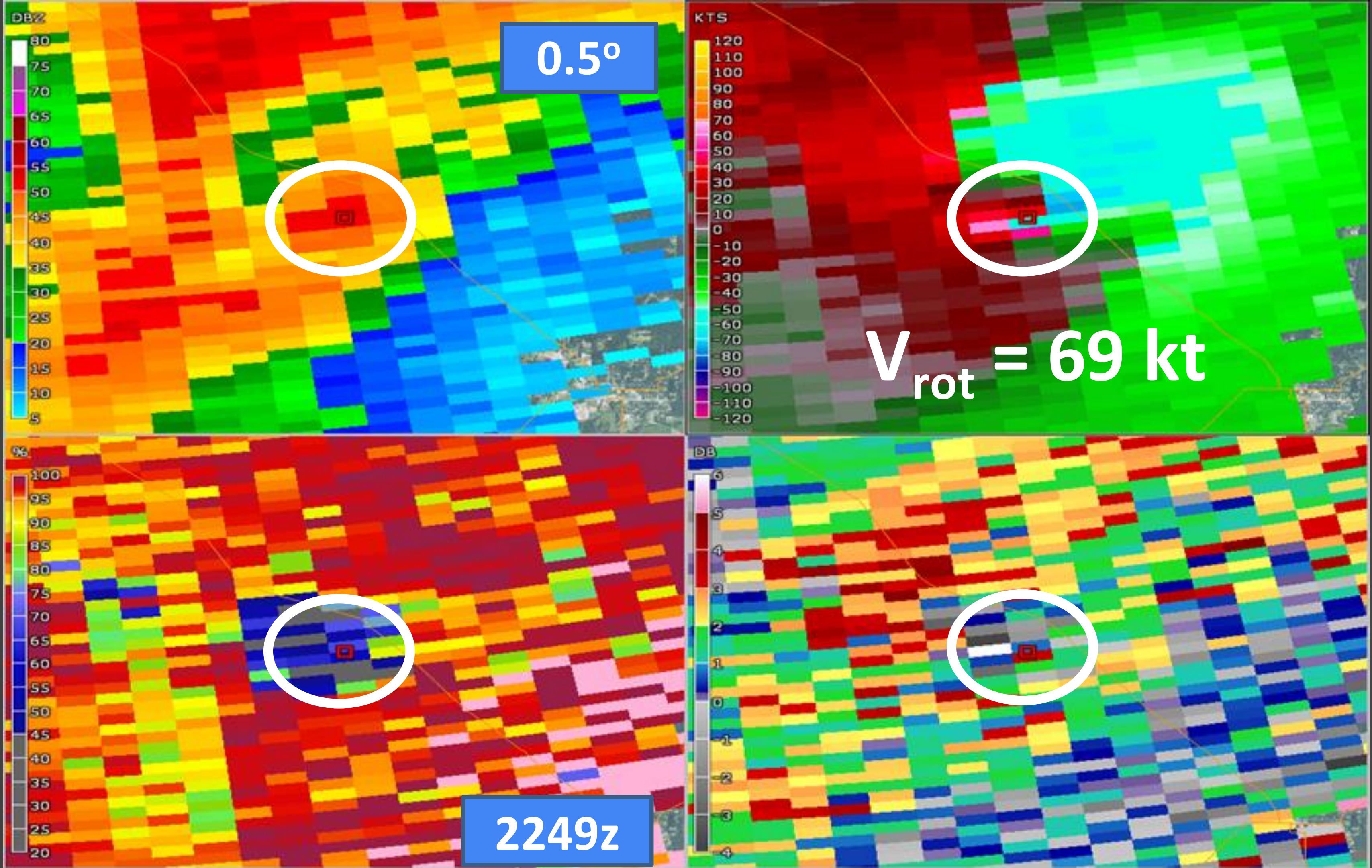
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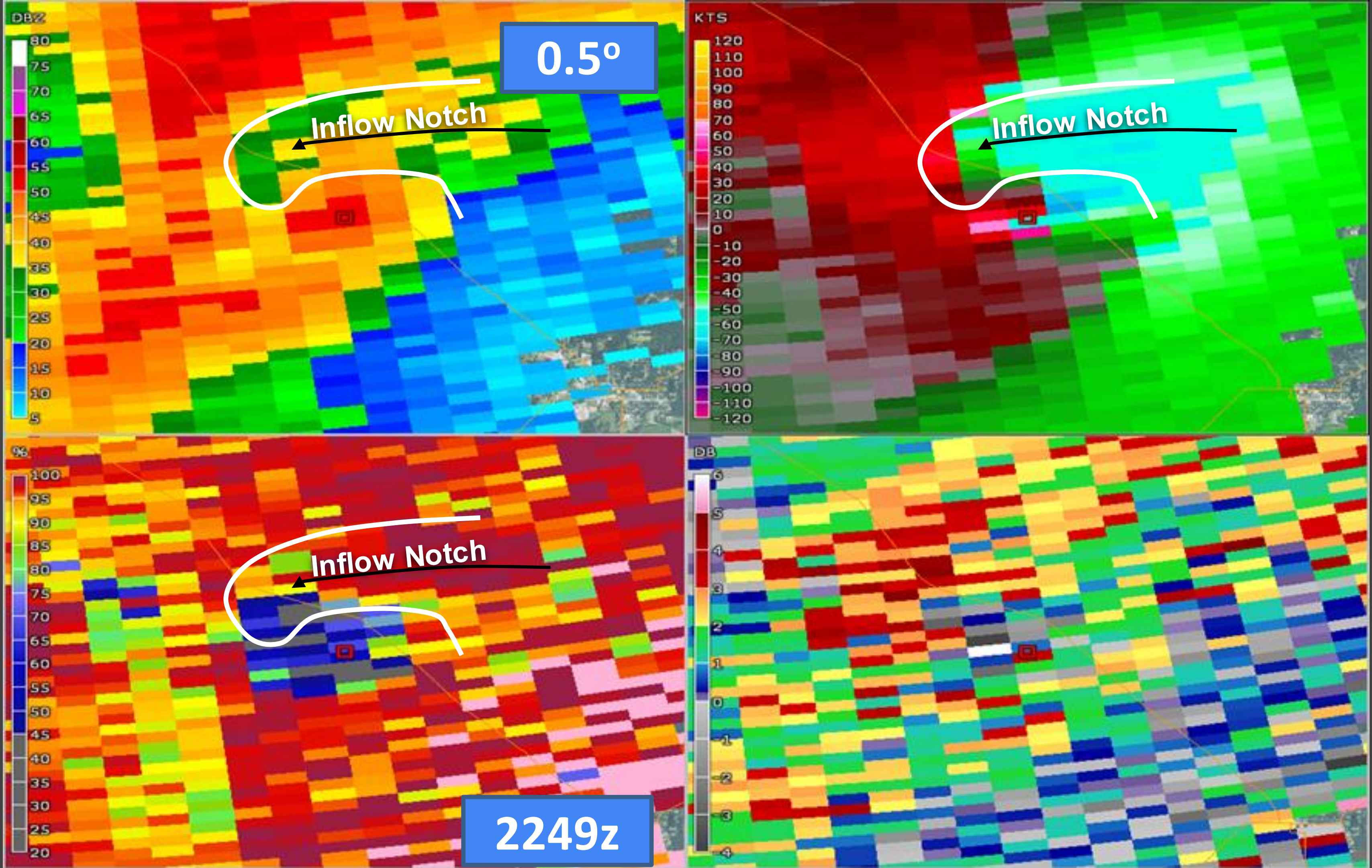
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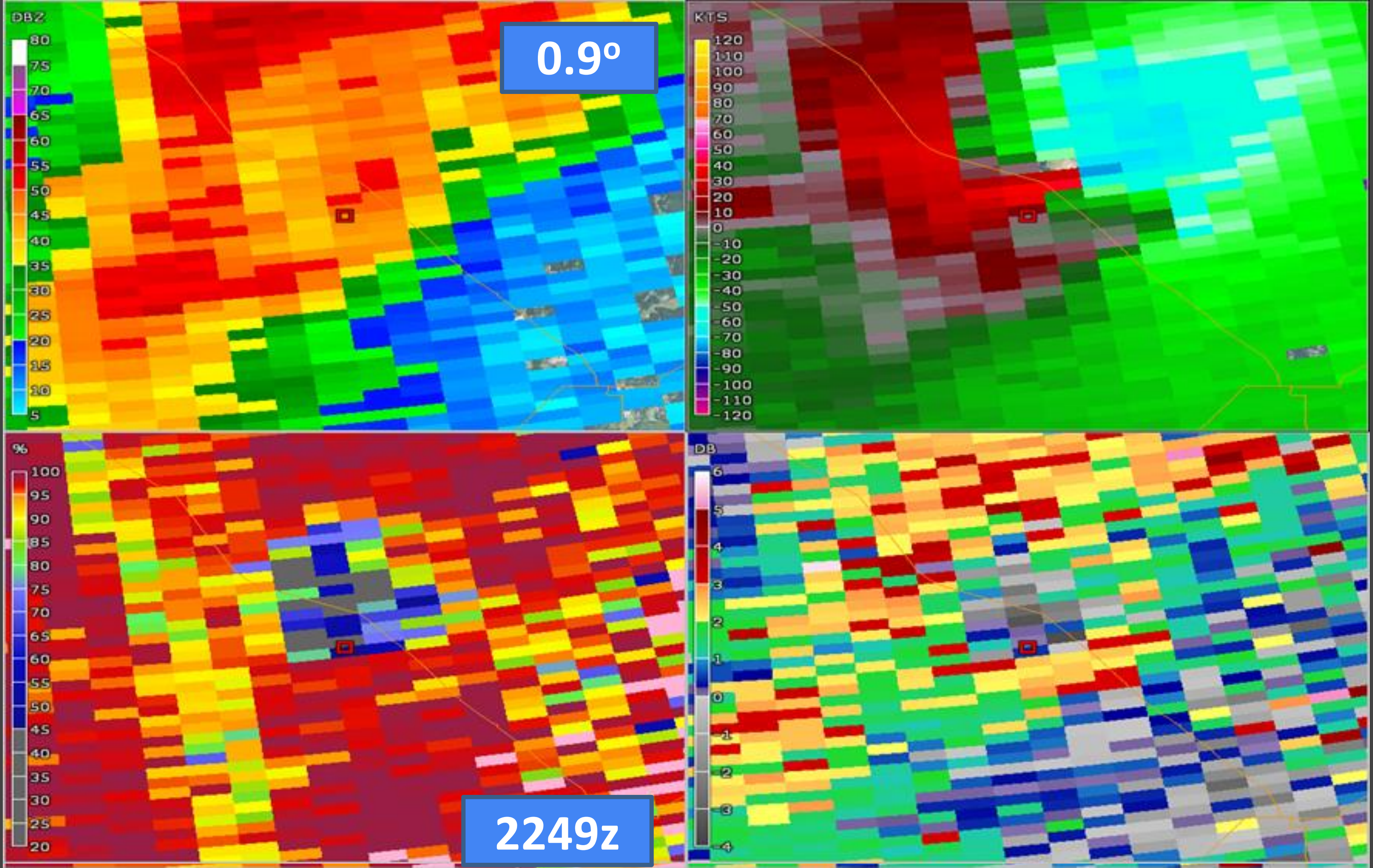
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Step 7: Check Conditional Tornado Probs

