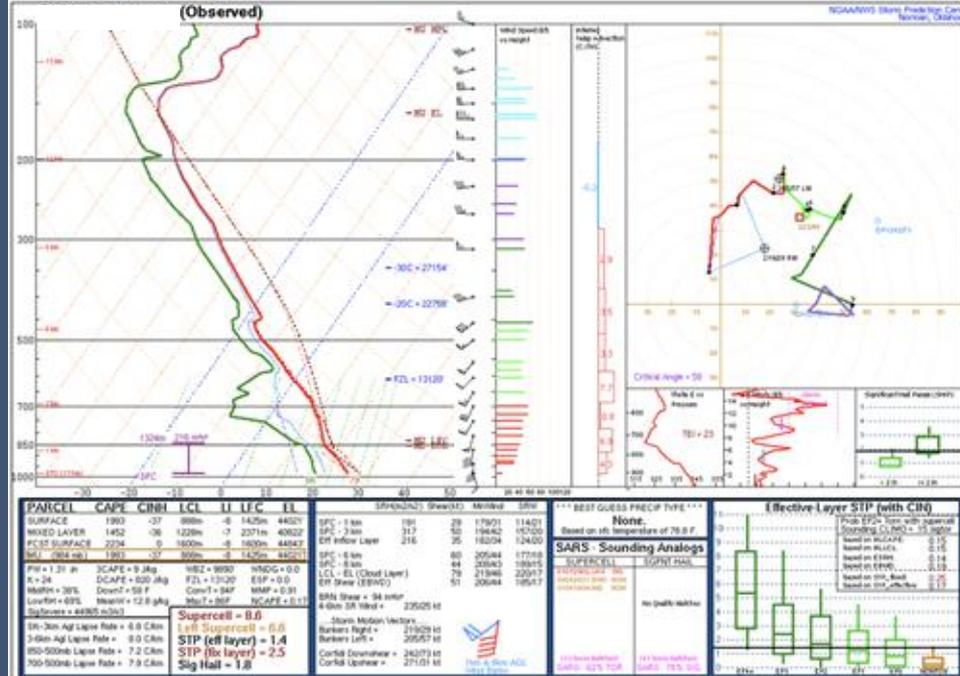
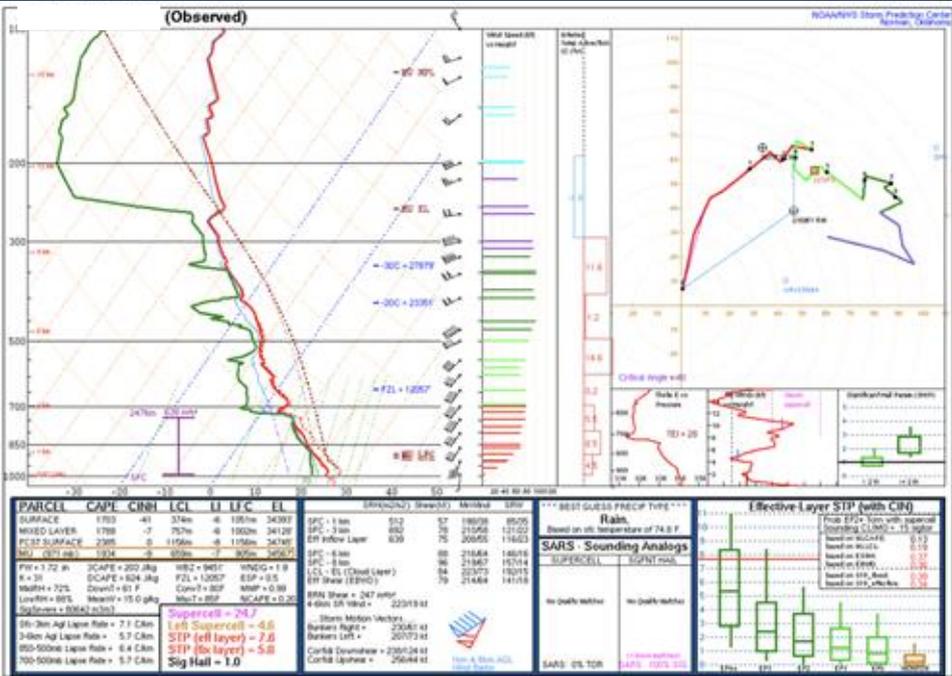




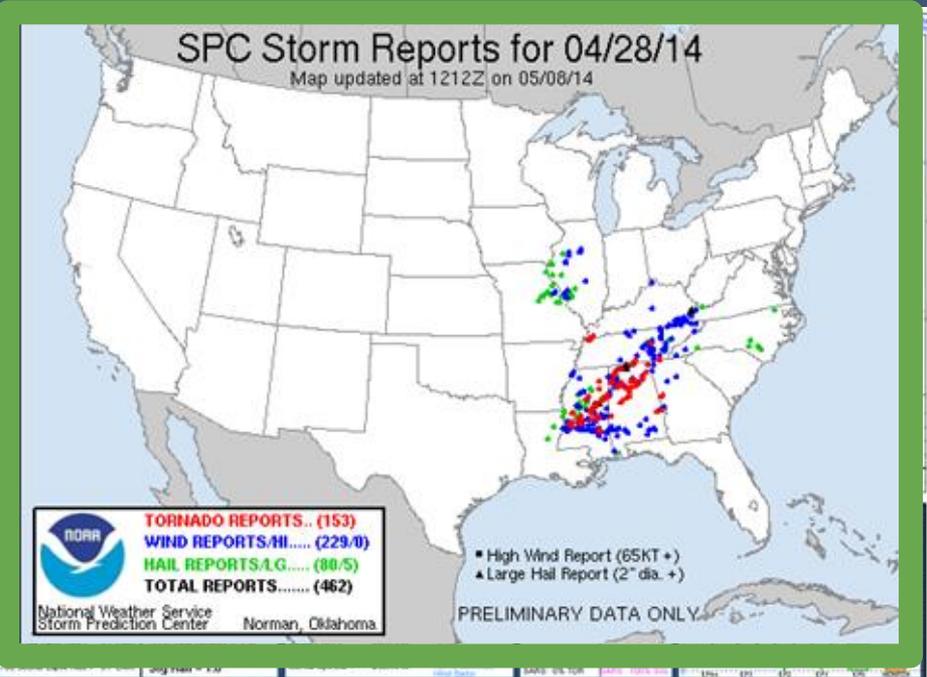


# A

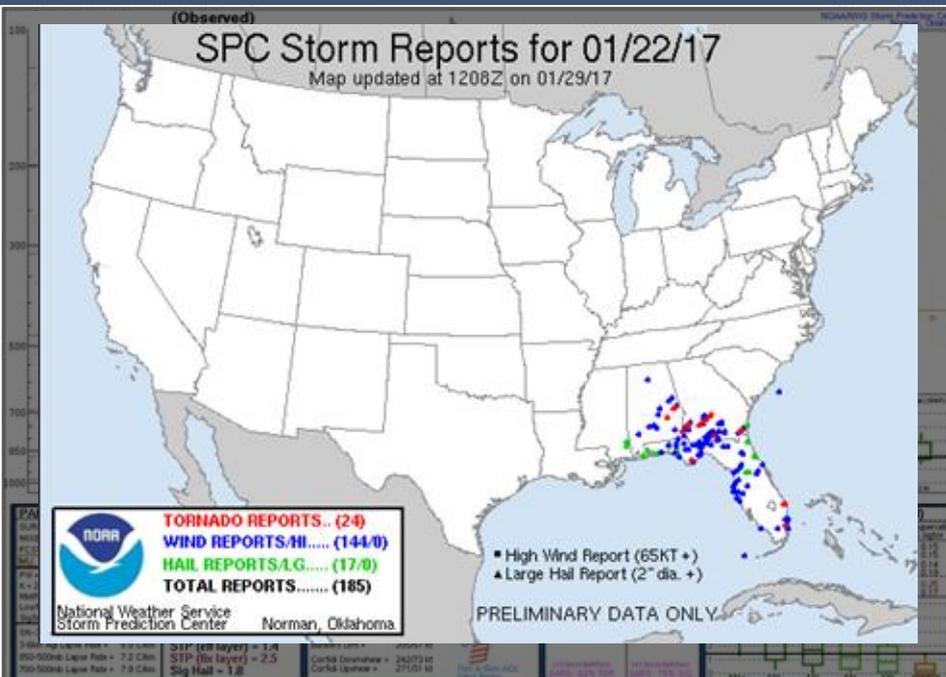
# B



# A



# B

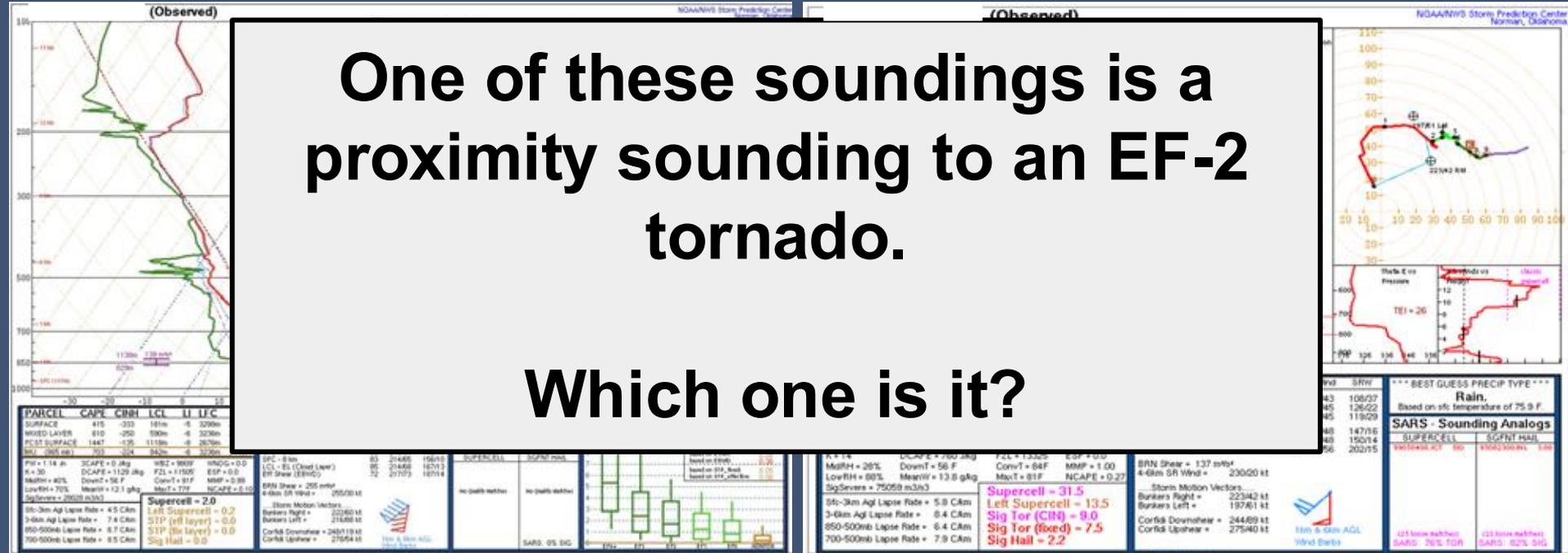


# A

# B

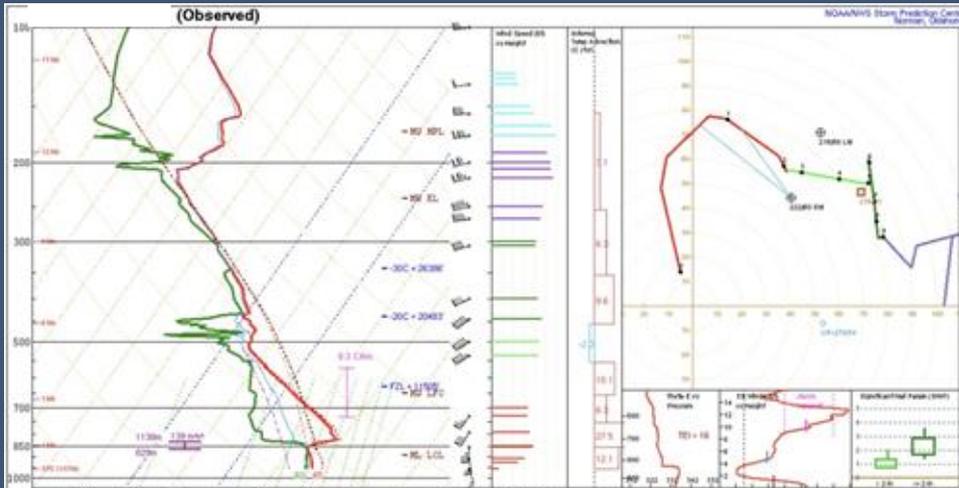
One of these soundings is a proximity sounding to an EF-2 tornado.

Which one is it?



# A

# B



IPARCEL	CAPE	CIN	LCL	LI	LFC	EL
SURFACE	415	-333	181m	-6	3200m	24004
MIXED LAYER	810	-250	500m	-6	3236m	28074
FCST SURFACE	1447	-175	1115m	-8	2670m	30042
MU (950 mb)	703	-243	843m	-4	3230m	34010

PARM	VAL	UNIT
PW	1.13 in	
K	14	
MdRH	40%	
LowRH	70%	
SigSevere	20029	mbh3

PARAM	VAL	UNIT
3-6m Agl Lapse Rate	4.5	C/m
3-6m Agl Lapse Rate	7.8	C/m
850-500mb Lapse Rate	6.7	C/m
500-500mb Lapse Rate	8.5	C/m

PARAM	VAL	UNIT
SFC - 1 km	1077	g/kg
SFC - 3 km	1118	g/kg
SFC - 6 km	129	g/kg
SFC - 8 km	89	g/kg
SFC - 10 km	83	g/kg
SFC - 12 km	82	g/kg
SFC - 14 km	72	g/kg

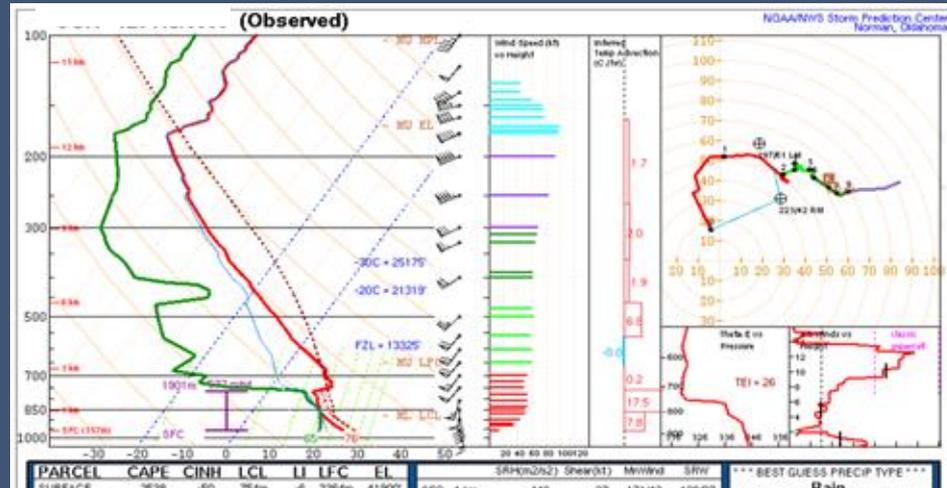
PARAM	VAL	UNIT
Storm Motion Vectors		
Bunkers Right	22380	kt
Bunkers Left	21689	kt
Corb'd Downshear	248119	kt
Corb'd Upshear	27554	kt

PARAM	VAL	UNIT
Storm Motion Vectors		
Bunkers Right	22342	kt
Bunkers Left	19761	kt
Corb'd Downshear	24489	kt
Corb'd Upshear	27540	kt

PARAM	VAL	UNIT
Storm Motion Vectors		
Bunkers Right	22342	kt
Bunkers Left	19761	kt
Corb'd Downshear	24489	kt
Corb'd Upshear	27540	kt



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Storm Motion Vectors		
Bunkers Right	22342	kt
Bunkers Left	19761	kt
Corb'd Downshear	24489	kt
Corb'd Upshear	27540	kt

# A

# B

SPC Filtered Storm Reports for 02/26/23  
Map updated at 1942Z on 02/26/23

SPC Filtered Storm Reports for 04/14/12  
Map updated at 1212Z on 04/24/12

The point: parameters will only take you so far!  
You need to know additional information about warm sector shape, residence time, storm mode, etc...  
to successfully anticipate the outcomes.