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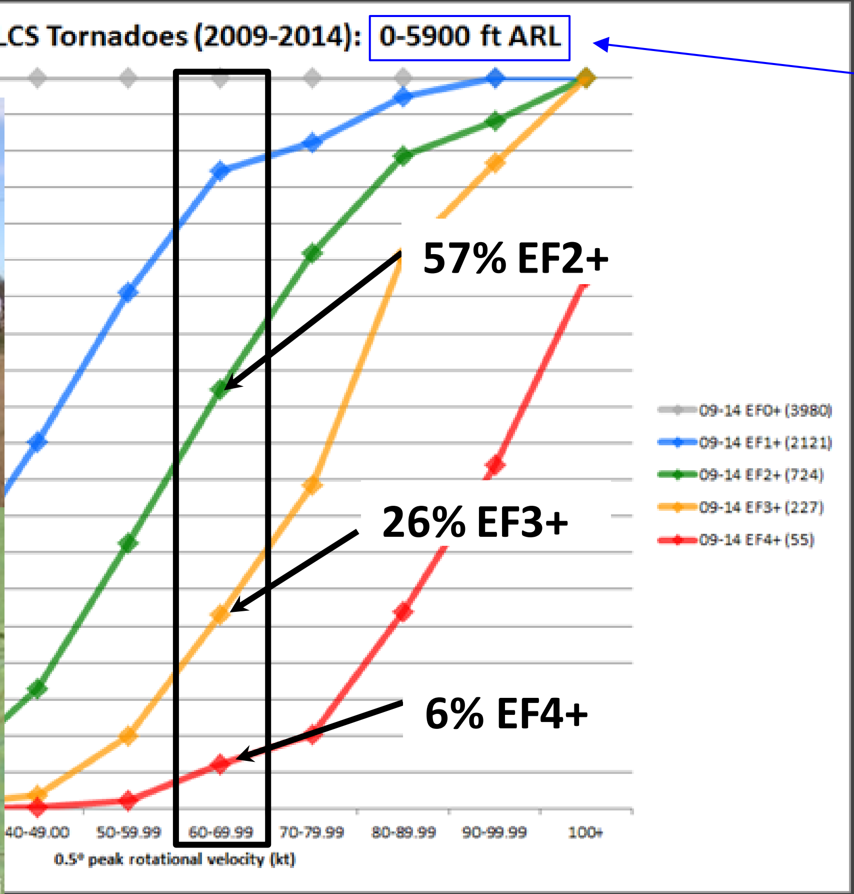

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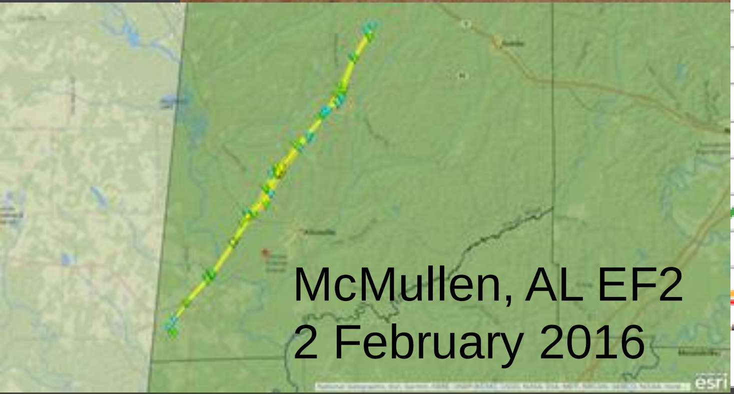
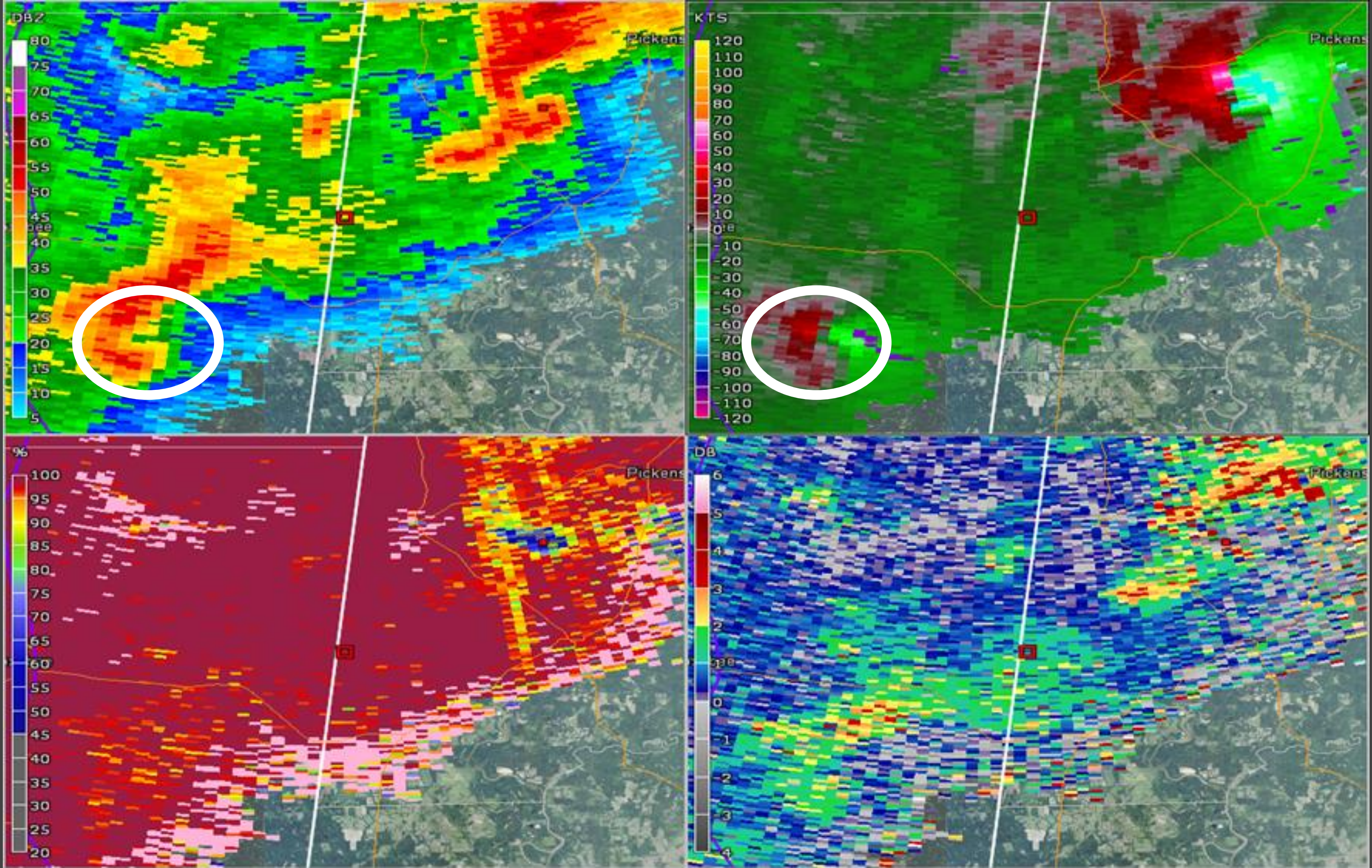


McMullen, AL EF2
2 February 2016



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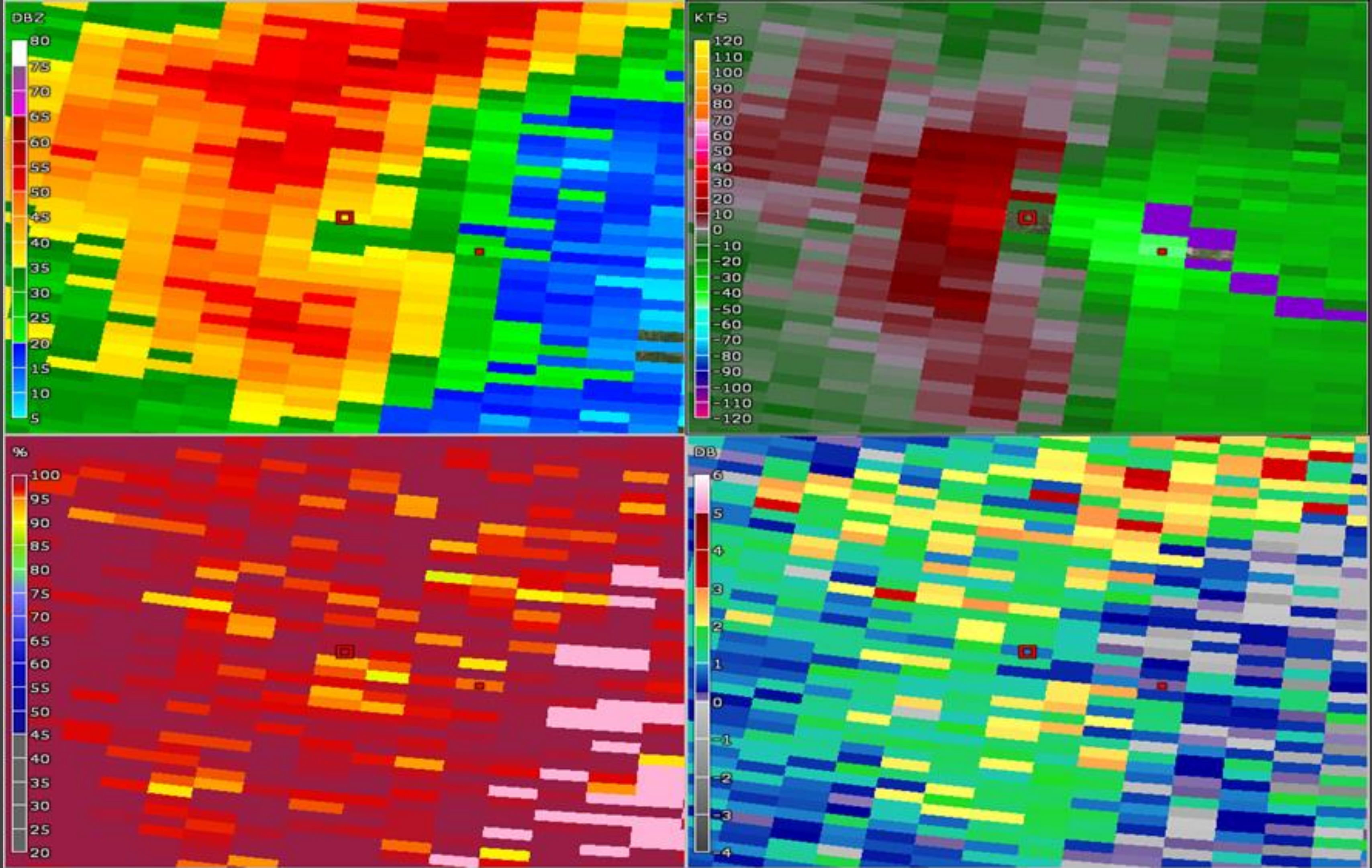

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-90
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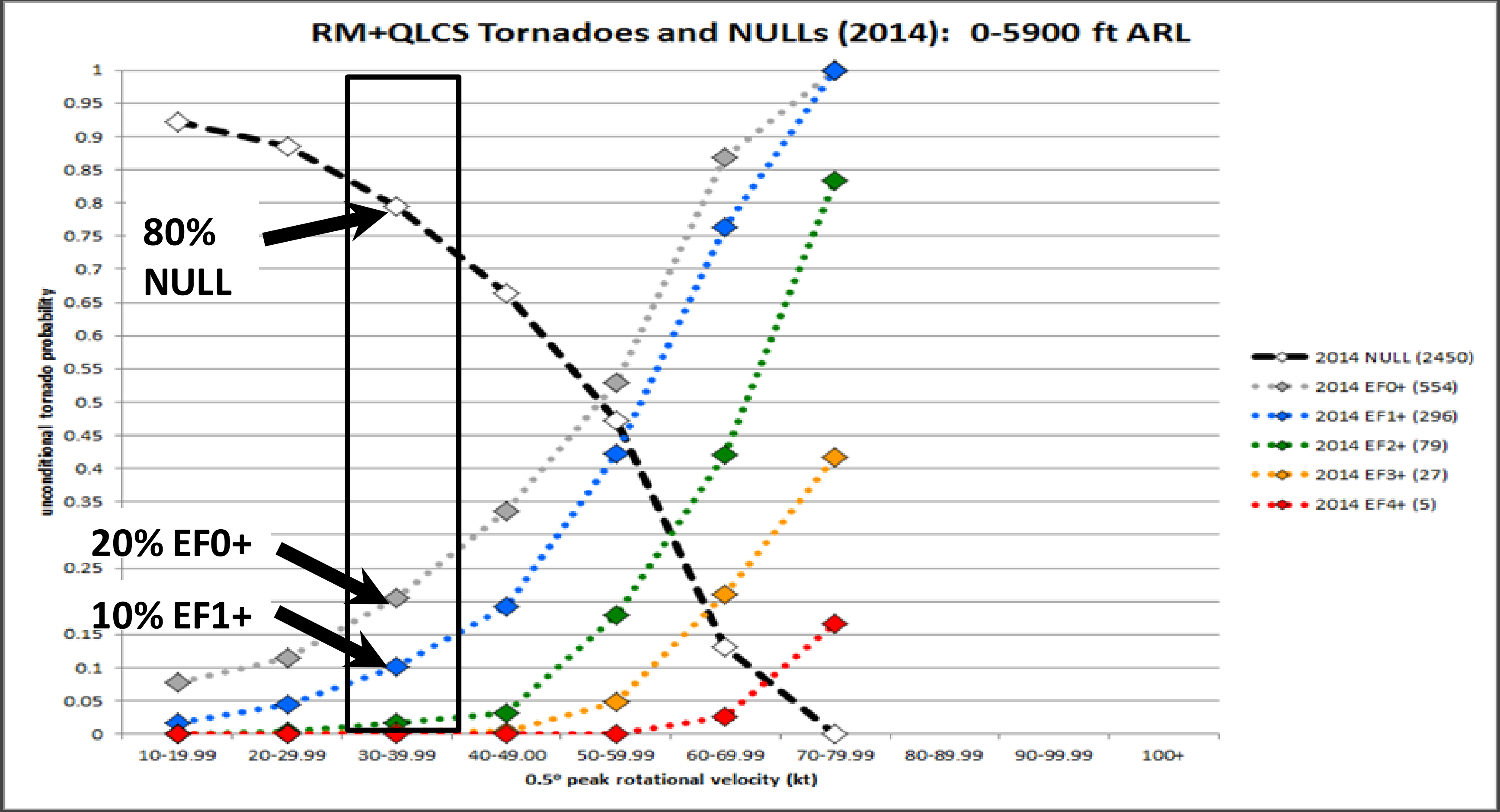
-110
-120
%
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
DB
6
5
4
3
2
1
0
-1
-2
-3
-4

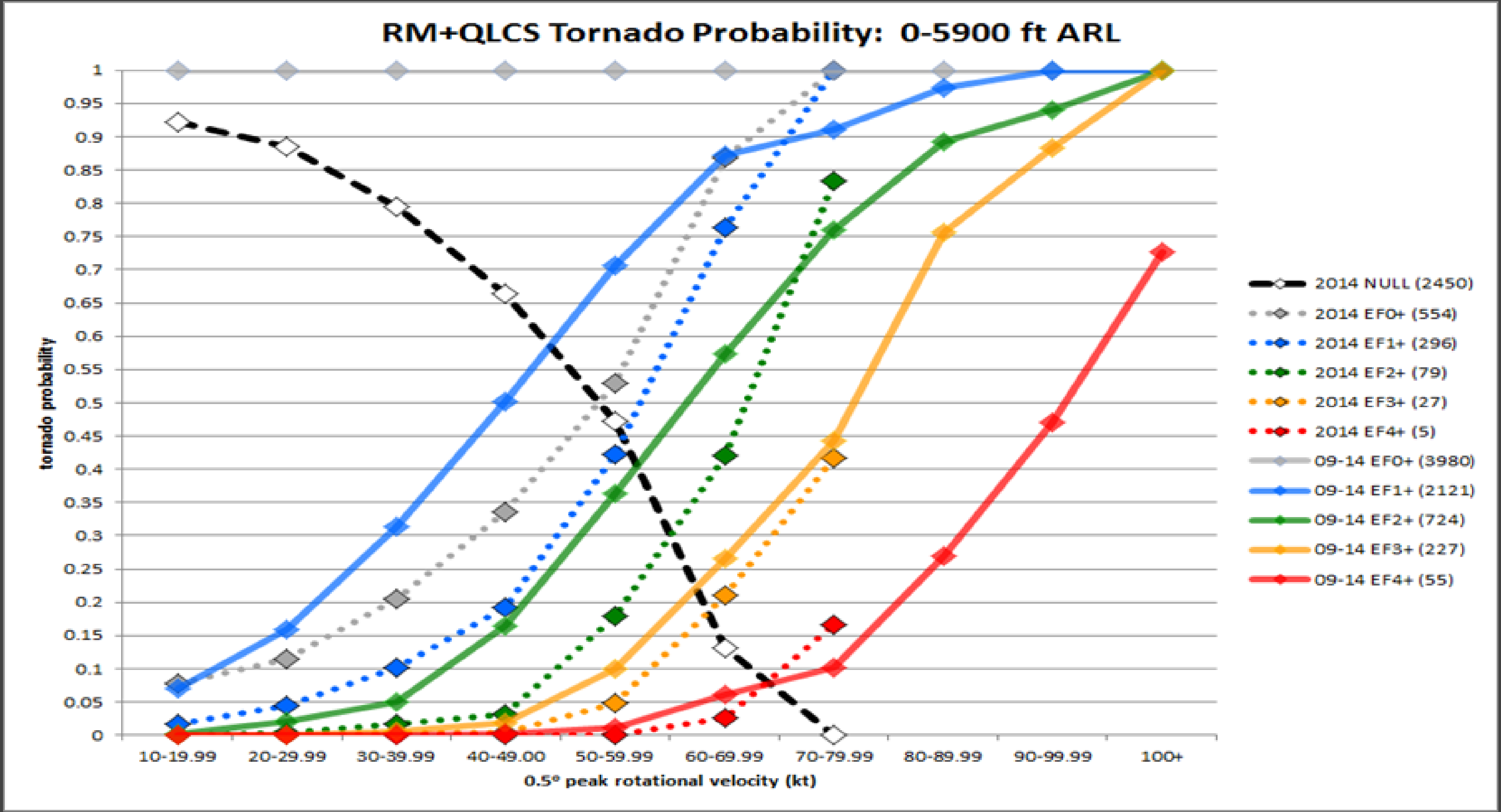
Unconditional Tornado Probabilities

- 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?