**TOTAL REPORTS..... (188)**  
National Weather Service  
Storm Prediction Center  
Norman, Oklahoma

▲ Large Hail Report (2" dia. +)  
PRELIMINARY DATA ONLY

**TOTAL REPORTS..... (344)**  
National Weather Service  
Storm Prediction Center  
Norman, Oklahoma

▲ Large Hail Report (2" dia. +)  
PRELIMINARY DATA ONLY

850-500mb Lapse Rate = 6.4 C/km    **Sig Top (fixed) = 7.5**  
700-500mb Lapse Rate = 7.9 C/km    **Sig Hail = 2.2**  
Lifted Lapse/Rate = 27540 ft    10m 3-5m AGL Wind Shear  
425 Snow Water    425 Snow Water  
SARS: 76% Snow    SARS: 62% Sig

# Importance of Vertical Shear

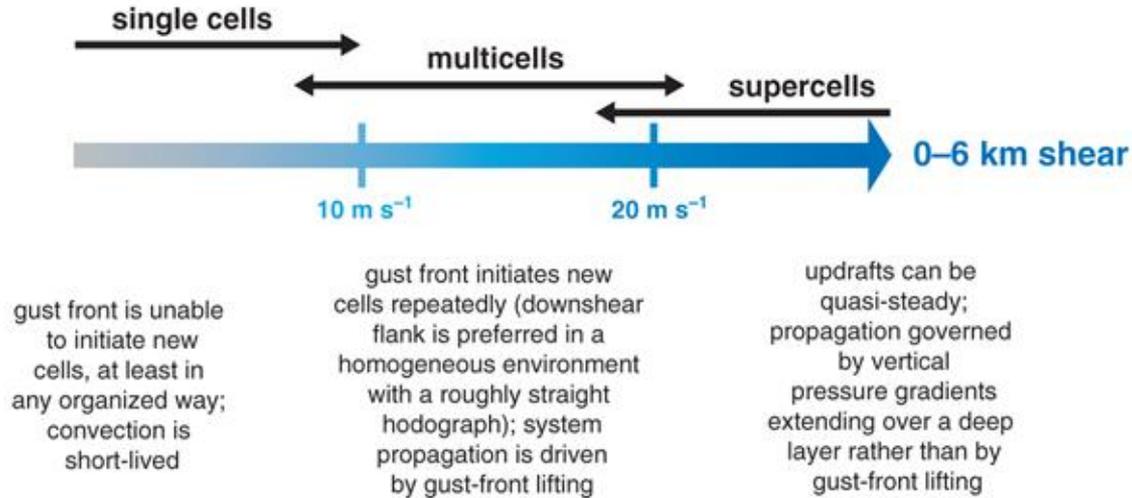
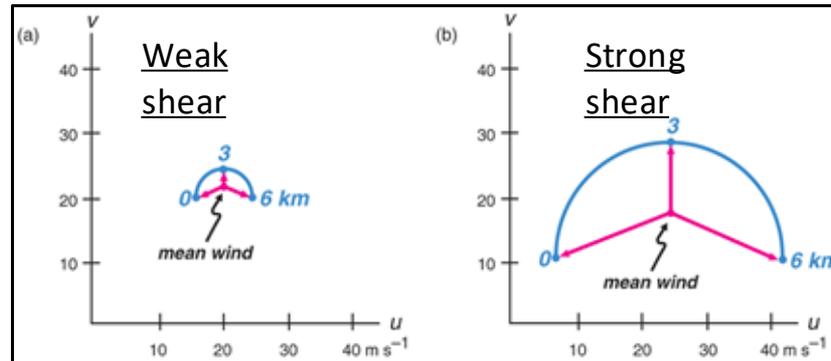


Figure 8.5

Spectrum of storm types as a function of vertical wind shear. Although the vertical shear exerts the greatest influence on storm type, other secondary factors can also affect the mode of convection (e.g., vertical distribution of buoyancy, moisture, and shear, as well as the means by which storms are initiated); thus, some overlap among storm types exists in this simple single-parameter depiction. The relationship between vertical wind shear magnitudes and the nature of cell regeneration/propagation is also shown. MR (2010)

# Importance of Vertical Shear

- Interference between precipitation and updraft is reduced as vertical shear increases
- Precipitation falls downwind of updraft
  - Strong storm-relative winds aloft blows precipitation away from updraft core
- Storm-relative inflow at low-levels can slow speed of gust front, limiting its ability to undercut updraft
- Dynamic pressure effects via vertical PGF in shear can produce strong lifting



MR (2010), Fig. 8.2

# Ordinary Thunderstorm (single cell)

- Consists of one updraft, outflow gust front spreads in all directions
- Forms in weak shear and modest CAPE, in weak synoptic forcing and typically occur just after max daytime heating
- Pulse severe possible (wind, hail)

- Lifetime approximated as  $\tau = \frac{H}{w_0} + \frac{H}{v_t}$

$$\tau = \frac{10^4 \text{ m}}{10 \text{ m s}^{-1}} + \frac{10^4 \text{ m}}{10 \text{ m s}^{-1}} = 10^3 \text{ s} + 10^3 \text{ s} = 2000 \text{ s} = 30 \text{ min}$$

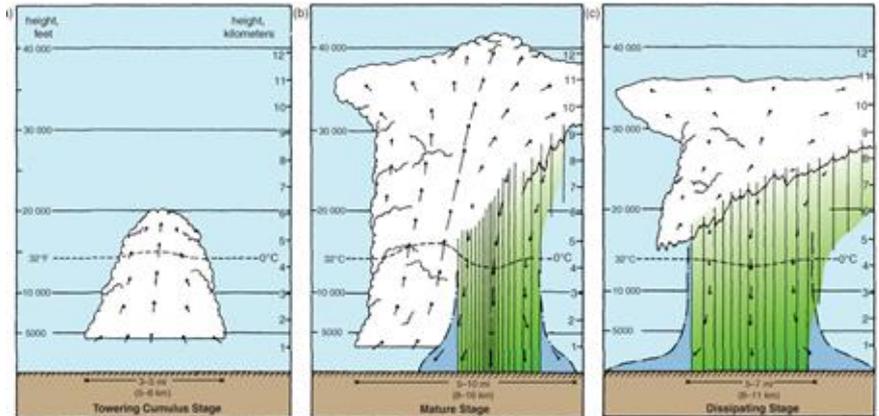
H=scale height

$w_0$ =average updraft speed

$v_t$ =terminal velocity of precipitation

- Life cycle:

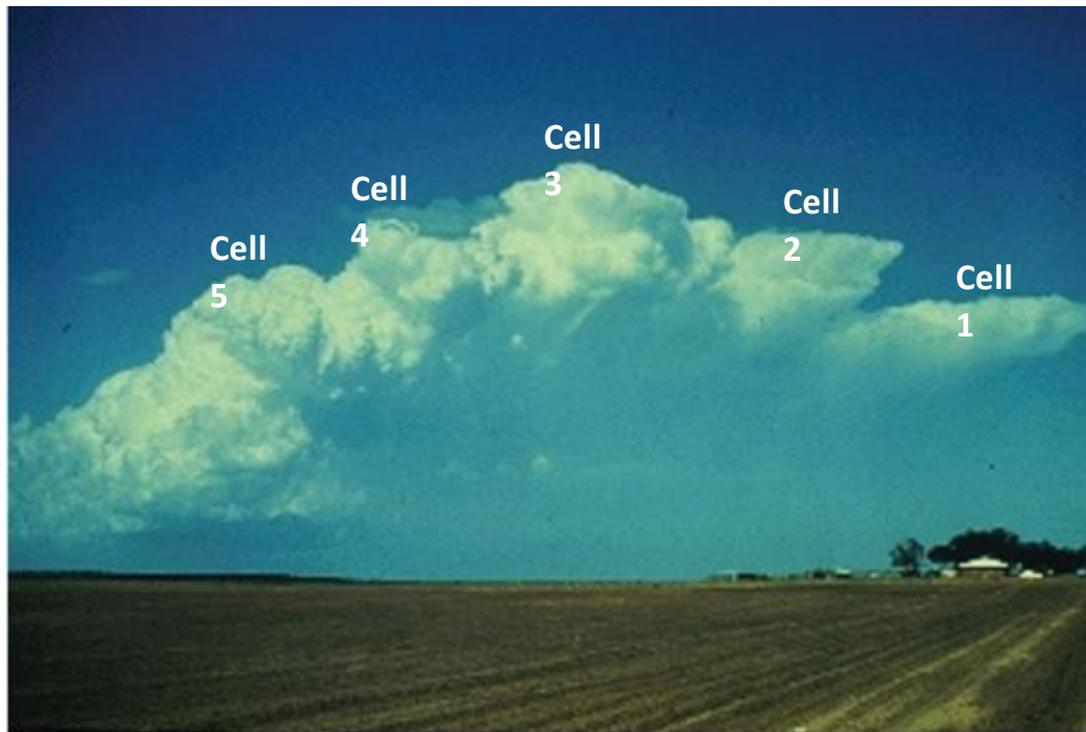
- Towering cumulus (only updraft)
- Mature (precipitation falls into updraft, downdraft and gust front forms, anvil forms)
- Dissipating stage (downdraft cuts off updraft; orphan anvil)



MR (2010), Fig.

# Multicell Convection

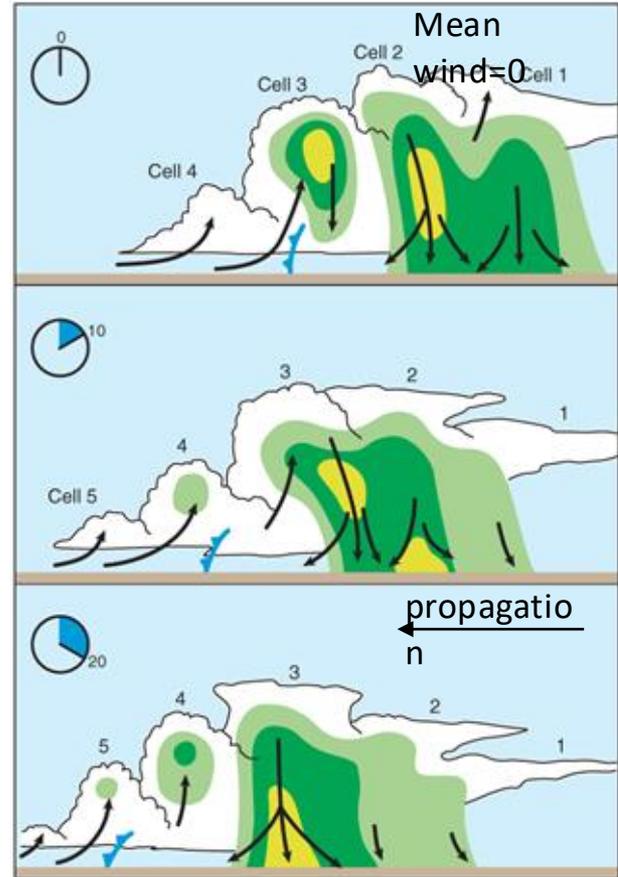
- Characterized by repeated development of new cells along the gust front
- Longer-lived cluster of storms in moderate vertical shear and small to large CAPE
- Individual storms in cluster may be ordinary, lasting 30-60 mins
- In high CAPE moderate shear, multicell convection can produce swaths of damaging winds and hail



MR (2010), Fig.

# Evolution of Multicell Convection

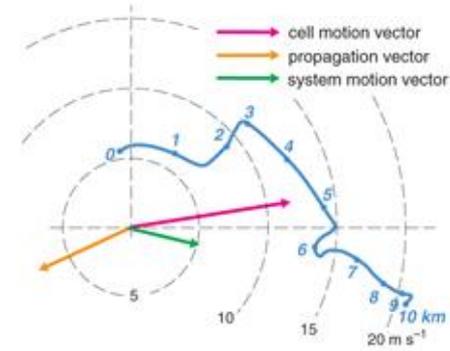
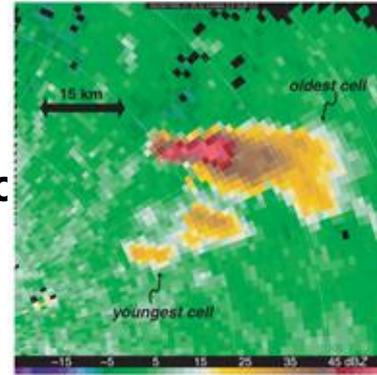
- Individual cells move with the mean wind averaged over their depth
- New cells initiate along gust front
- @ Time 0:
  - Cell 1 – dissipative stage
  - Cell 2 – mature stage
  - Cell 3 – precipitation beginning to form
  - Cell 4 – towering cumulus stage
- @ Time 10:
  - Cell 1 – orphan anvil
  - Cell 2 – dissipative stage
  - Cell 3 – mature stage
  - Cell 4 – precipitation beginning to form
  - Cell 5 – towering cumulus stage
- @ Time 20: ...and so on.