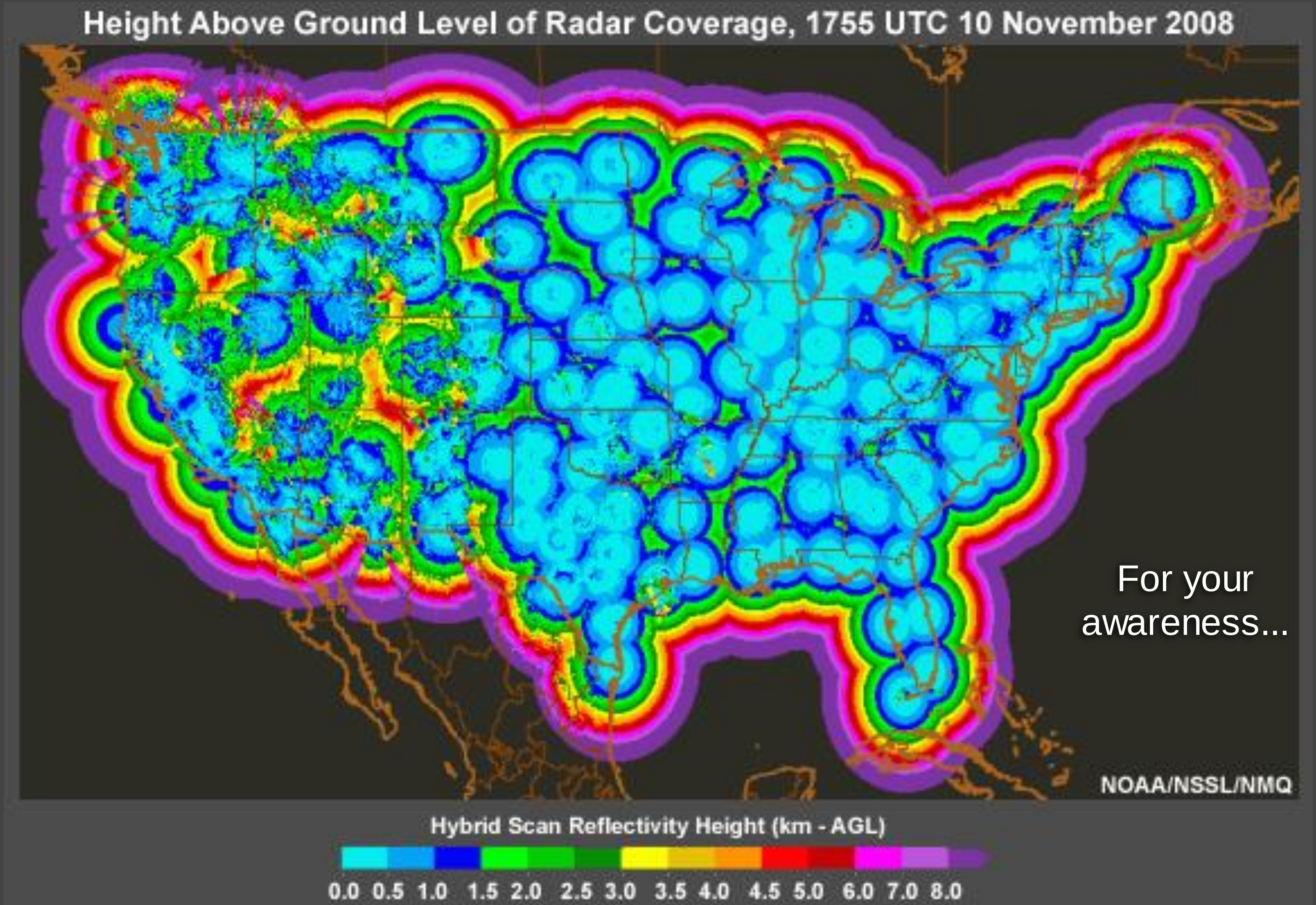


Combined Tornado Probabilities

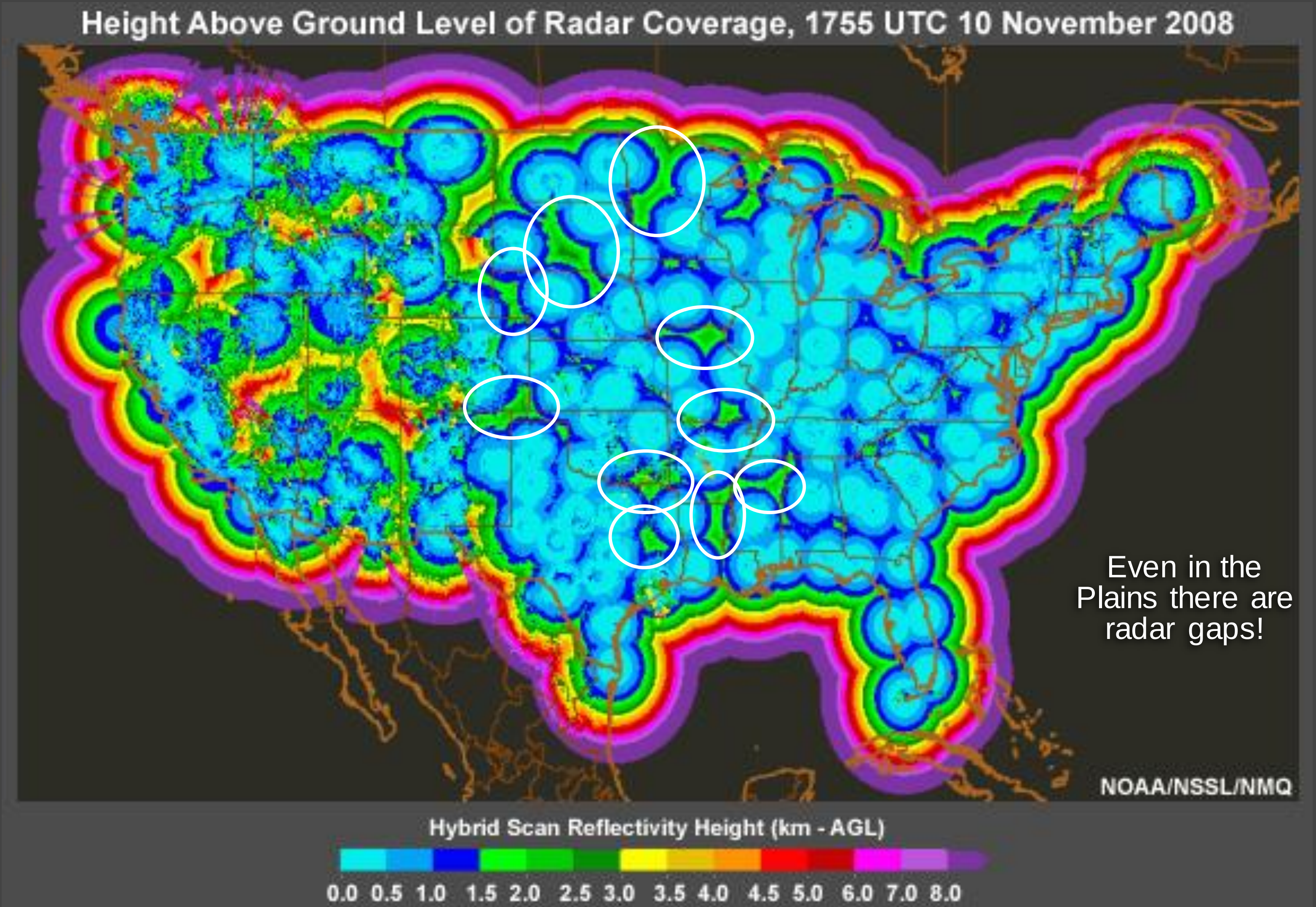


Need to consider influences of beam height/range

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

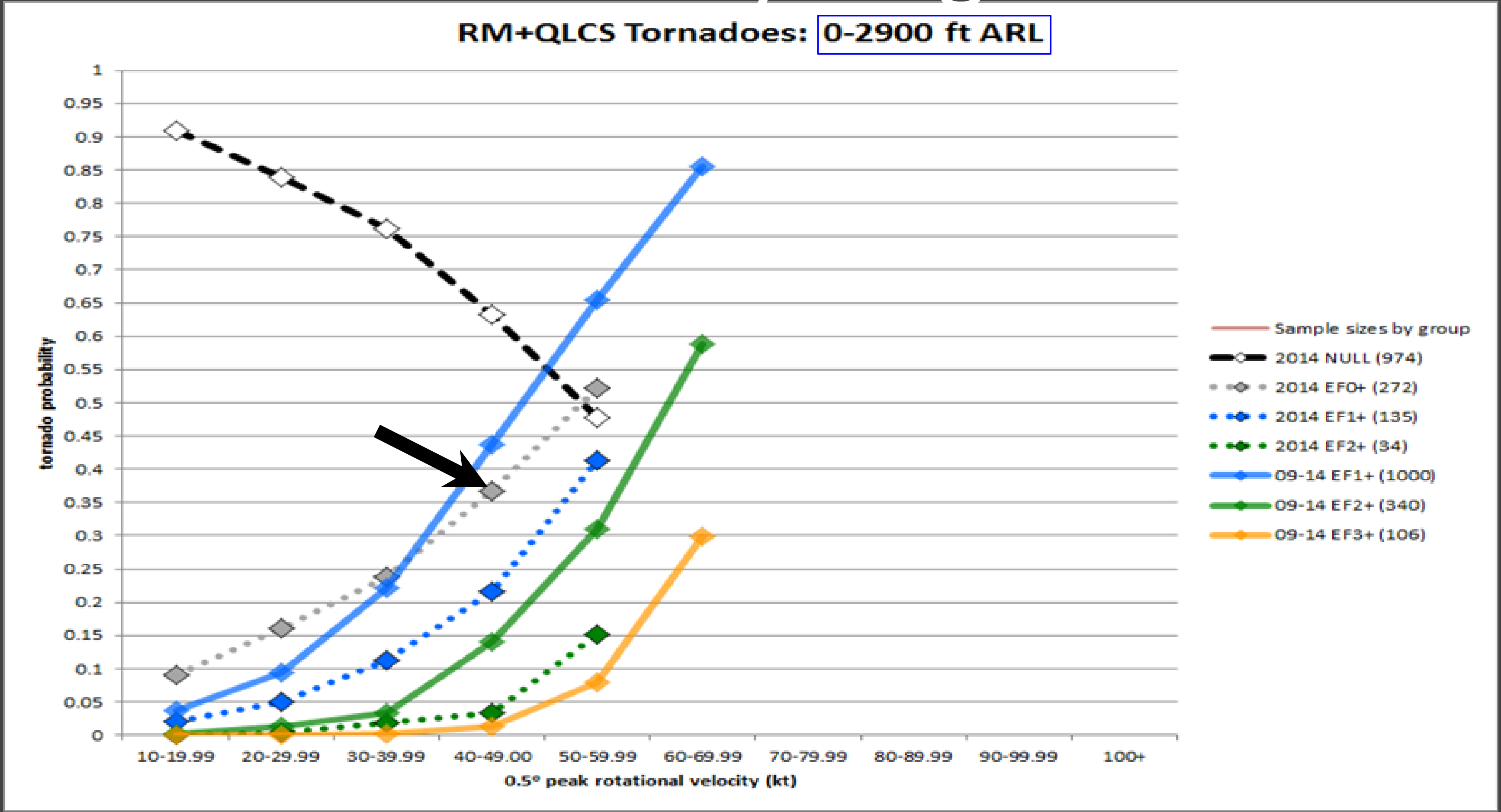


For your awareness...

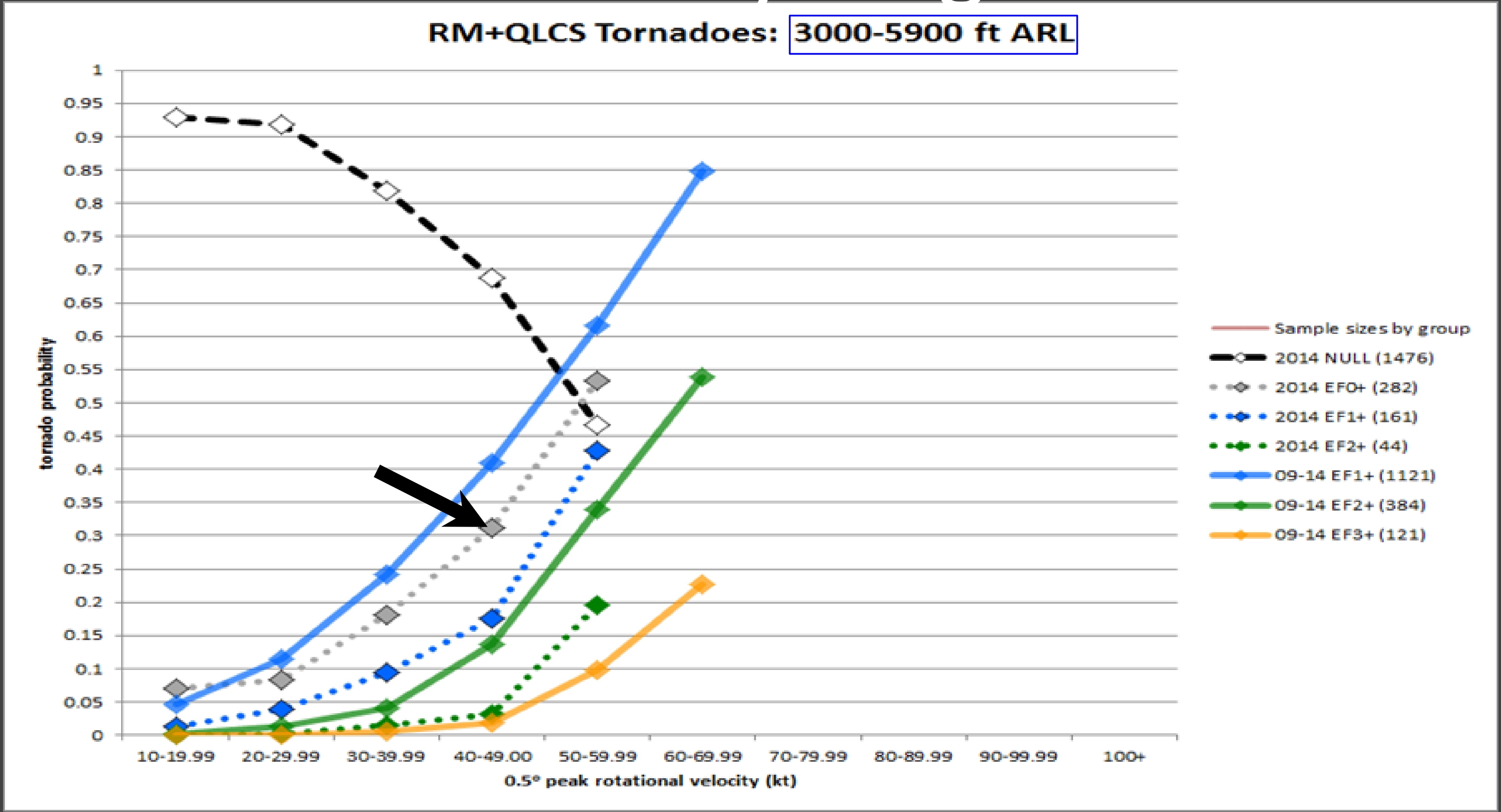


Even in the Plains there are radar gaps!