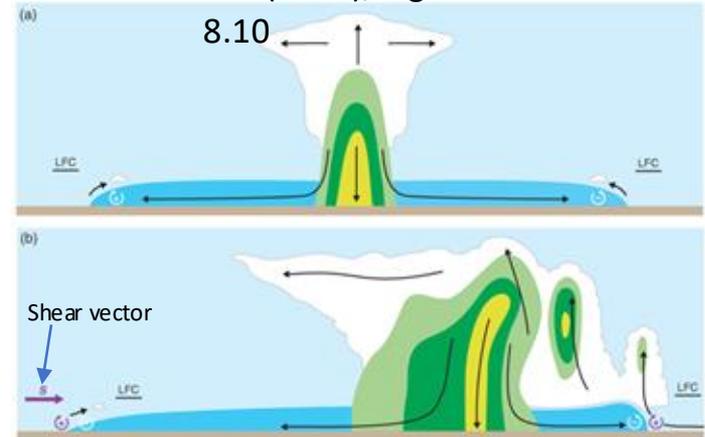
MR (2010), Fig.

# Movement versus propagation

- Individual cells move with the mean wind
- Repeated development of new cells on flank of system leads to propagation of system
- Total motion is cell motion+propagation
- New cells develop on gust front on downshear side of cold pool
- Will cover more of this with MCS motion later



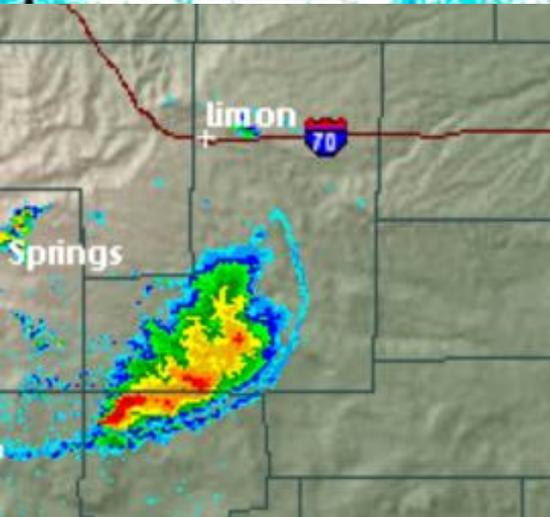
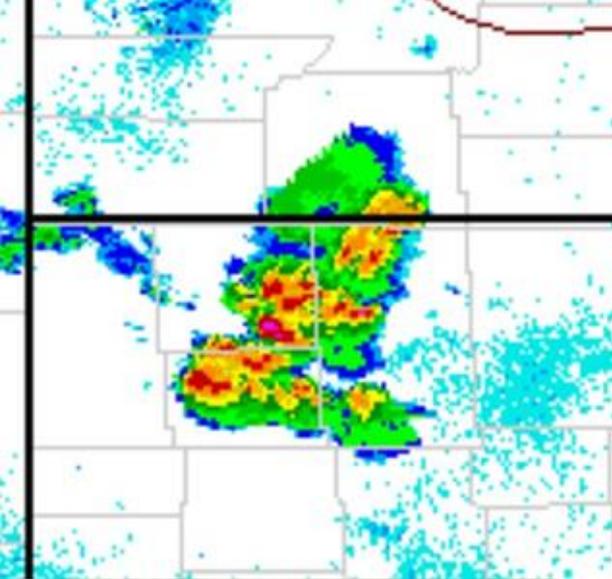
MR (2010), Fig.

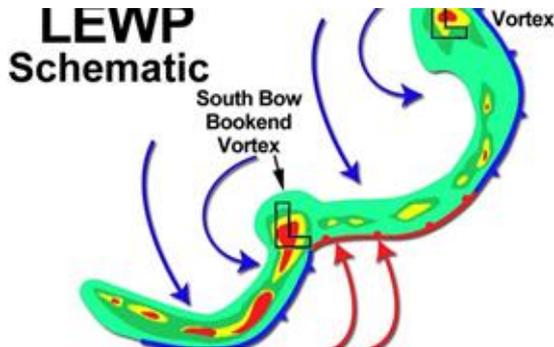


MR (2010), Fig.

# Multi Cell Clusters

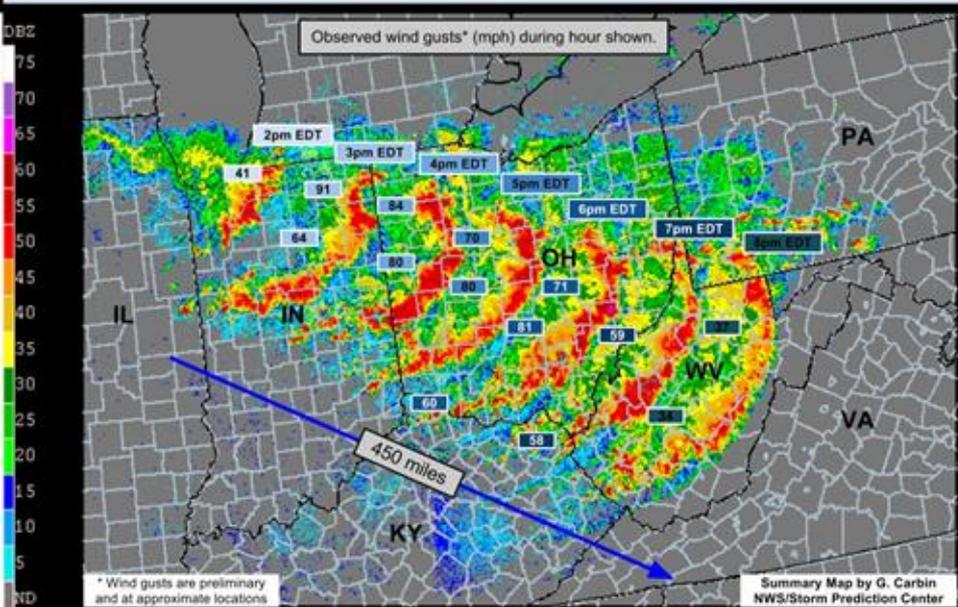
- Aggregates of multi-cell storms are common over parts of the Southeast in the summer. Each storm can be in a different phase of the life cycle.
- Can act as a loosely organized MCS or as vague as a large convective blob.
- Forcing is usually weak and the primary risk is damaging outflow winds from collapsing storms but can also produce hail.





# Squall Lines/Mesoscale Convective Systems (MCS)

June 29, 2012 Midwest/Ohio Valley Derecho  
 Radar Imagery Composite Summary 18-00 UTC  
 ~450 miles in 6 hours / Average Speed ~75 mph



- Storm self-propagation dominated by cold pool driven ascent.
- Can take multiple forms
  - Serial MCS
  - Progressive MCS
  - LEWPs (line echo wave patterns)
  - Bow echos
  - Derechos
- Usually more organized than clusters with stronger vertical shear.
- Can produce Damaging wind gusts tornadoes and some hail.

# Supercells

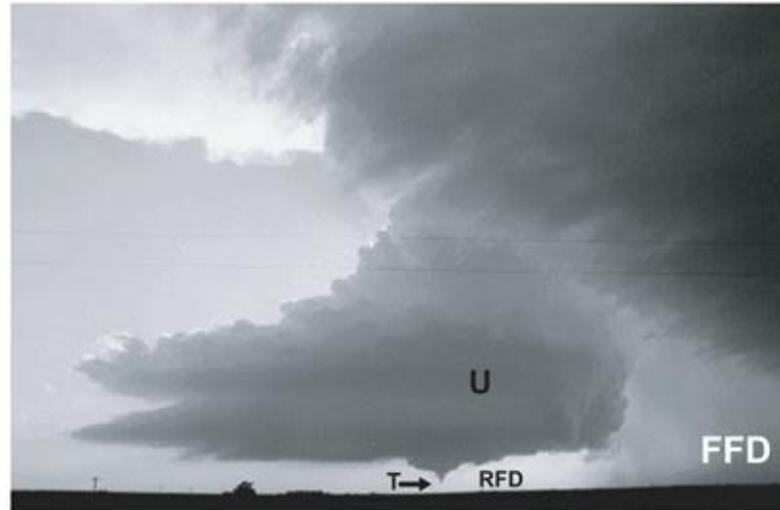
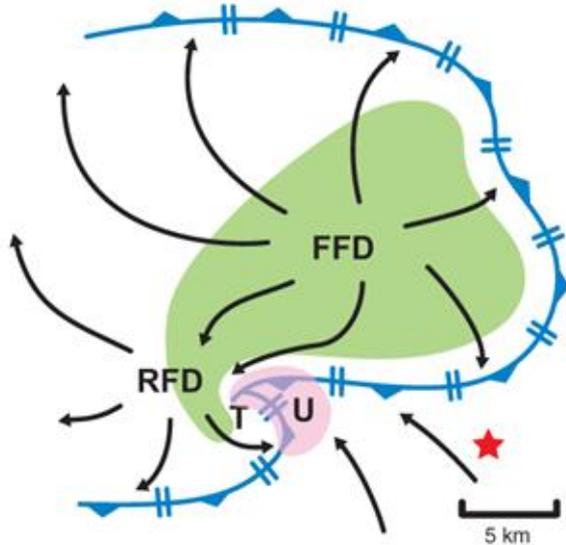
- **Characterized by a thunderstorm with a sustained, deep, rotating updraft  $\Rightarrow$  mesocyclone**
- **Occur in strong vertical shear through a deep layer (big storm-relative winds), but high CAPE not necessary**
- **Motion deviates significantly from mean wind**
- **Vertical PGF enhances updraft, a special property of supercells**



MR (2010), Fig.  
8.17

# Supercell Features

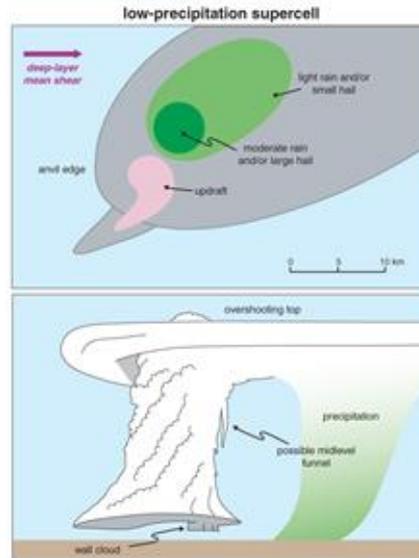
- Single, long-lived, quasi-steady, rotating, precipitation free, updraft
- Wall cloud at updraft base where humid, rain-cooled air drawn upward
- Two downdraft regions: rear flank downdraft (RFD) and forward flank downdraft (FFD)



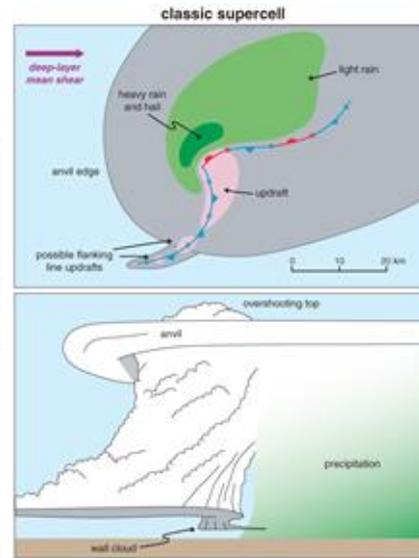
MR (2010), Fig.

# Supercell Types

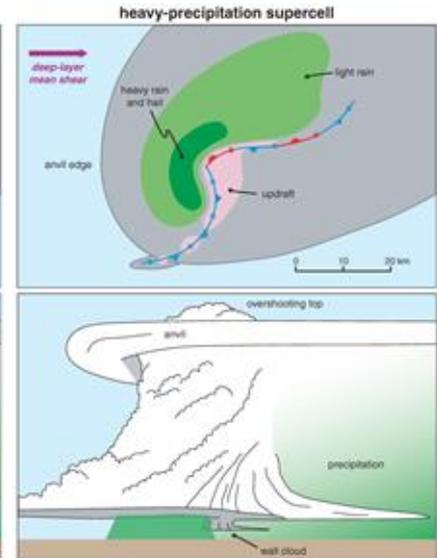
- For isolated storms, supercell type is (maybe) a function of storm-relative winds (SRW) at level of anvil (9–12 km AGL)
- Weak upper-level storm-relative winds (<18 m/s): **HP**; moderate (18-28 m/s): **classic**; strong (>28 m/s): **LP**
- For multiple storms in close proximity, precipitation from one storm may seed another storm, favoring **HP** types
- Stronger SRW favors larger updrafts resistant to entrainment.



MR (2010), Fig.

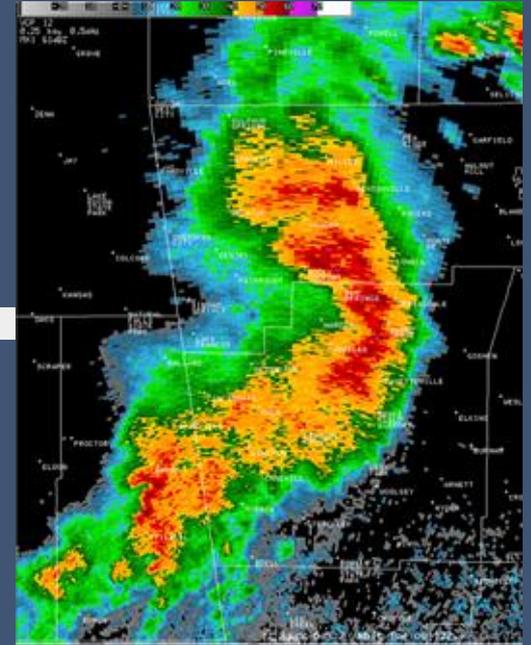
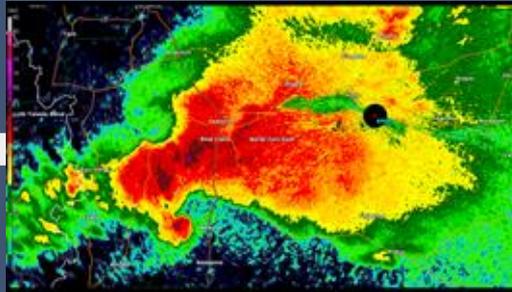
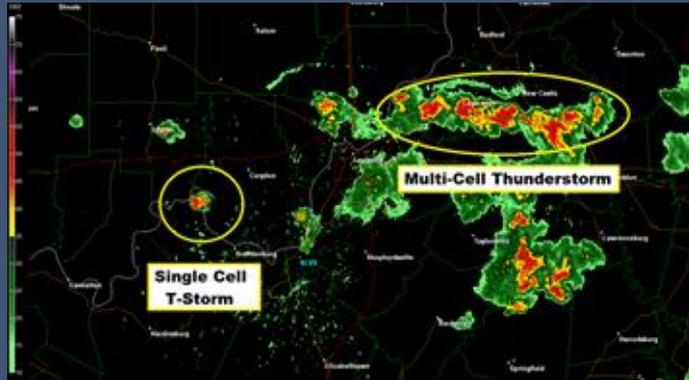


MR (2010), Fig.



MR (2010), Fig.

# Storm Mode Spectrum



How do we anticipate the storm mode?

# Storm Mode Basics

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping



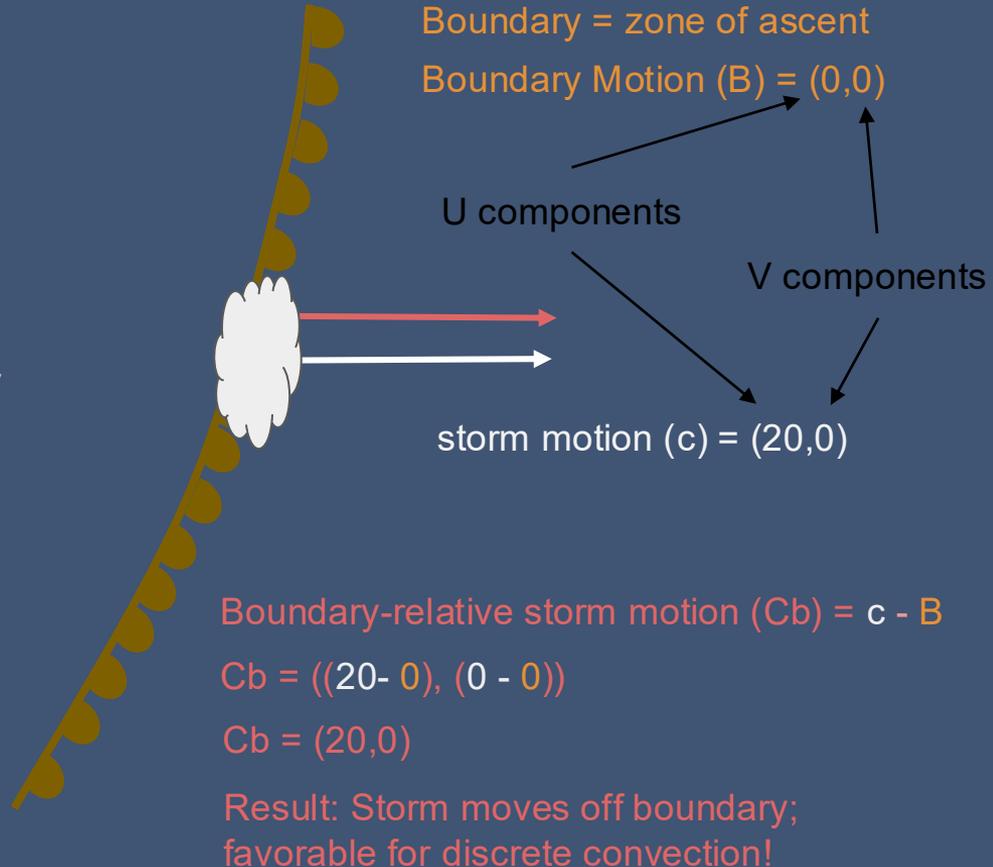
All of these must be taken into account to anticipate storm mode for the first few hours after convective initiation.

Numerous combinations are possible!

# Storm Mode Basics

Consider each of these:

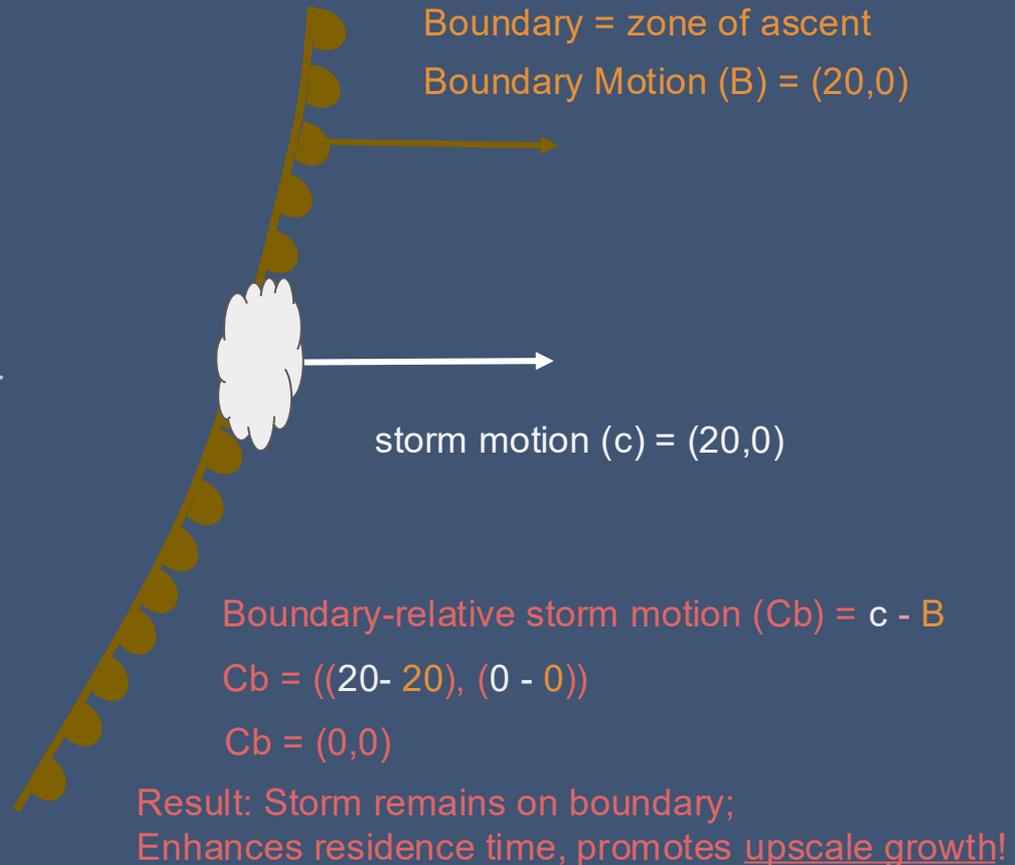
- 1) **Boundary-relative storm motion**
- 2) Boundary-relative deep-layer shear
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- 4) Strength of forcing for ascent
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# Storm Mode Basics

Consider each of these:

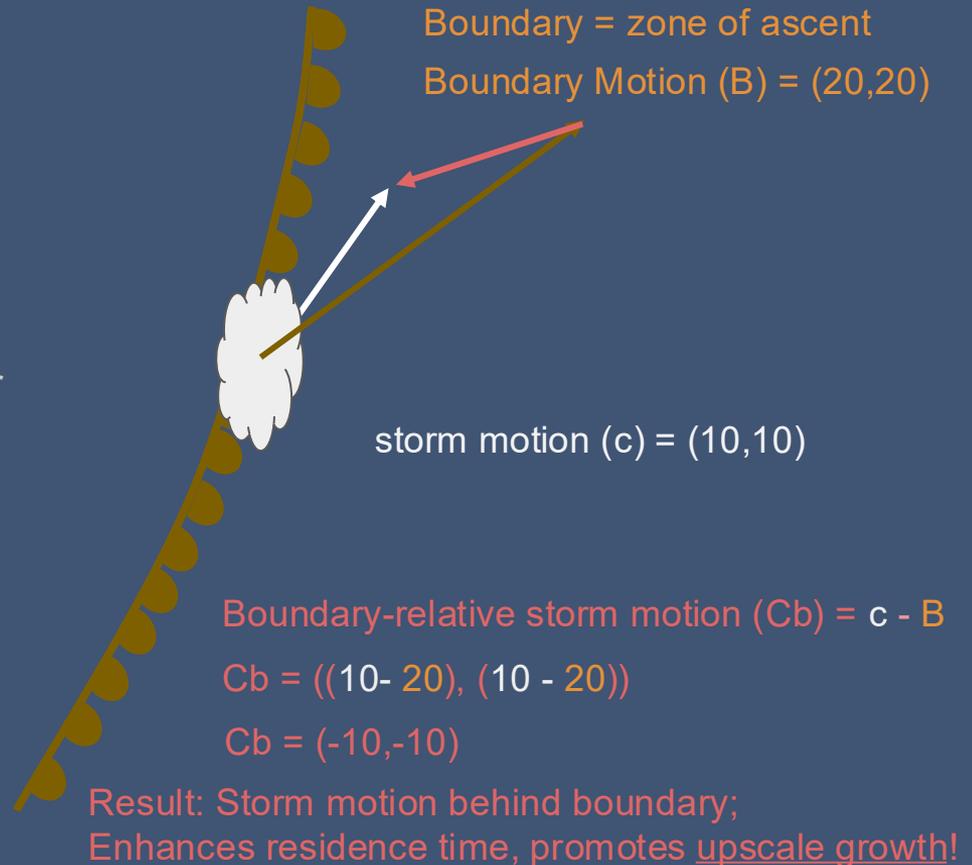
- 1) **Boundary-relative storm motion**
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
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# Storm Mode Basics

Consider each of these:

- 1) **Boundary-relative storm motion**
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping



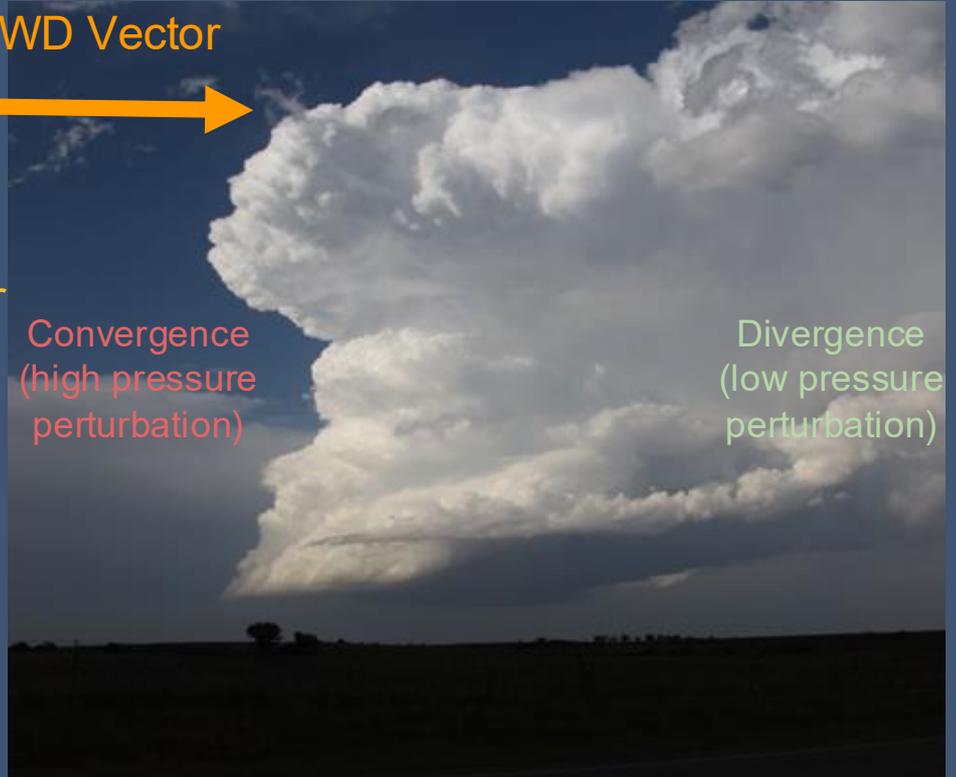
# Storm Mode Basics

## Downshear Pressure Perturbation

Consider each of these:

- 1) Boundary-relative storm motion
- 2) **Boundary-relative deep-layer shear**
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping

Effective BWD Vector



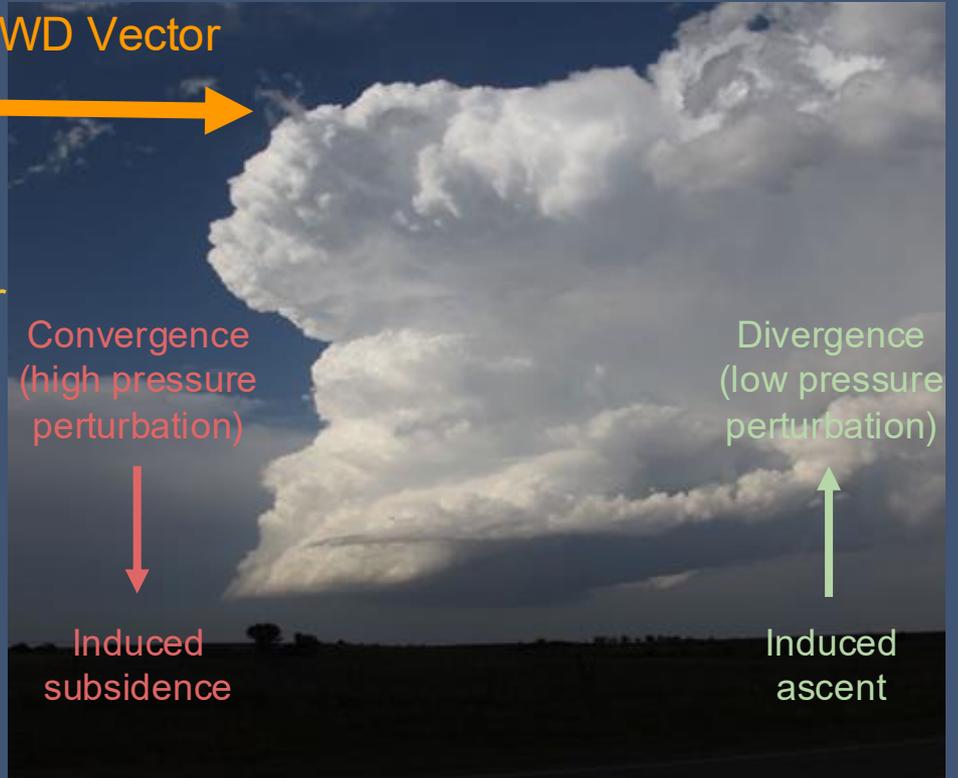
# Storm Mode Basics

## Downshear Pressure Perturbation

Consider each of these:

- 1) Boundary-relative storm motion
- 2) **Boundary-relative deep-layer shear**
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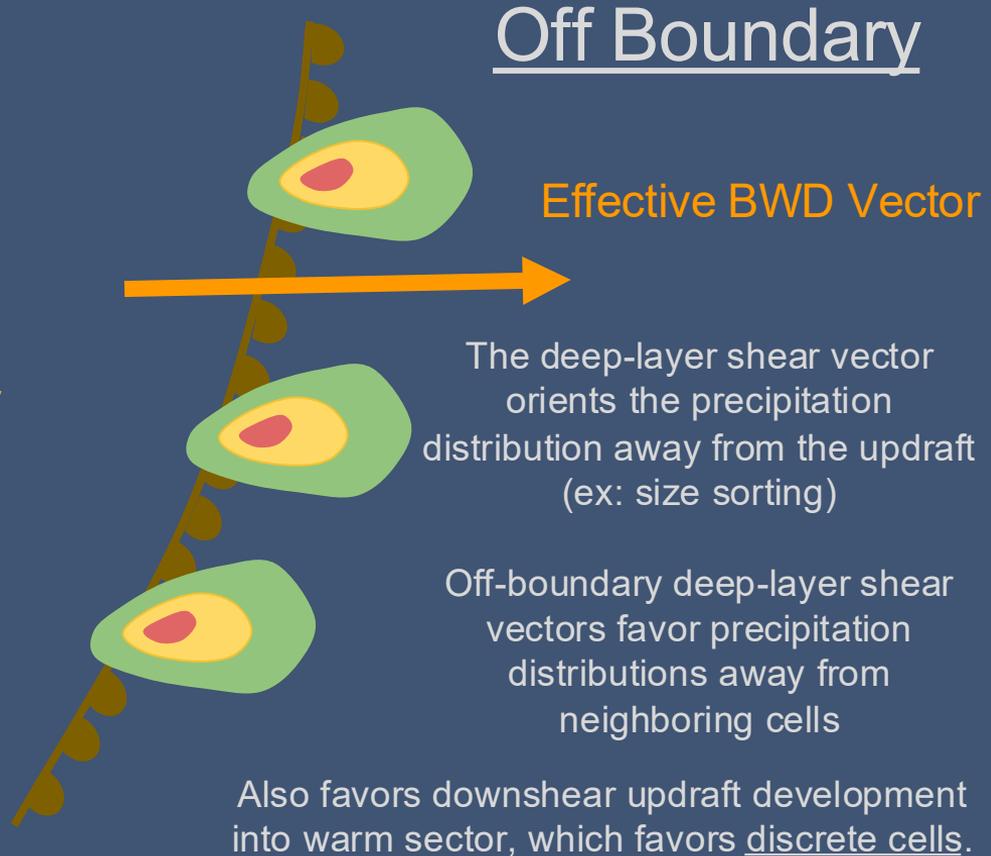
Effective BWD Vector



# Storm Mode Basics

Consider each of these:

- 1) Boundary-relative storm motion
- 2) **Boundary-relative deep-layer shear**
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping

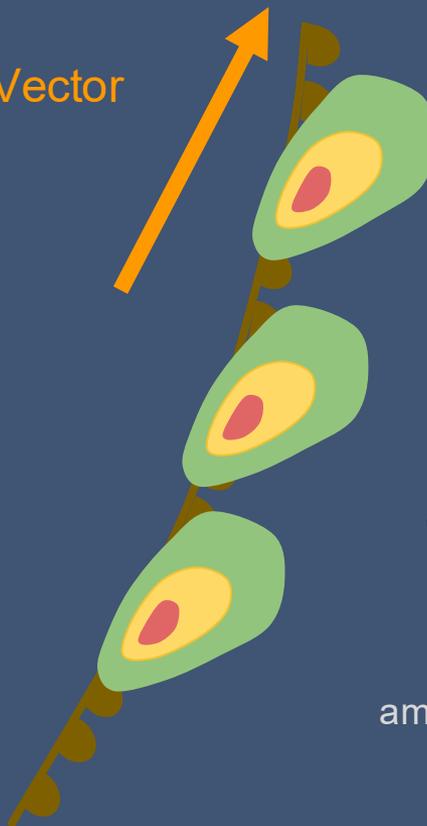


# Storm Mode Basics

Effective BWD Vector

Consider each of these:

- 1) Boundary-relative storm motion
- 2) **Boundary-relative deep-layer shear**
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping



## Along Boundary

Deep-layer shear vectors along the boundary favor precipitation (and outflow/cold pool) distributions towards the updraft regions of neighboring storms.

Also favors downshear updraft development in close proximity to neighboring storms.

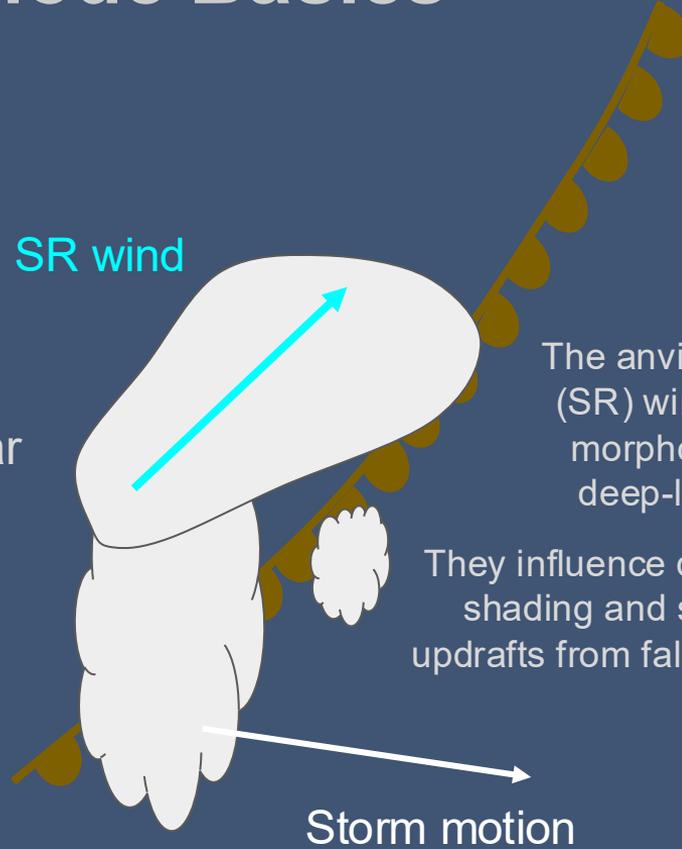
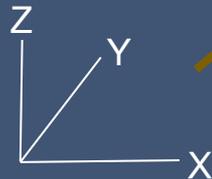
This tends to favor cold pool amalgamation and upscale growth.

# Storm Mode Basics

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) **Storm-relative anvil-level winds**
- 4) Strength of forcing for ascent
- 5) Strength of capping

Anvil-level SR wind



The anvil-level storm relative (SR) winds influence storm morphology similar to the deep-layer shear vector.

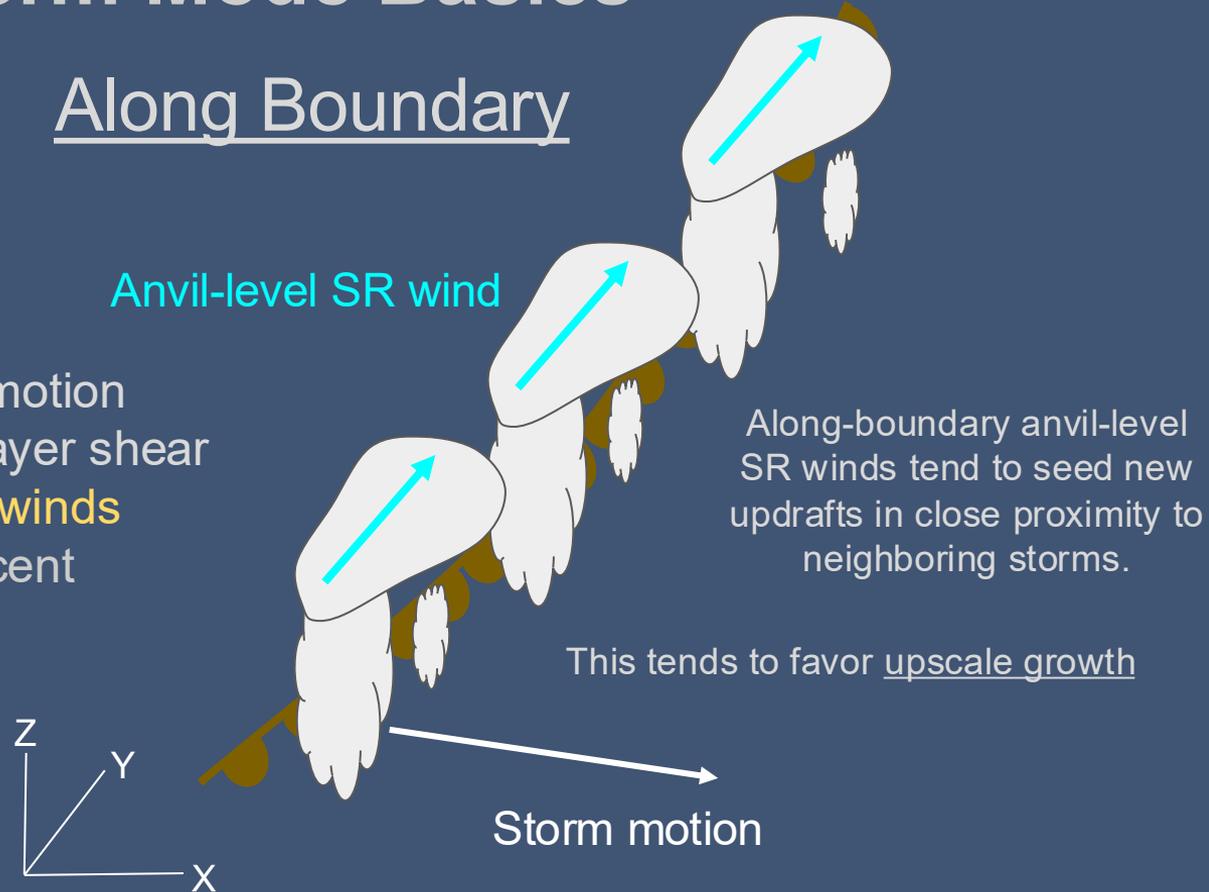
They influence downstream anvil shading and seeding of new updrafts from fallout hydrometeors

# Storm Mode Basics

## Along Boundary

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) **Storm-relative anvil-level winds**
- 4) Strength of forcing for ascent
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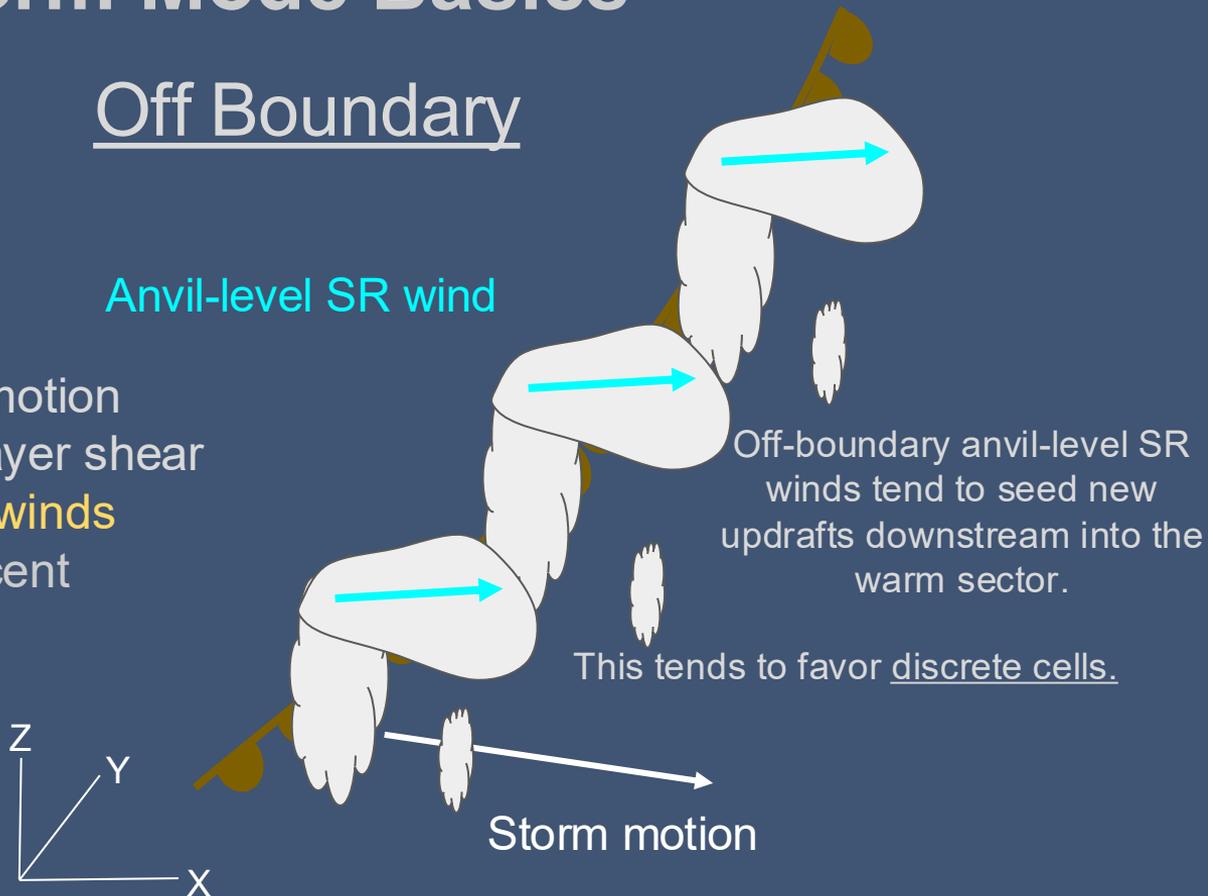
# Storm Mode Basics

## Off Boundary

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) **Storm-relative anvil-level winds**
- 4) Strength of forcing for ascent
- 5) Strength of capping

Anvil-level SR wind



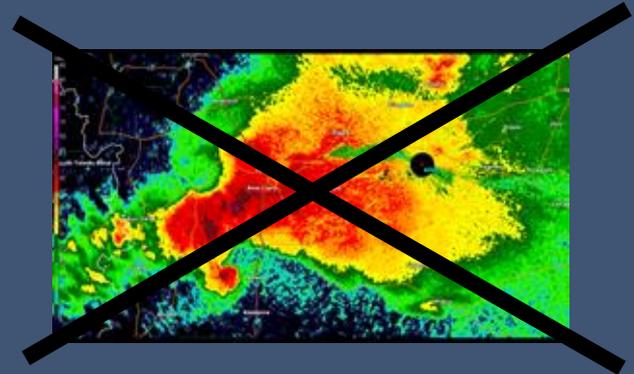
# Storm Mode Basics

No Lift?

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) **Strength of forcing for ascent**
- 5) Strength of capping

No storms!



# Storm Mode Basics

## Weak Ascent

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) **Strength of forcing for ascent**
- 5) Strength of capping



Fewer initial cells, greater spacing between cells,  
less chance of storm interactions  
(even if shear/anvil-level winds aren't favorable)

This tends to favor discrete cells.