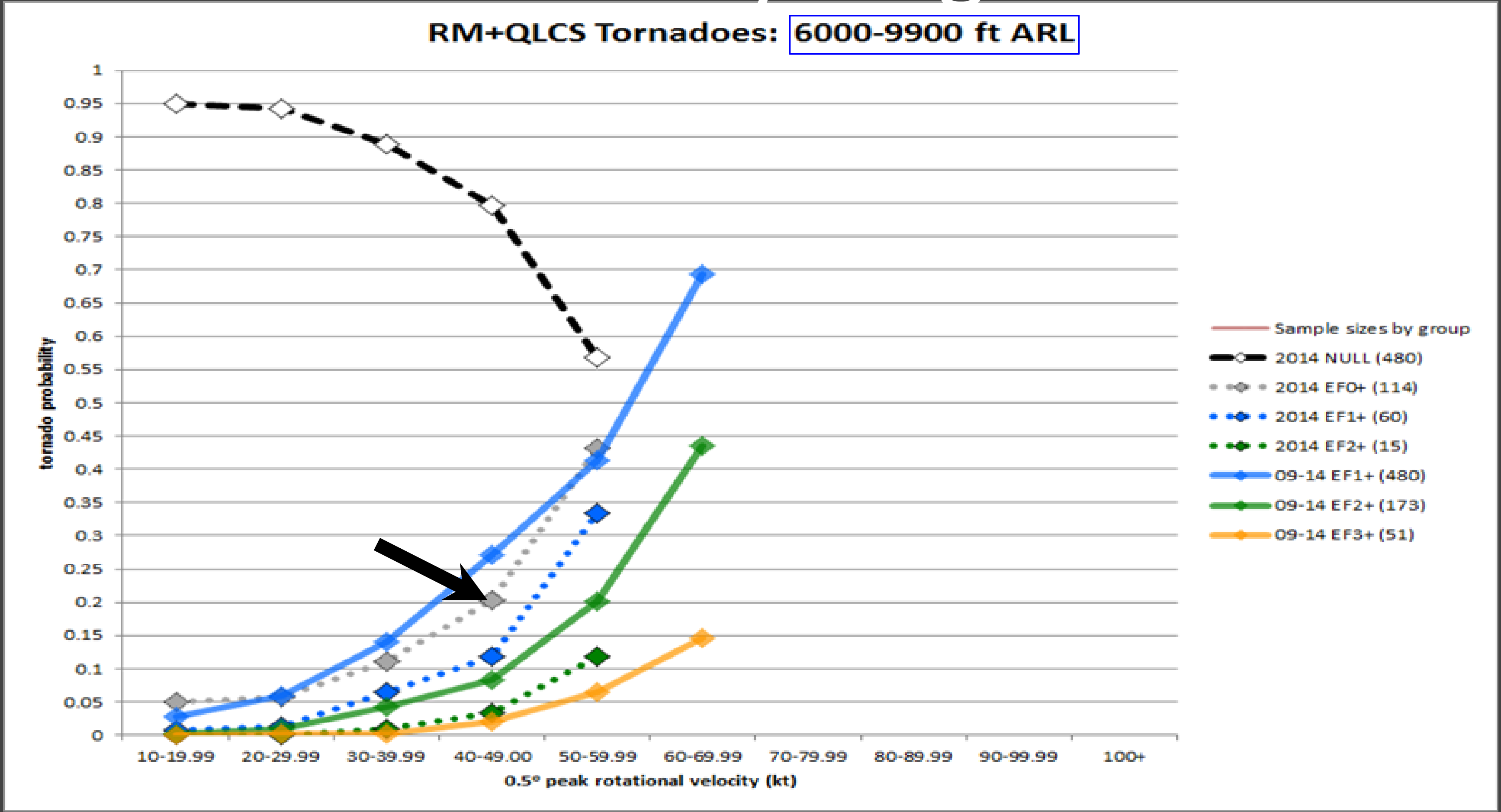
Variations by height ARL



Variations by height ARL

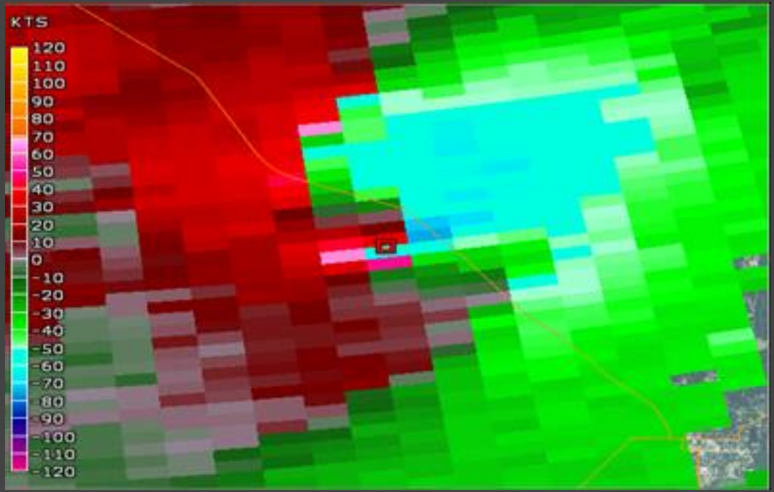


Variations by height ARL

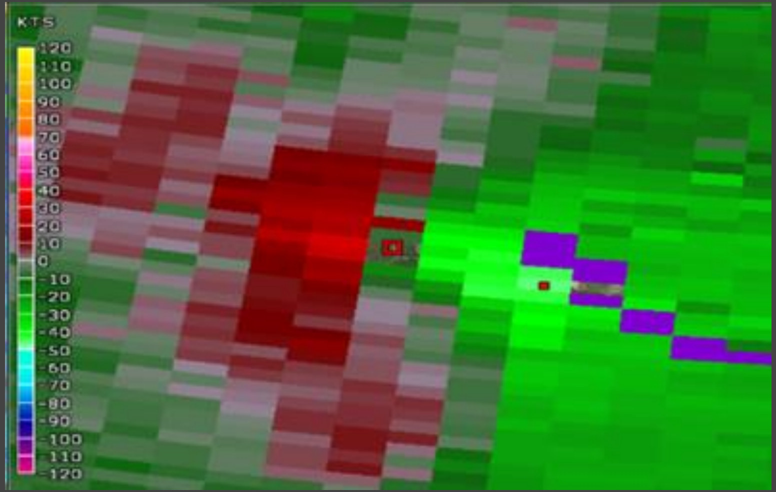


Need to consider influences of circulation diameter

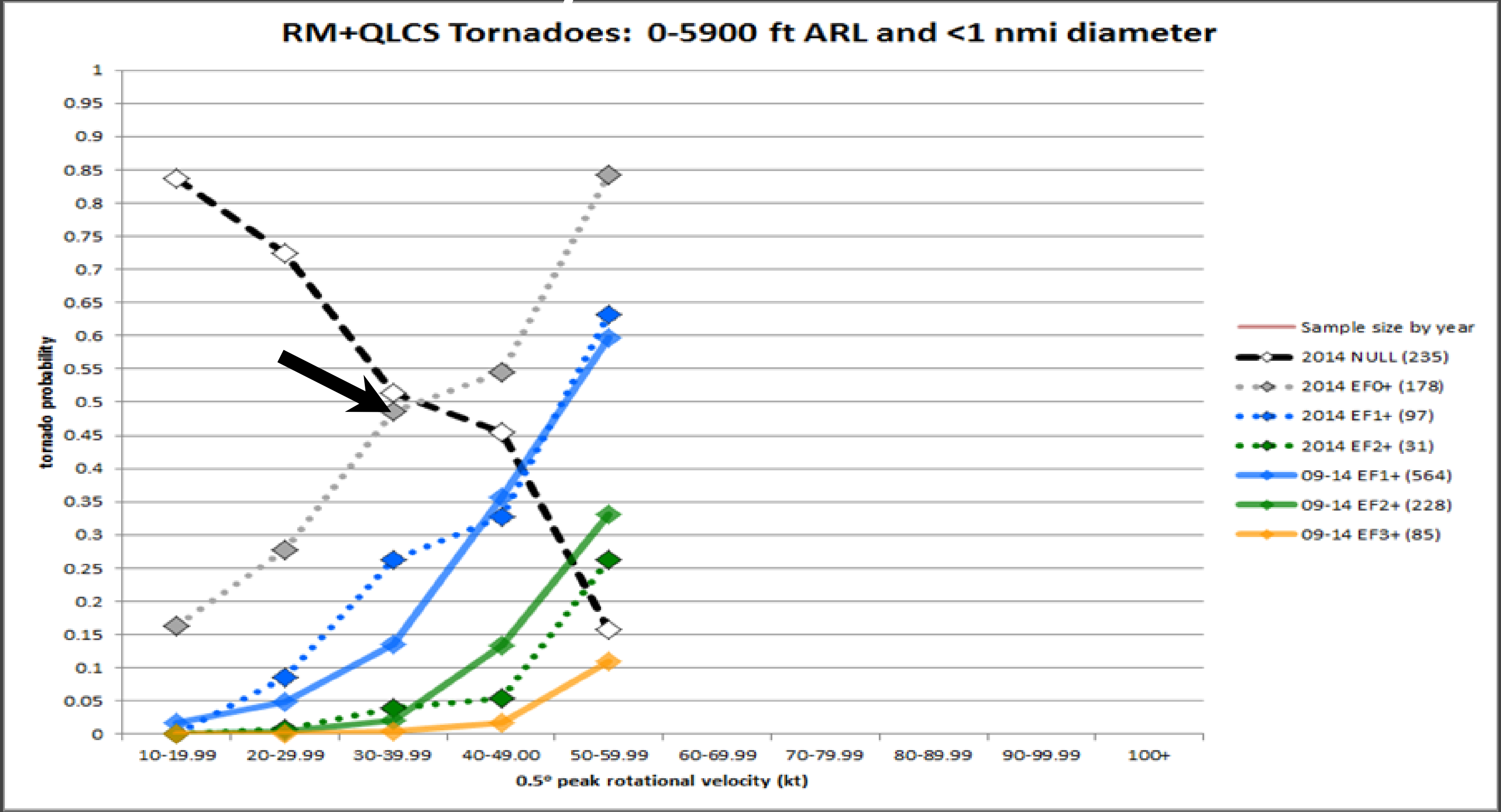
- Lower tornado probabilities with broad circulations
- Higher tornado probabilities with tight circulations



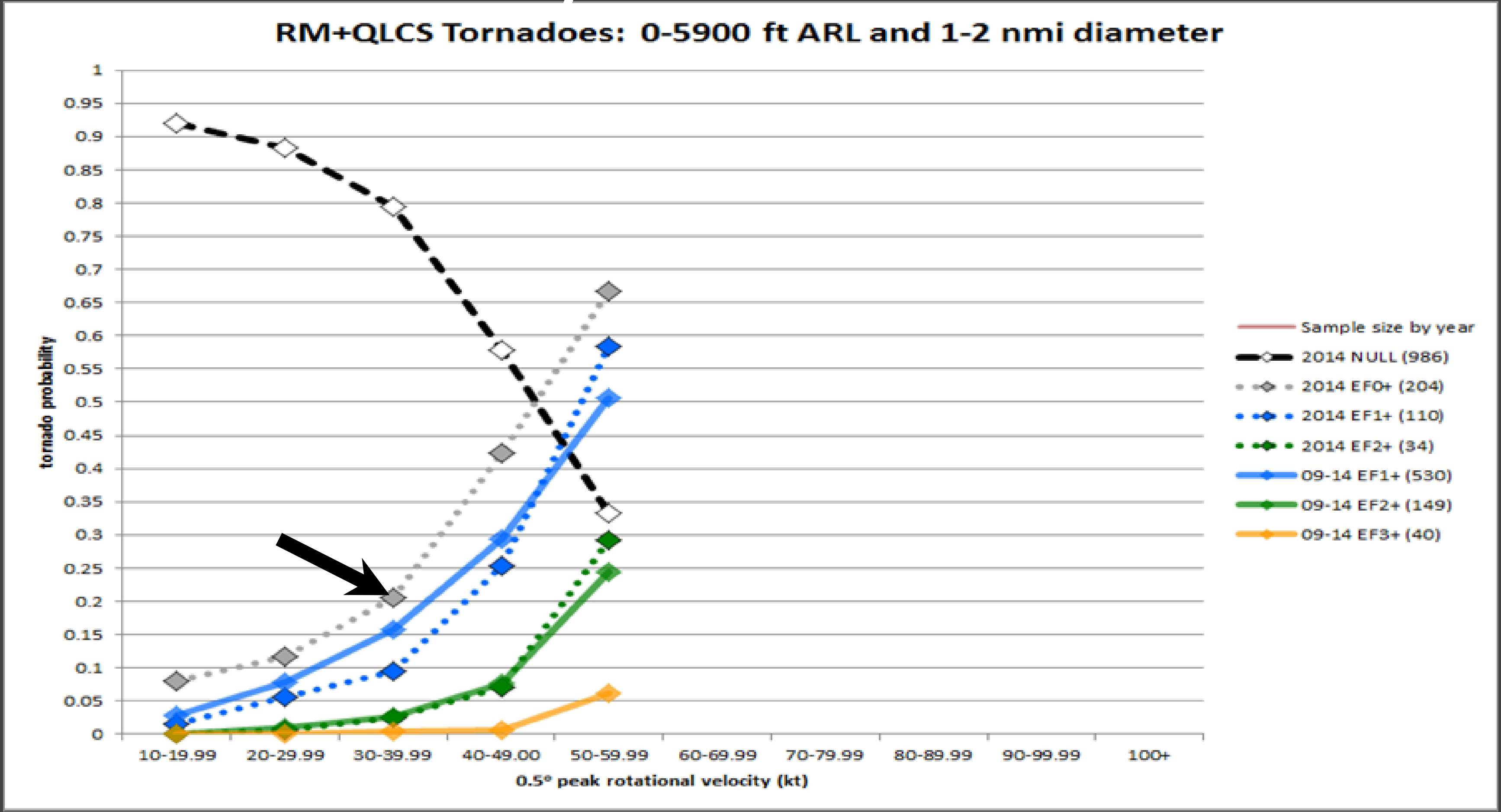
vs.



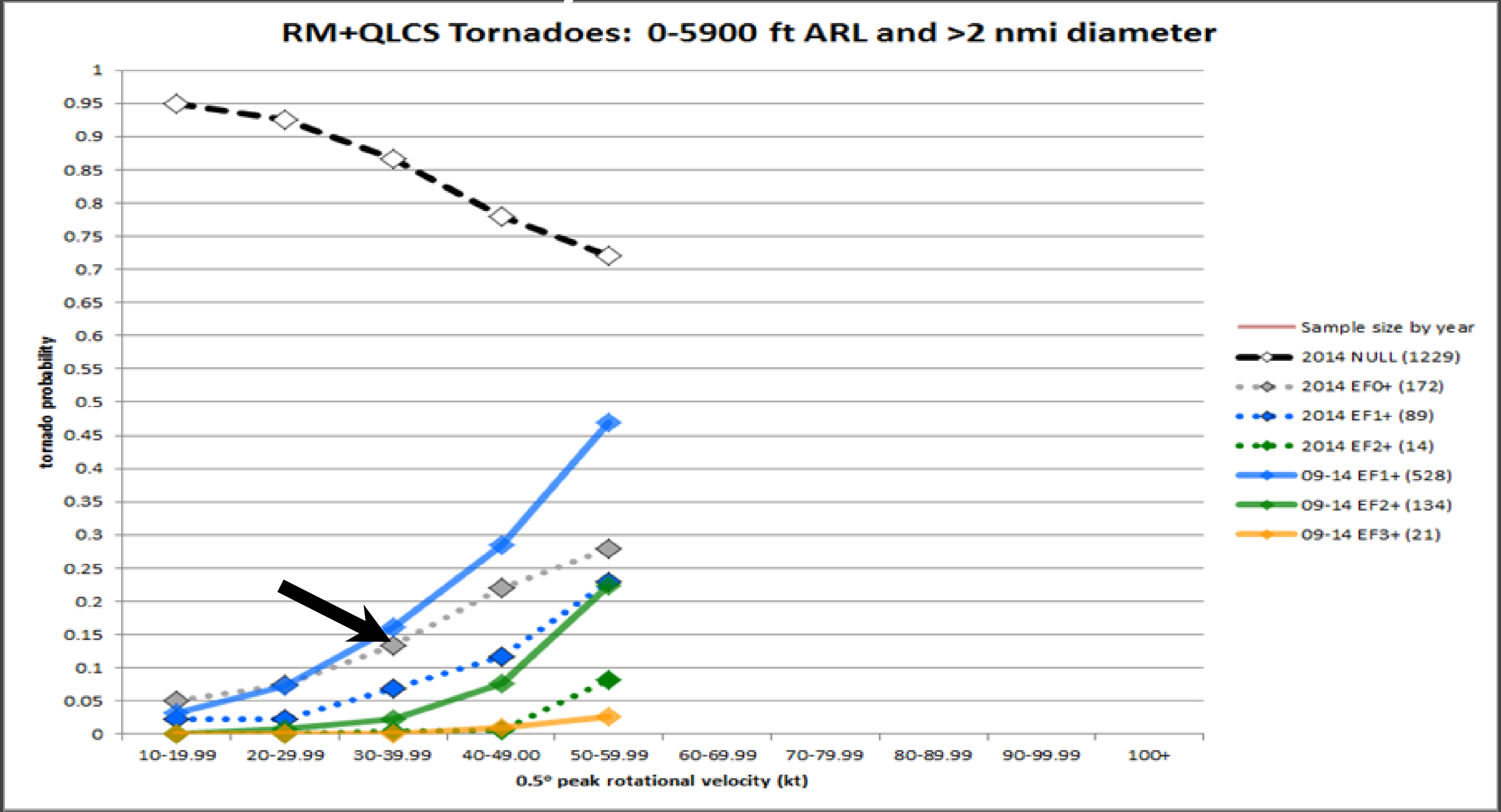
Variations by circulation diameter



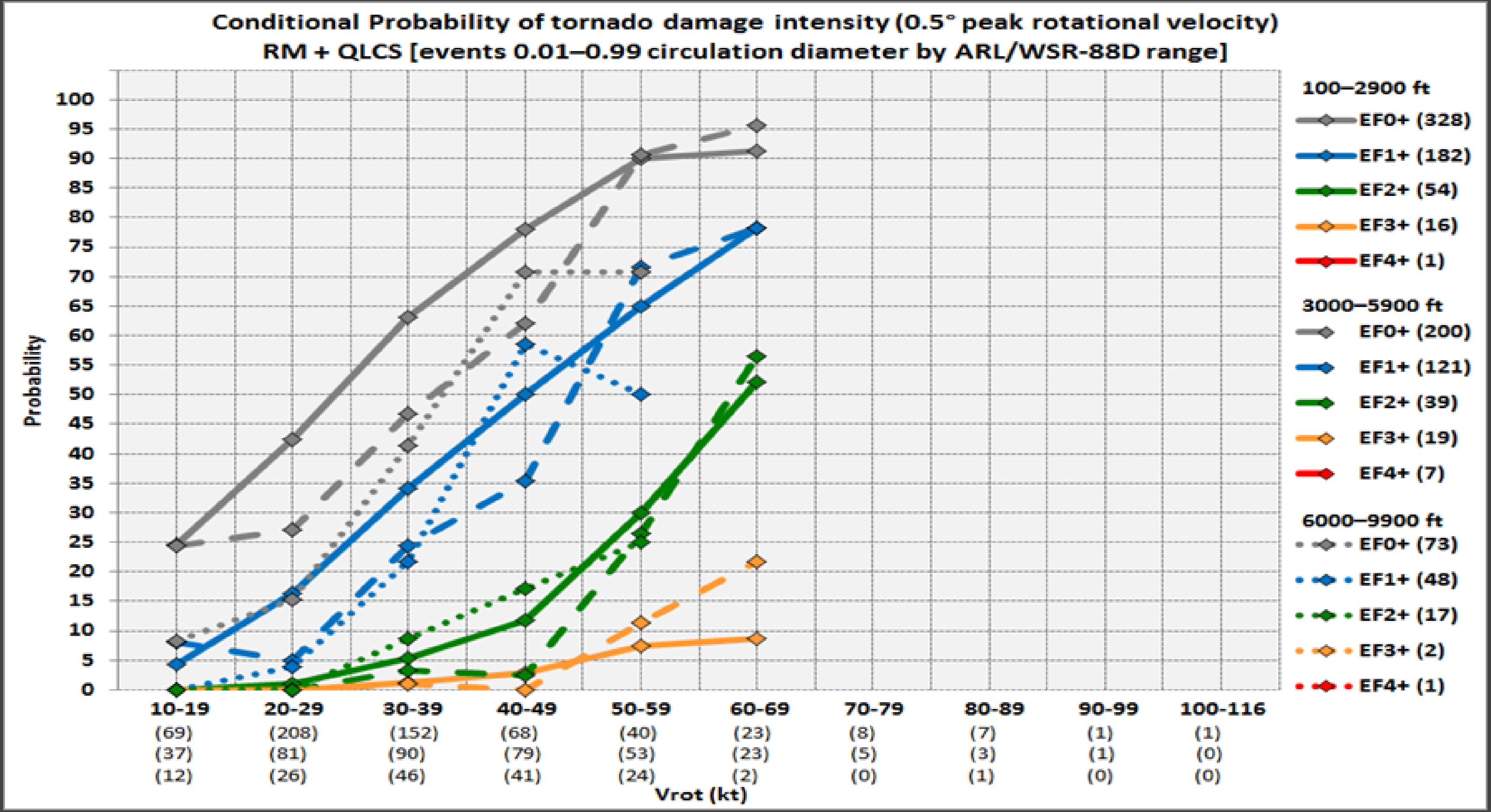
Variations by circulation diameter



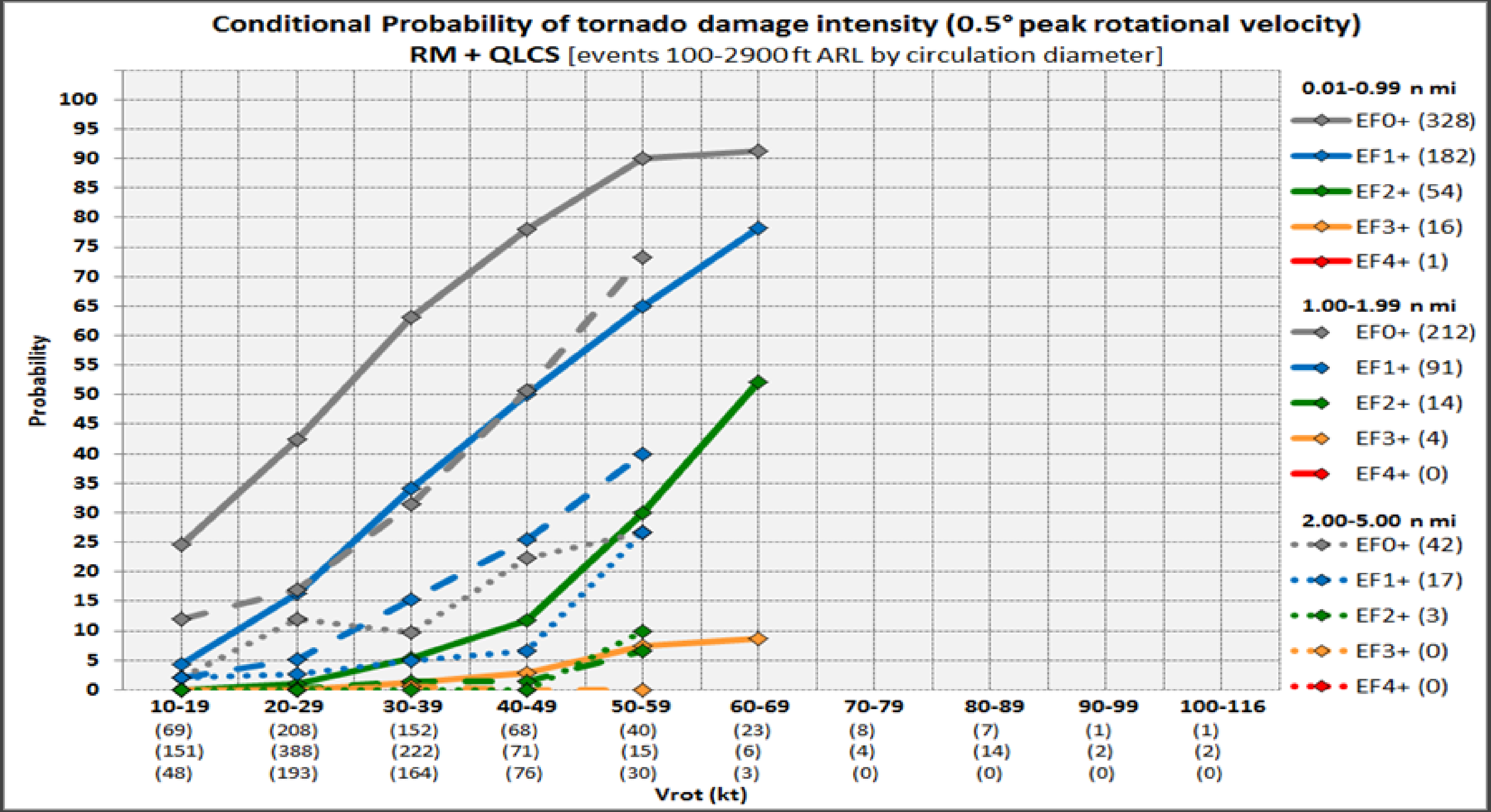
Variations by circulation diameter