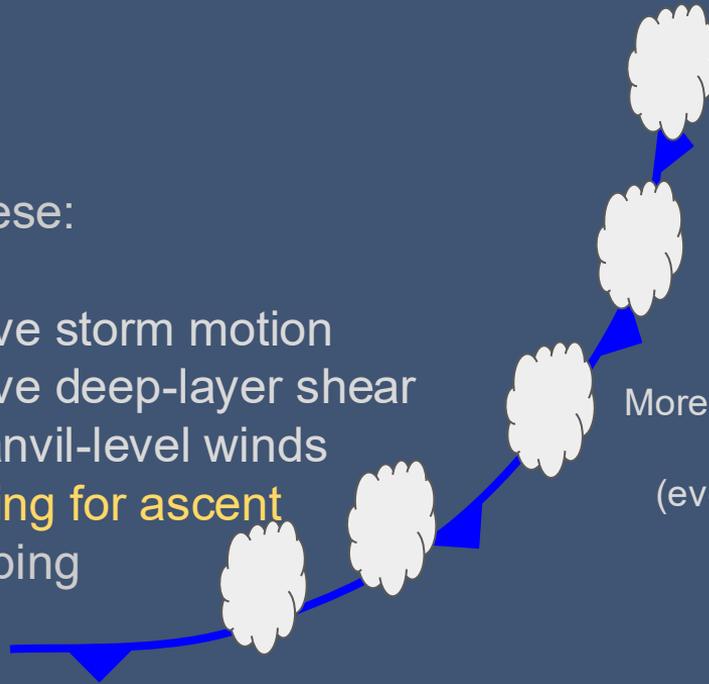
Weak forcing mechanisms:  
Drylines  
Weak outflow boundaries  
Confluence axes

# Storm Mode Basics

## Strong Ascent

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) **Strength of forcing for ascent**
- 5) Strength of capping



More initial cells, smaller spacing between cells, higher chance of storm interactions (even if boundary-relative storm motions are favorable for discrete)

This tends to favor upscale growth.

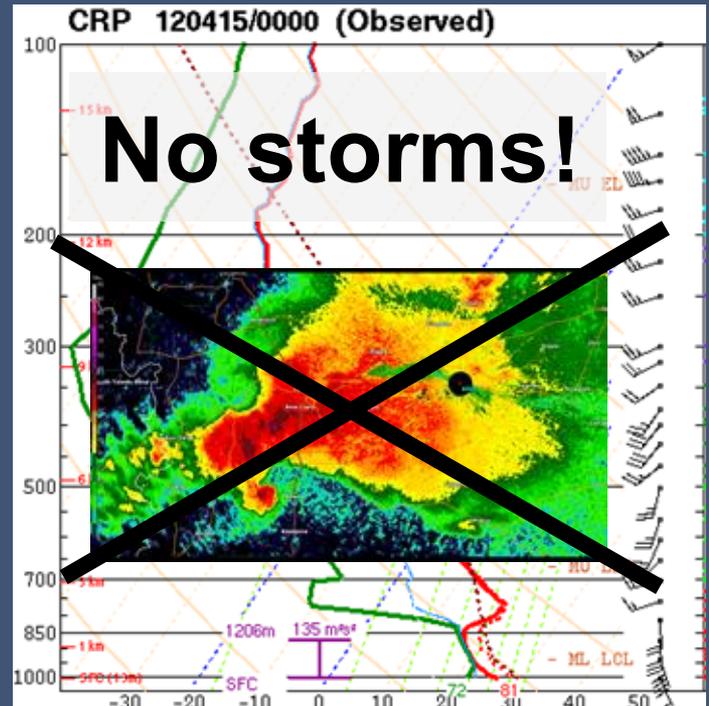
Strong forcing mechanisms:  
Surging cold fronts  
Strong outflow boundaries

# Storm Mode Basics

“Nuclear” cap?

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping

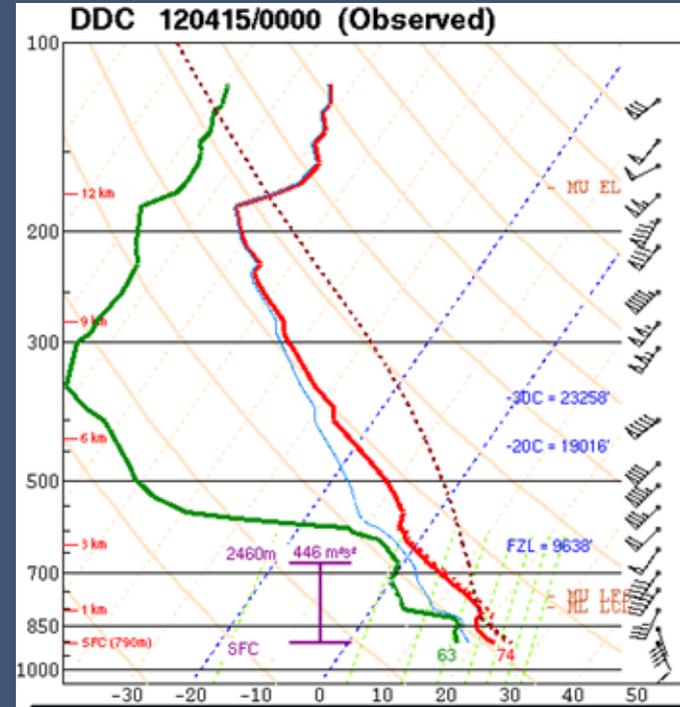


# Storm Mode Basics

## Weak cap?

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) **Strength of capping**



Limits number of initial storms: favorable for discrete cells

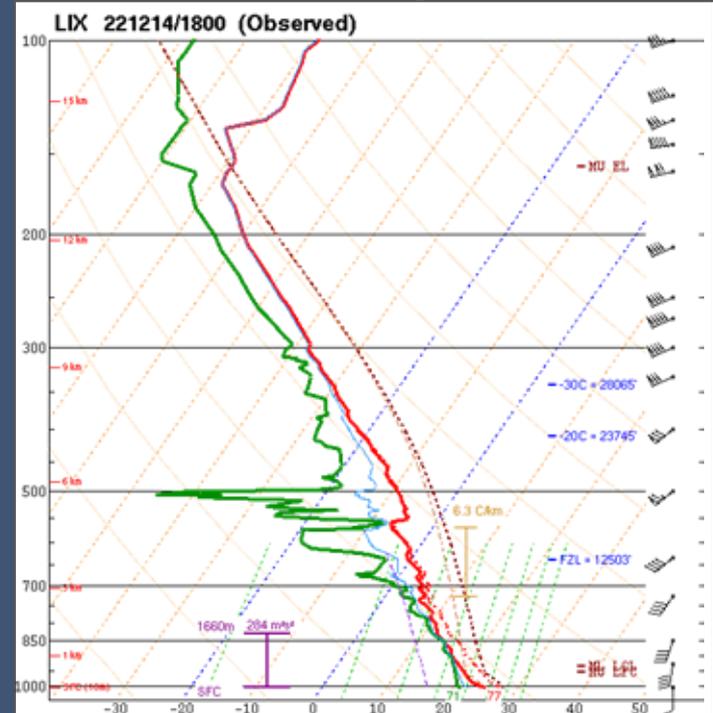
# Storm Mode Basics

## No cap?

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) **Strength of capping**

Remember: numerous combinations are possible!



Allows for numerous storms, favors upscale growth

# Storm Mode Basics

Consider each of these:

- 1) Boundary-relative storm motion
- 2) Boundary-relative deep-layer shear
- 3) Storm-relative anvil-level winds
- 4) Strength of forcing for ascent
- 5) Strength of capping

How do I weight each of these factors?

# Storm Mode Basics

Consider each of these:

Primary influencing factor

1) Strength of forcing for ascent

2) Boundary-relative storm motion

3) Boundary-relative deep-layer shear

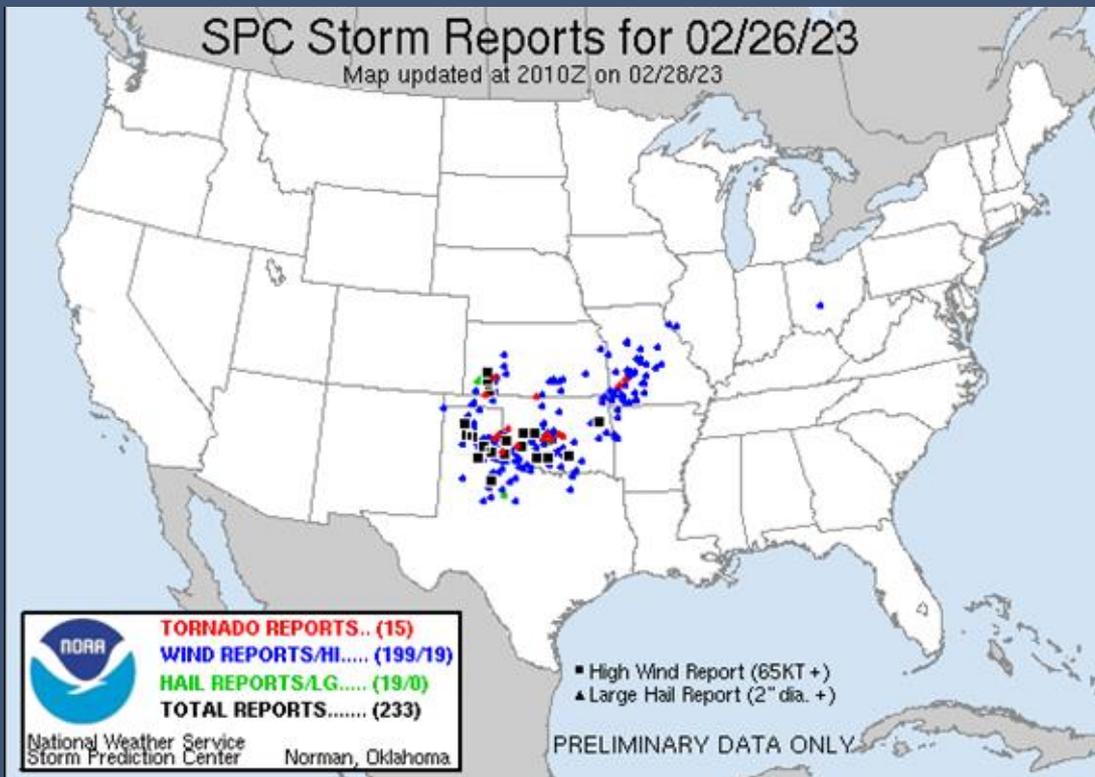
4) Storm-relative anvil-level winds

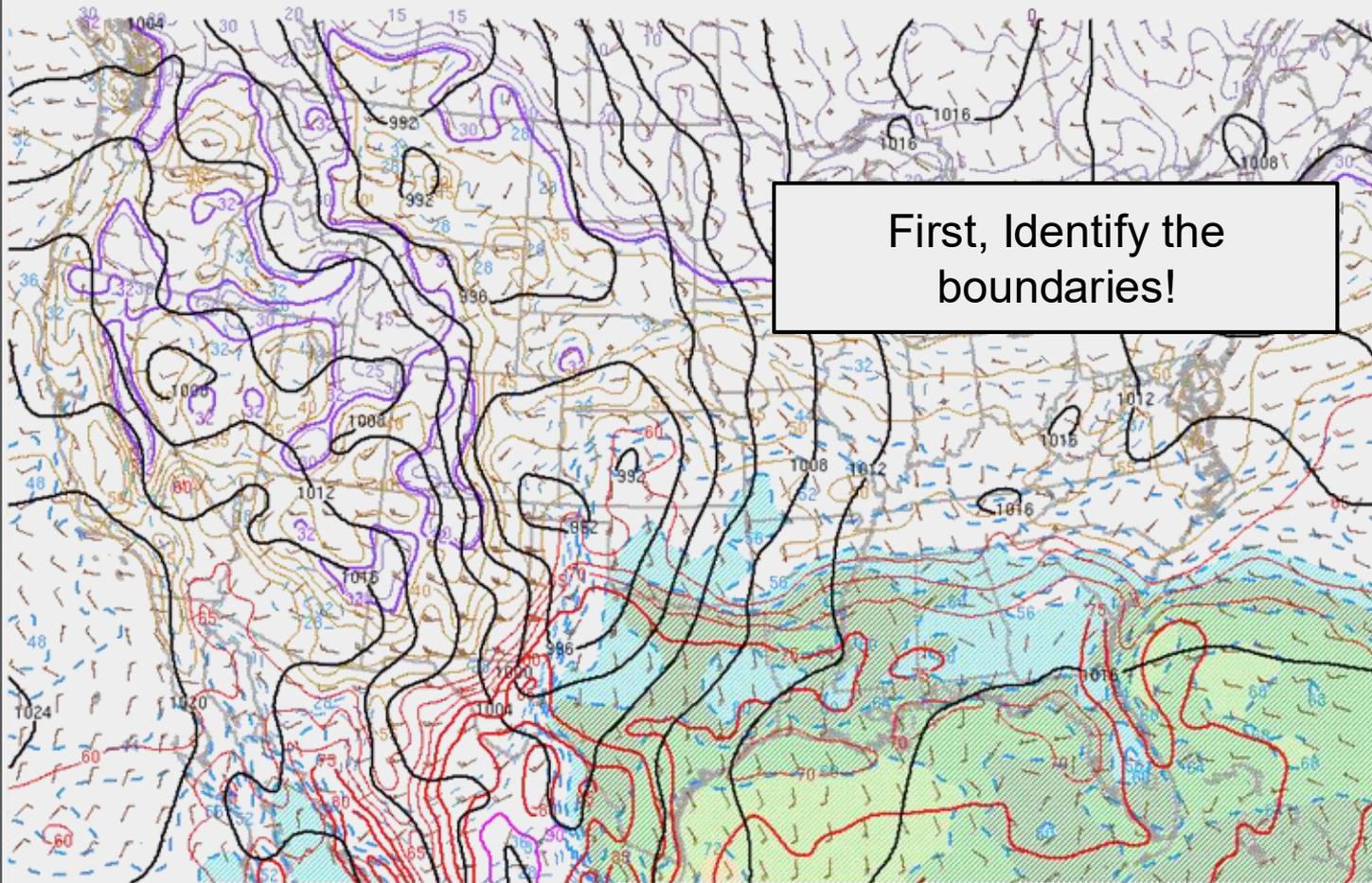
5) Strength of capping

Secondary influencing factors

Modulating factor

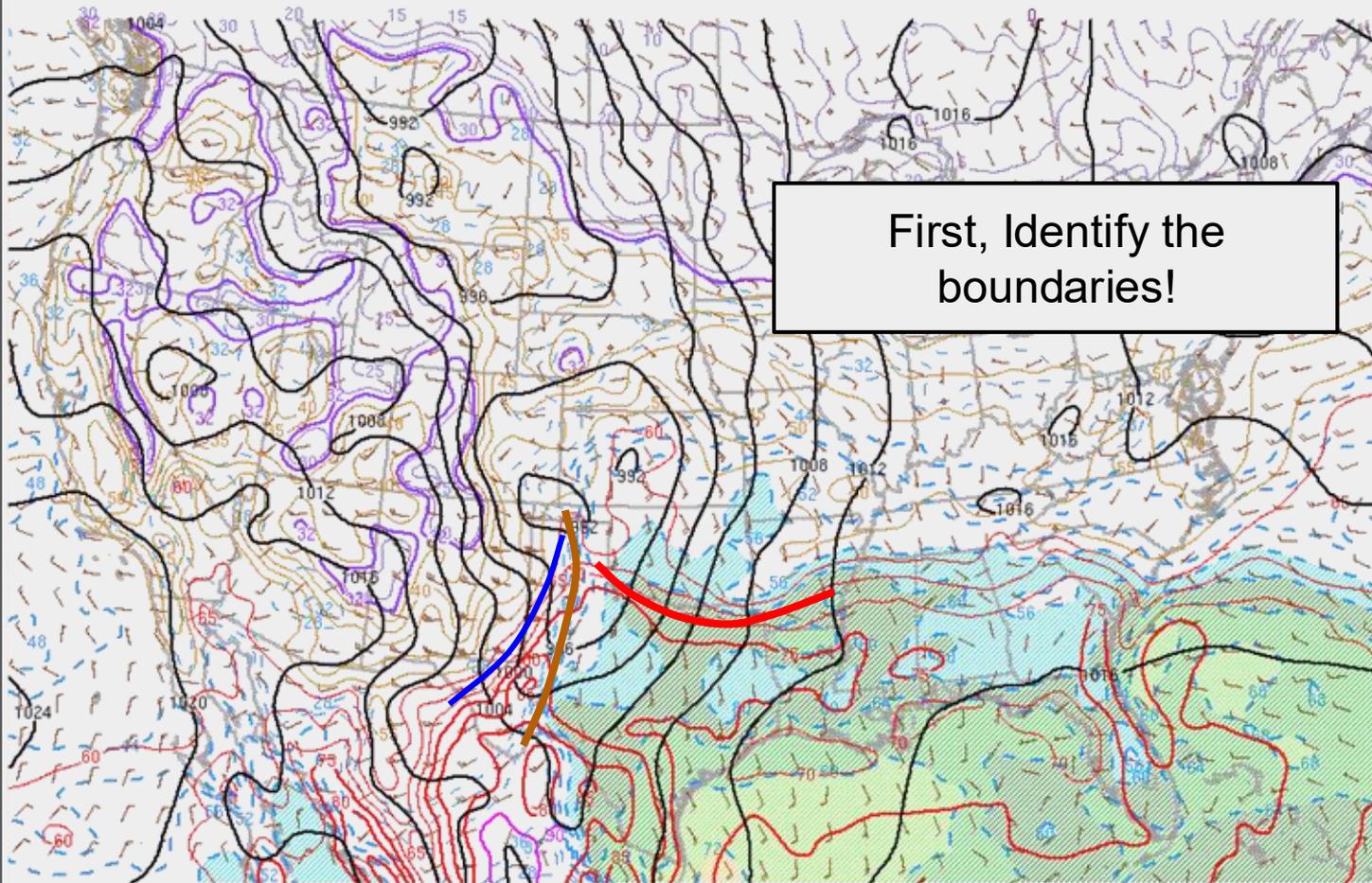
# Storm Mode Basics: Quick Example





230227/0000 Surface temp, dewpoint, and pmsl



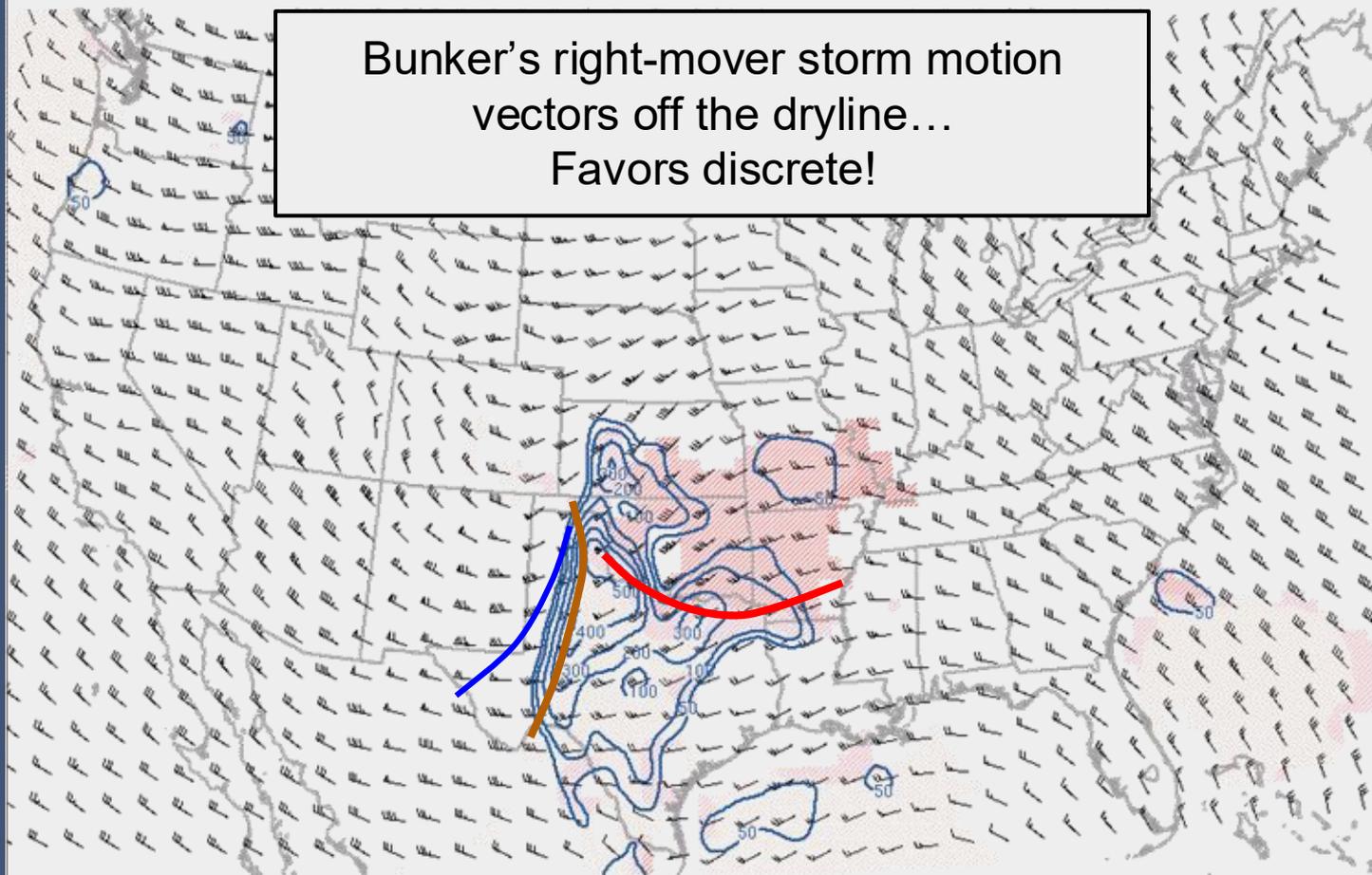


First, Identify the boundaries!

230227/0000 Surface temp, dewpoint, and pmsl

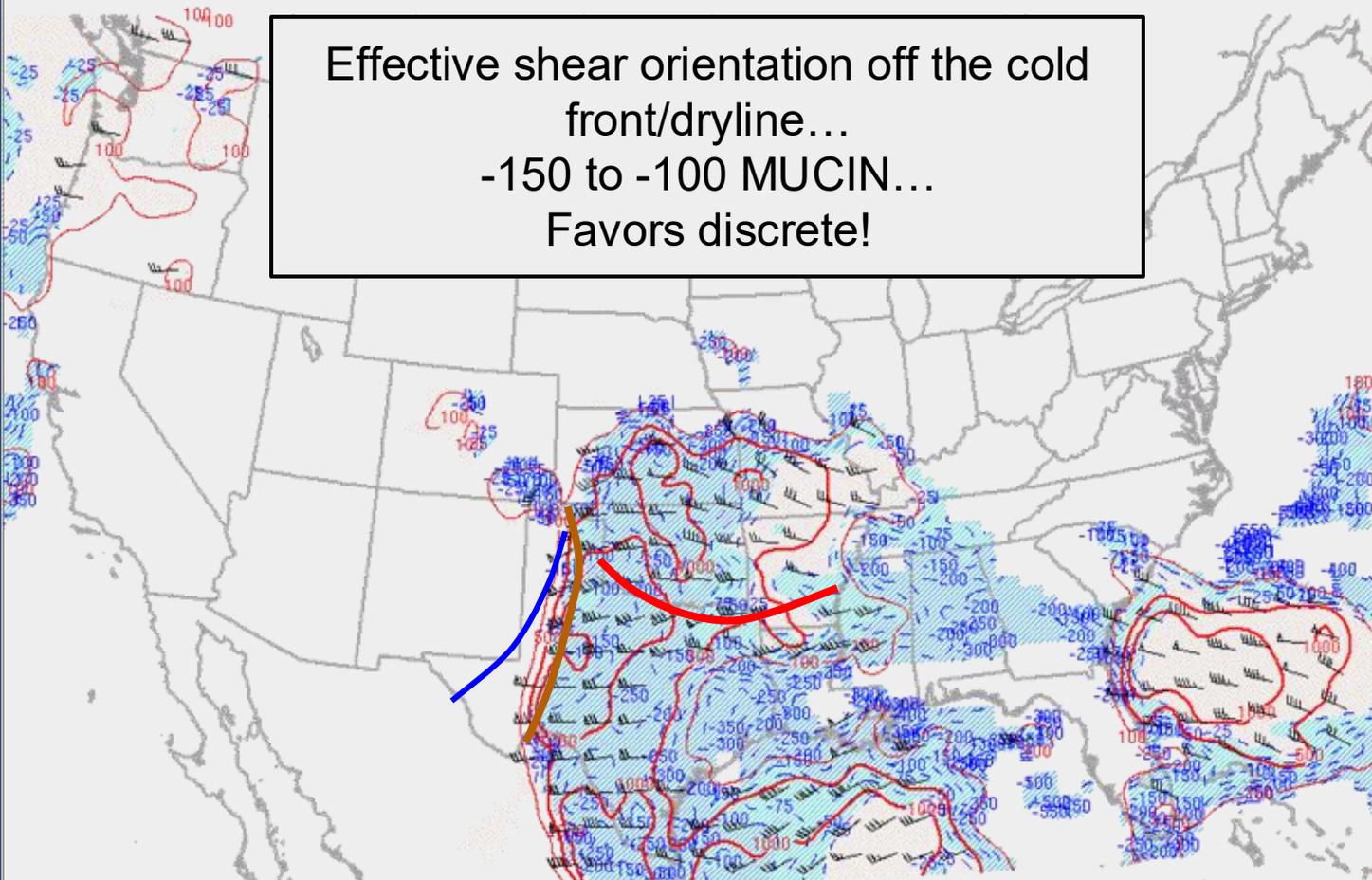


Bunker's right-mover storm motion  
vectors off the dryline...  
Favors discrete!



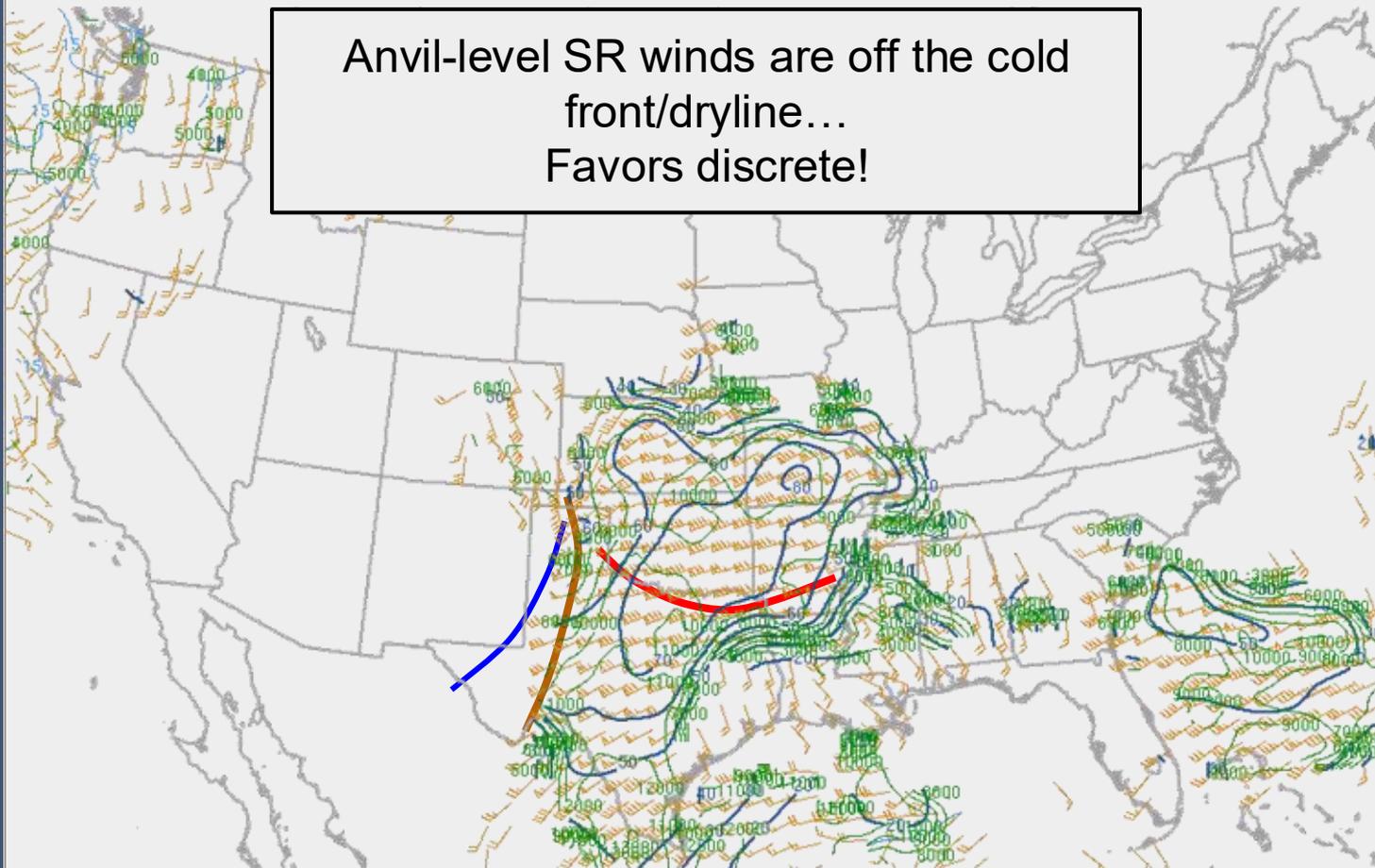
230227/0000 Eff. Inflow Base (fill, m AGL), ESRH (m2/s2) and storm motion (kt)

Effective shear orientation off the cold  
front/dryline...  
-150 to -100 MUCIN...  
Favors discrete!