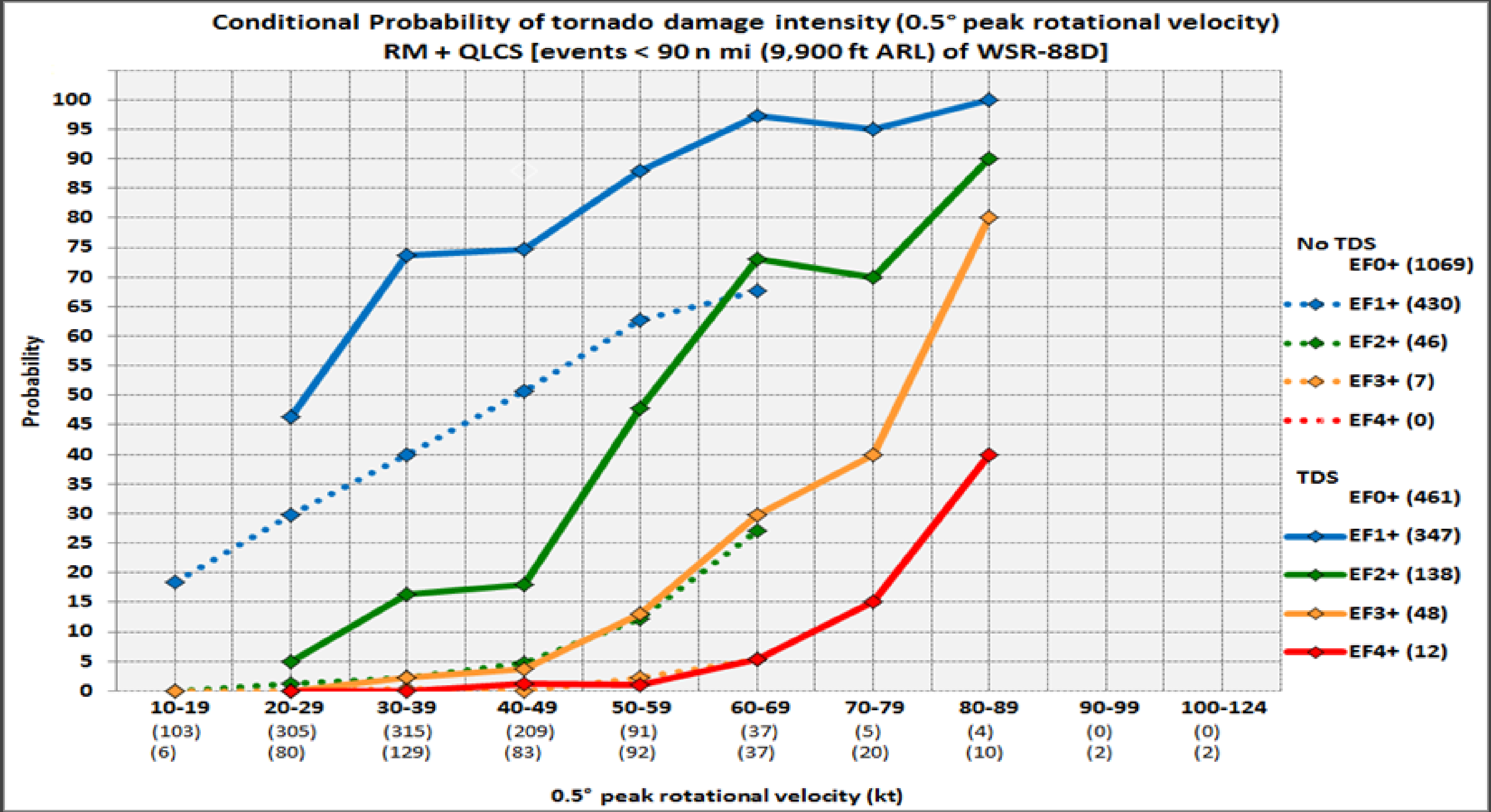
Conditional Probs by Height ARL



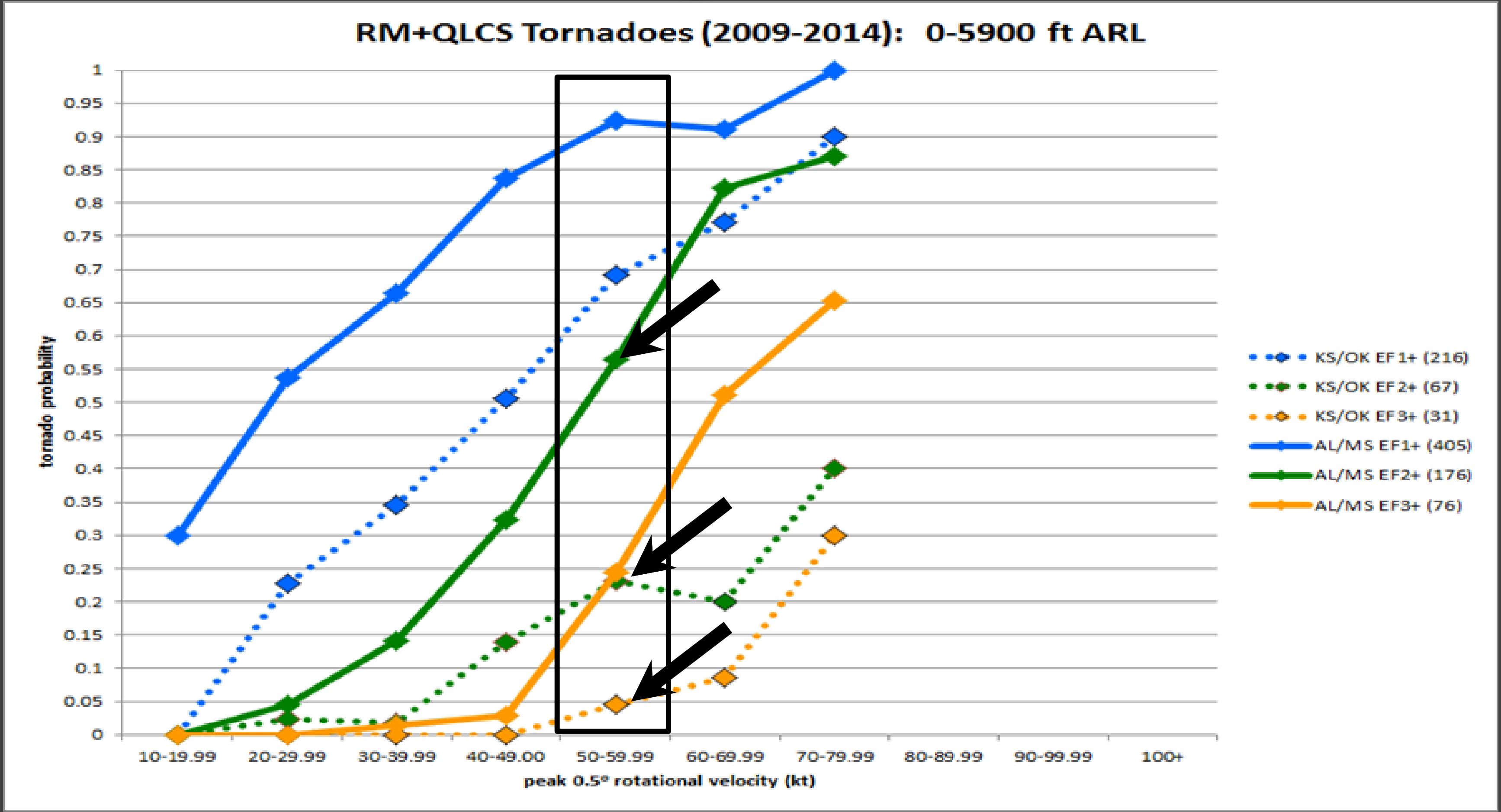
Conditional Probs by Distance



Conditional Probs (TDS vs. No-TDS)

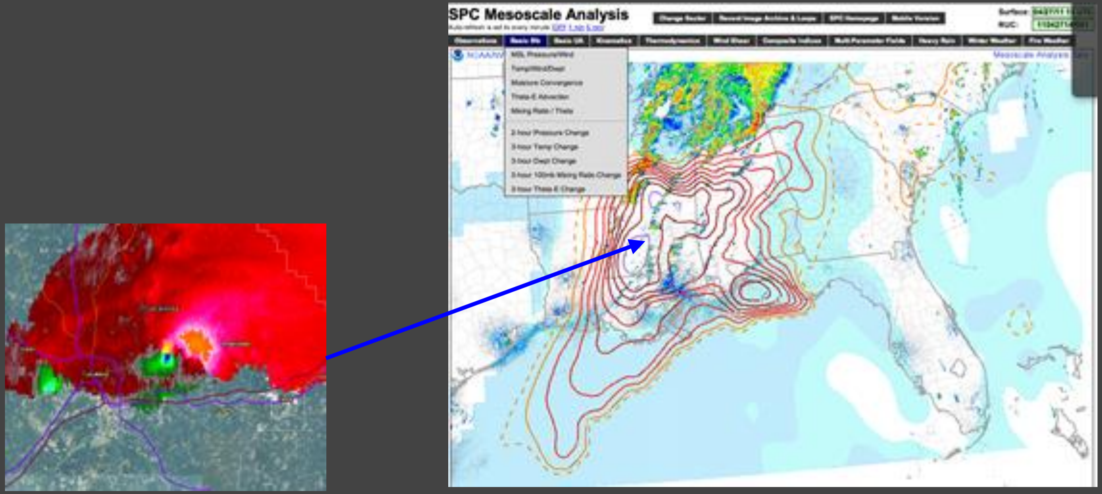


What about regional differences?

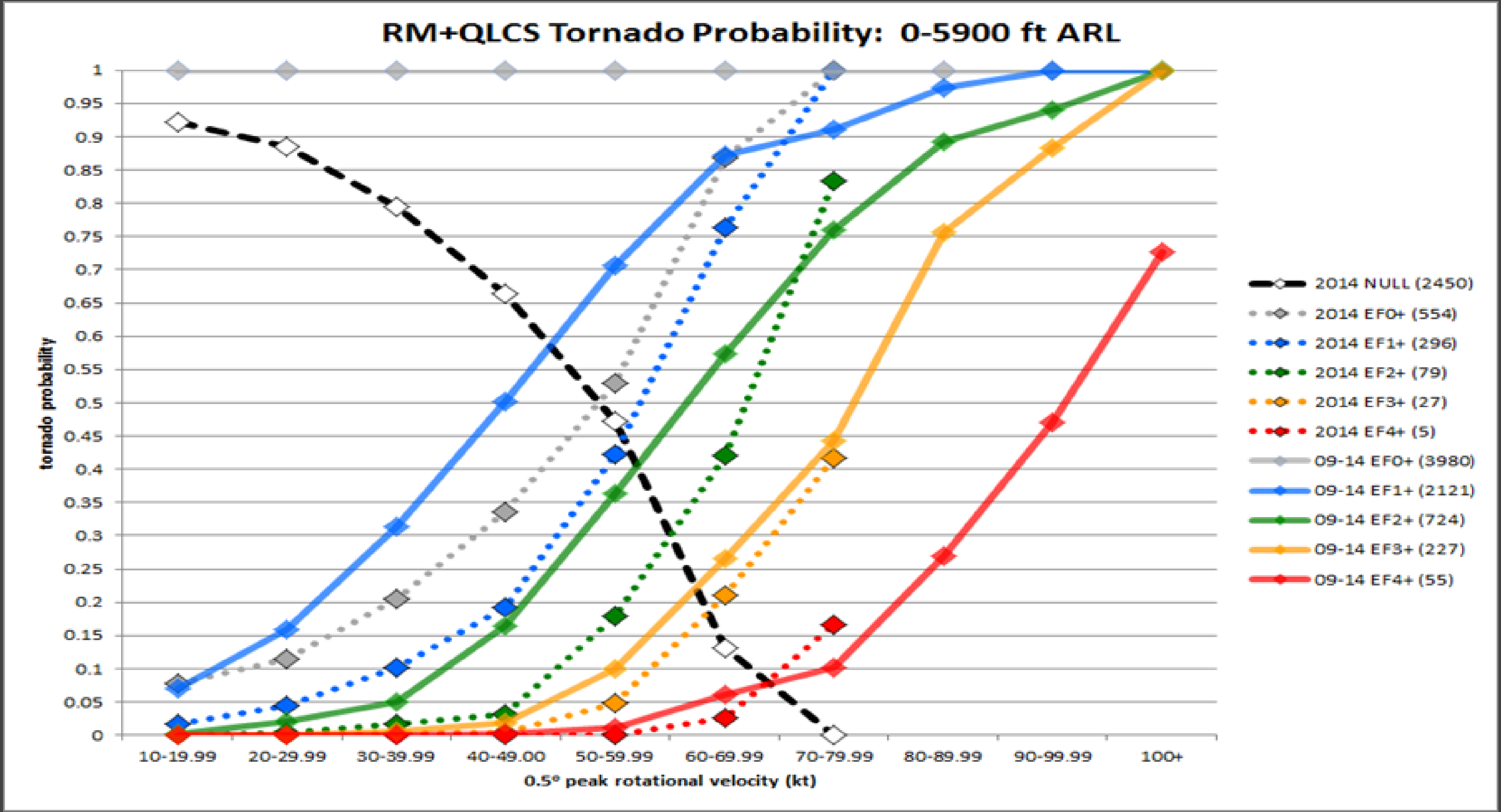


Need to consider storm environment

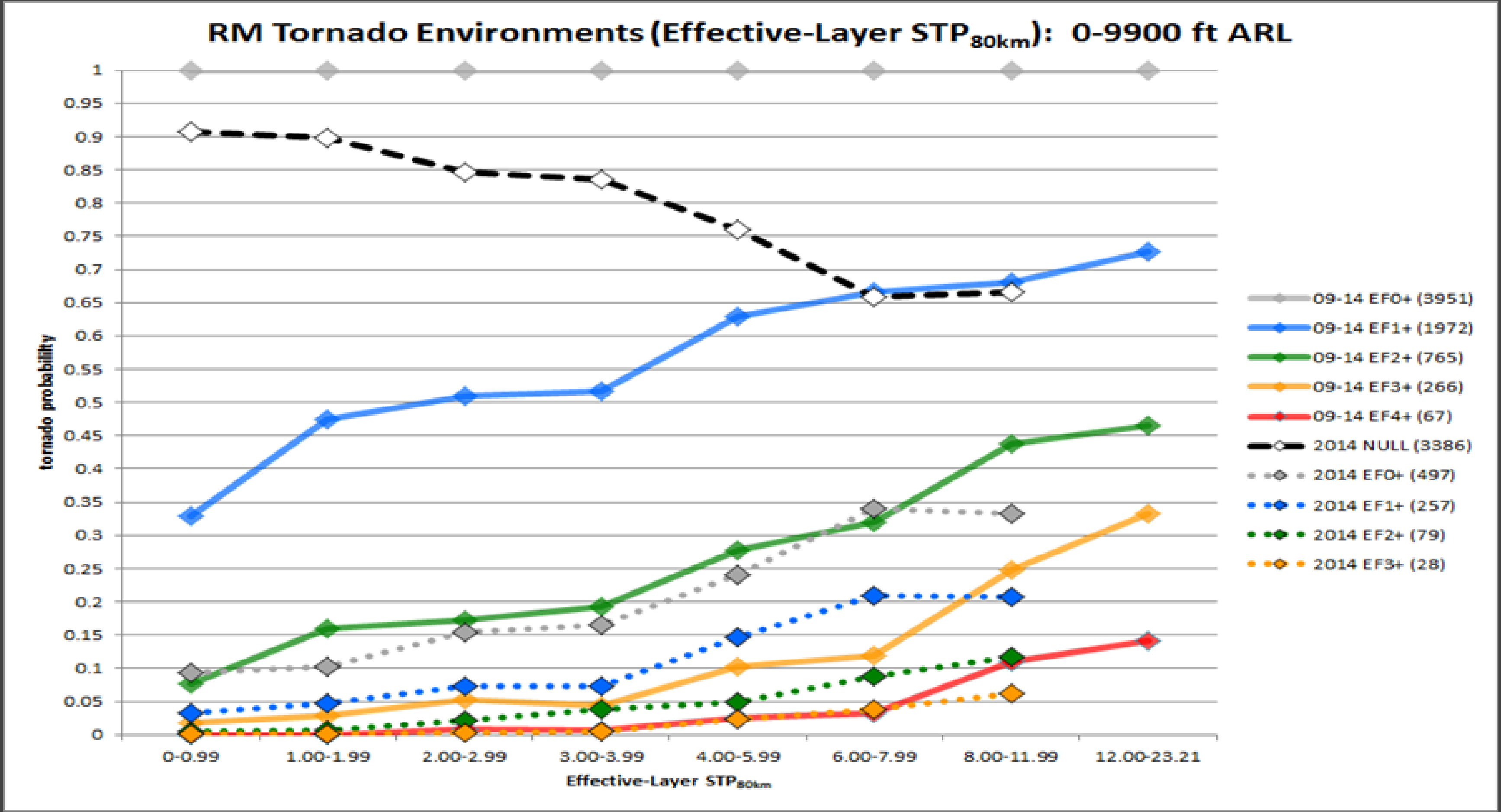
- So far we've only considered WSR-88D signatures, but the env can help!
- Try to keep the environment estimate simple
  - Look at significant tornado parameter (STP)
  - Take max value within 80 km of each storm
    - Forecasters consider more than a point value!

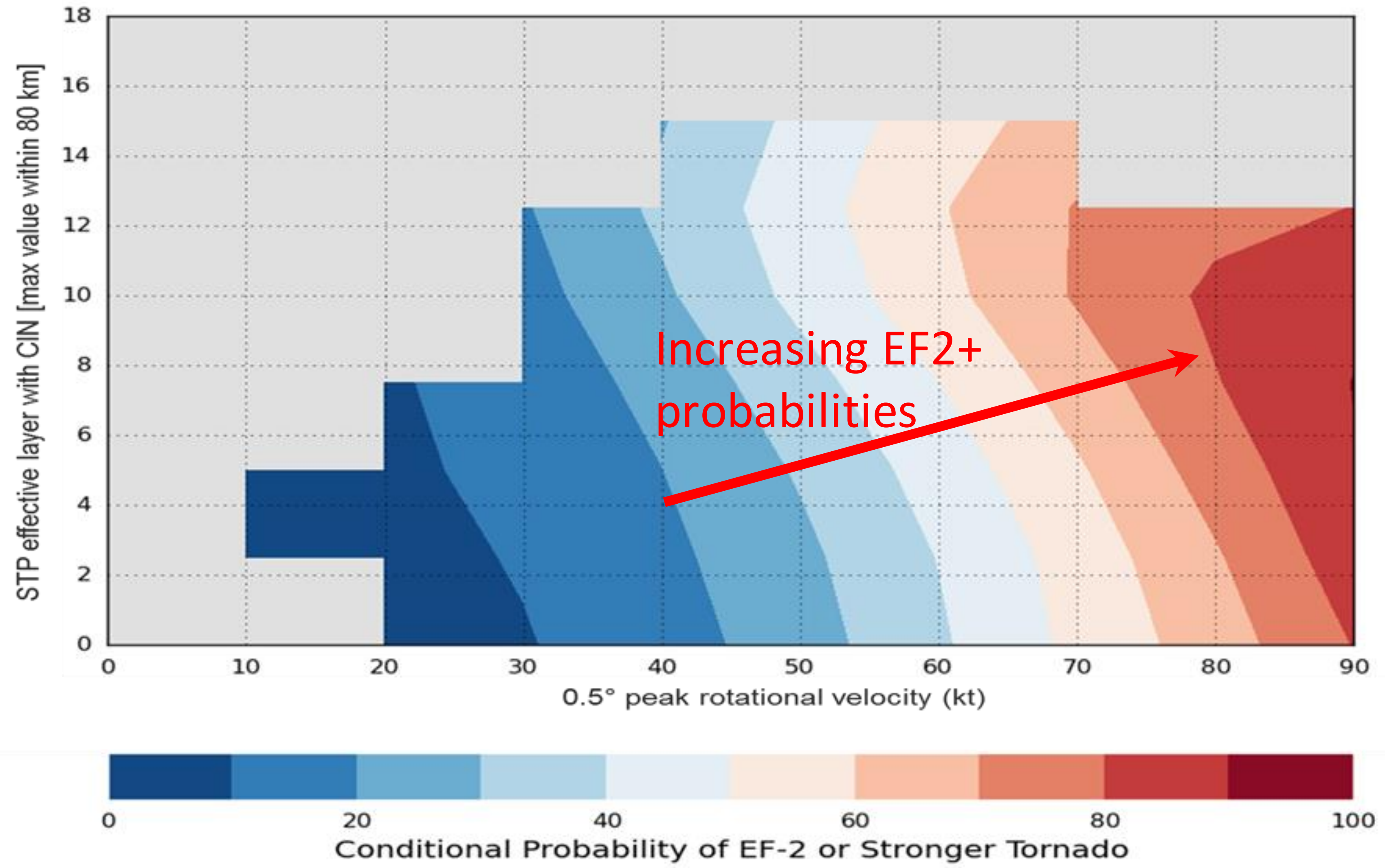


Tornado Probabilities by Vrot



Tornado Probabilities by Eff. STP




STP effective layer with CIN [max value within 80 km]
0.5° peak rotational velocity (kt)
Increasing EF2+ probabilities
Conditional Probability of EF-2 or Stronger Tornado

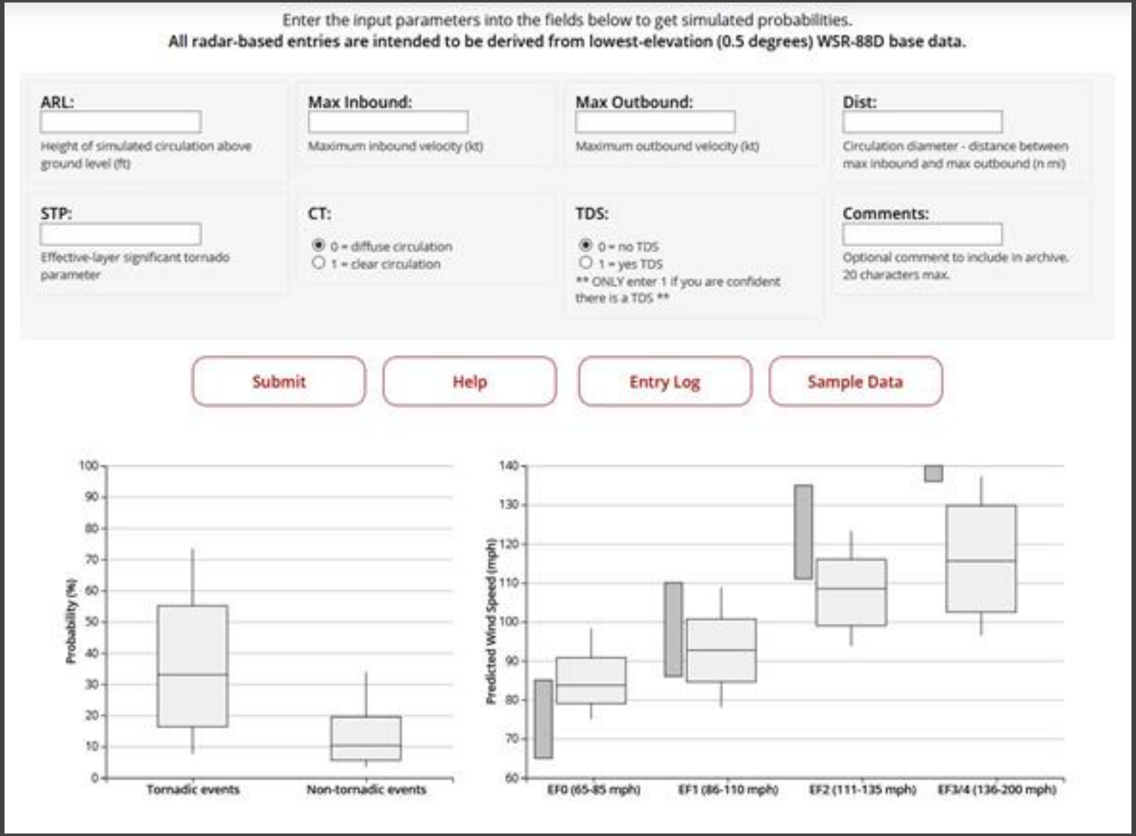
Tornado Probabilities by Eff. STP

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



Questions?