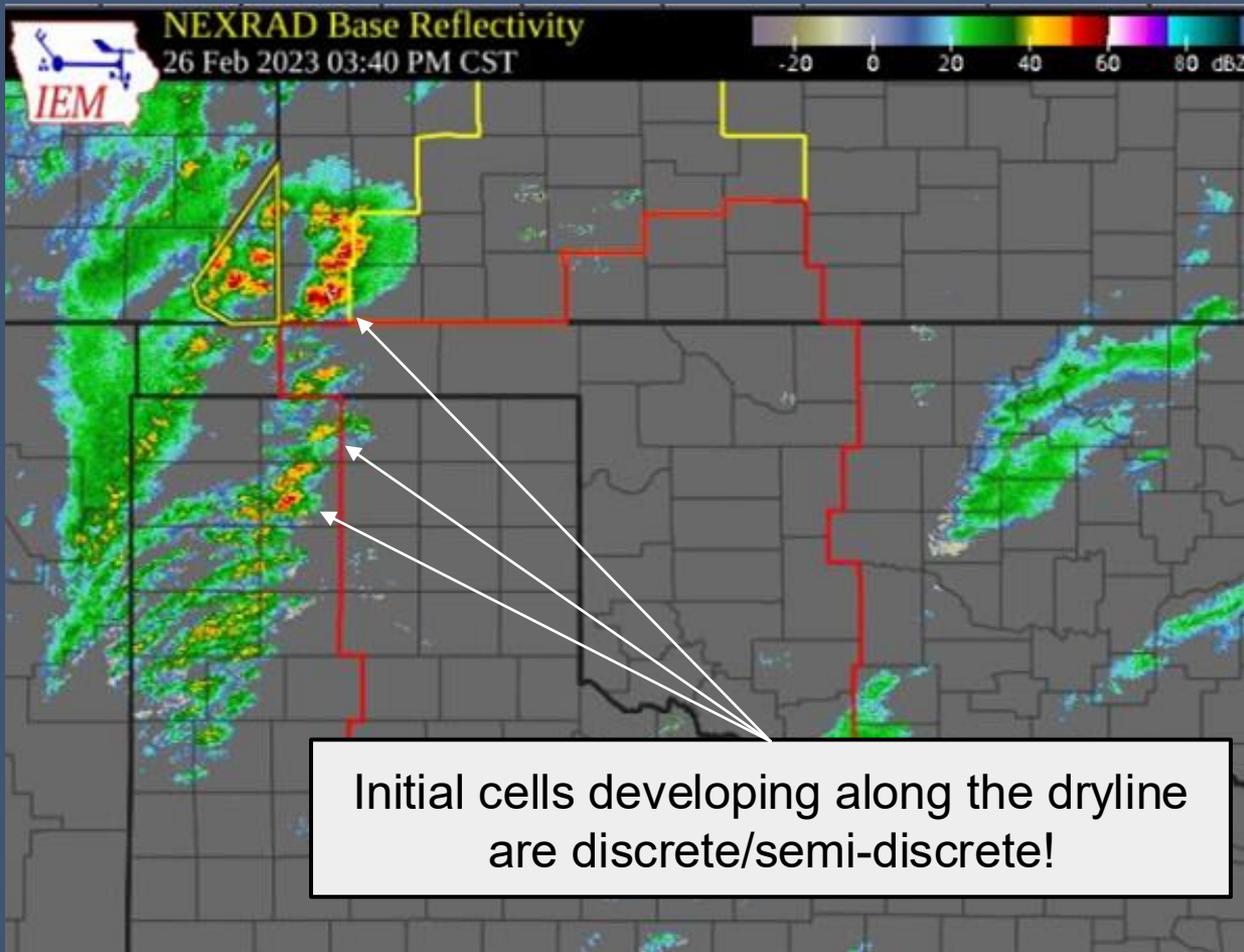


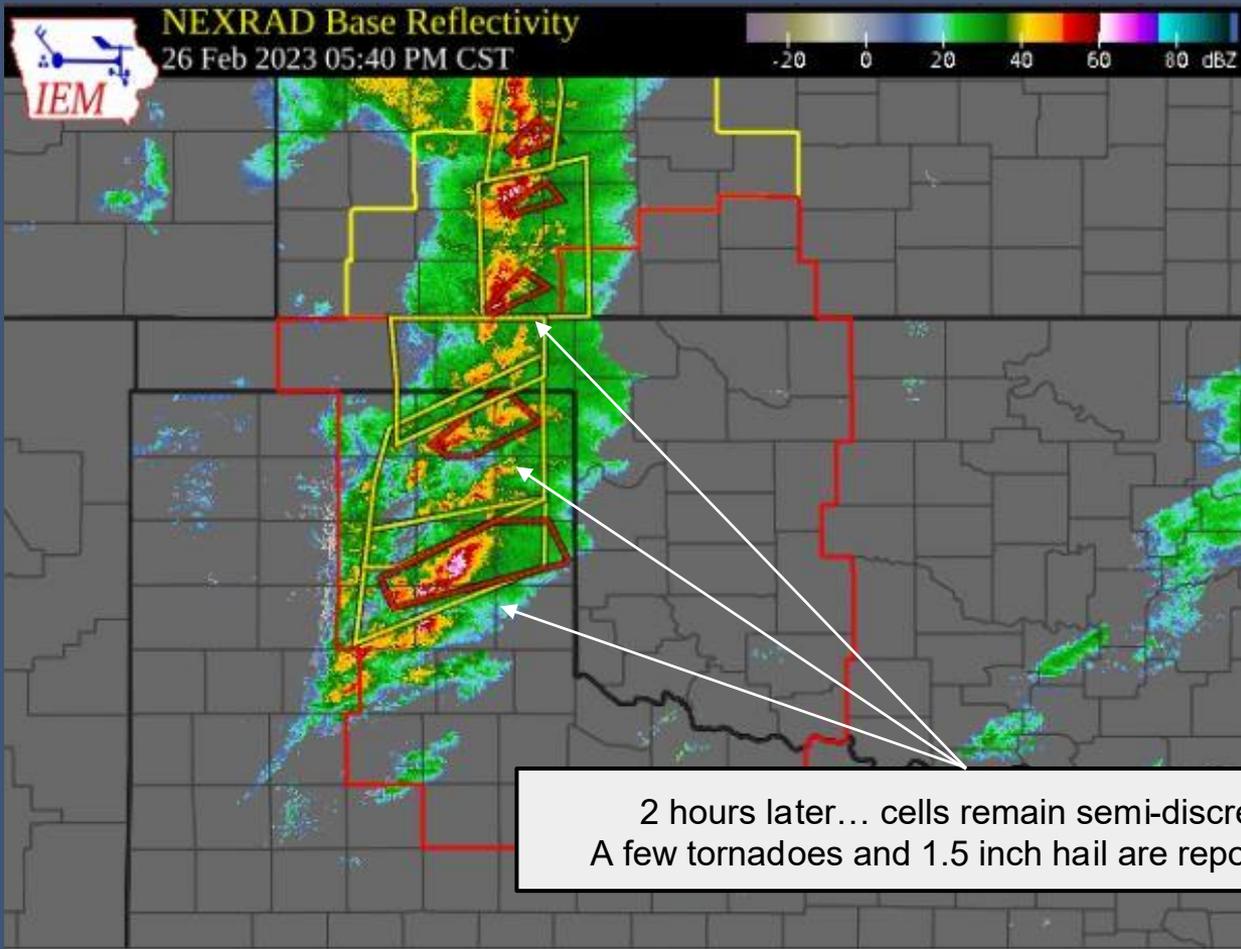
230227/0000 MUCAPE (red), MUCIN (fill) and effective bulk shear (kt)

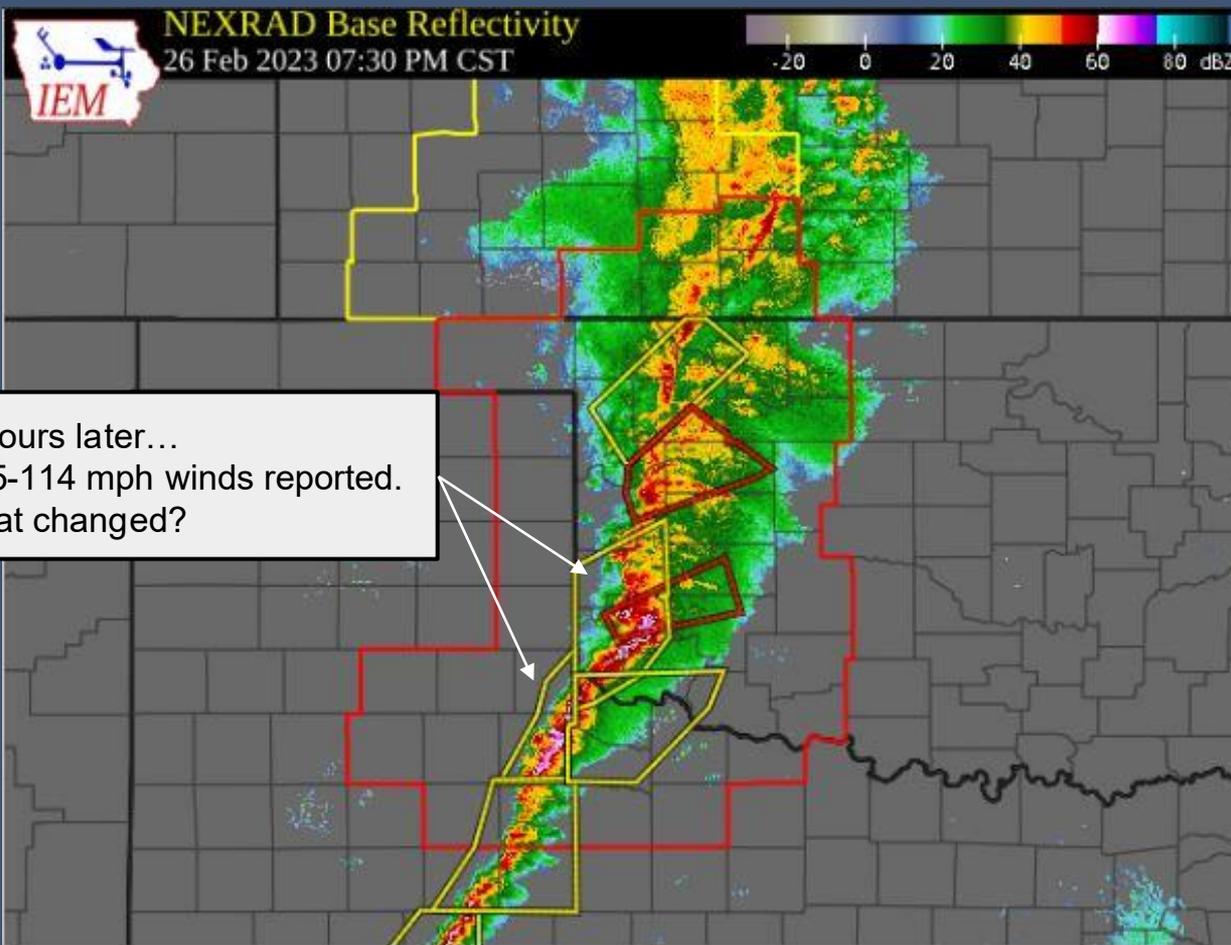
Anvil-level SR winds are off the cold front/dryline...  
Favors discrete!



230227/0000 Anvil SR Winds (kt) and EL height for "best" CAPE parcel (m AGL)



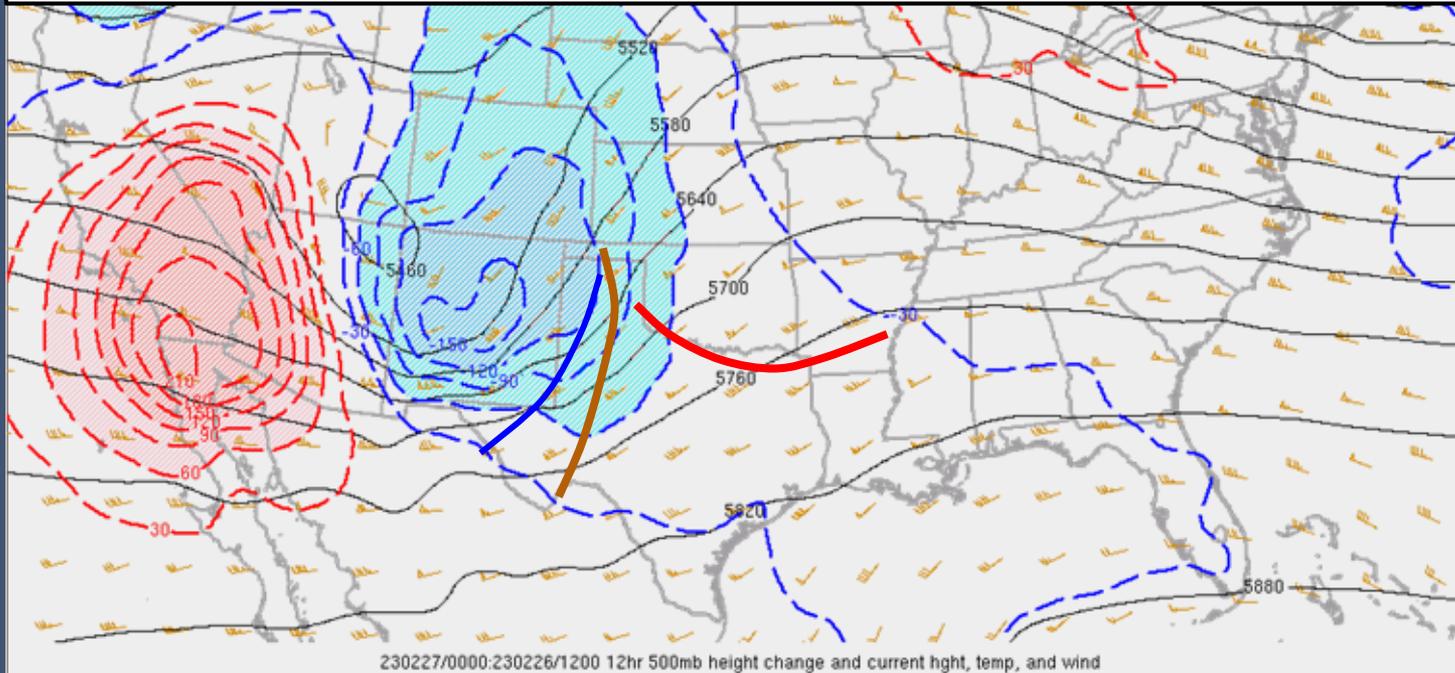




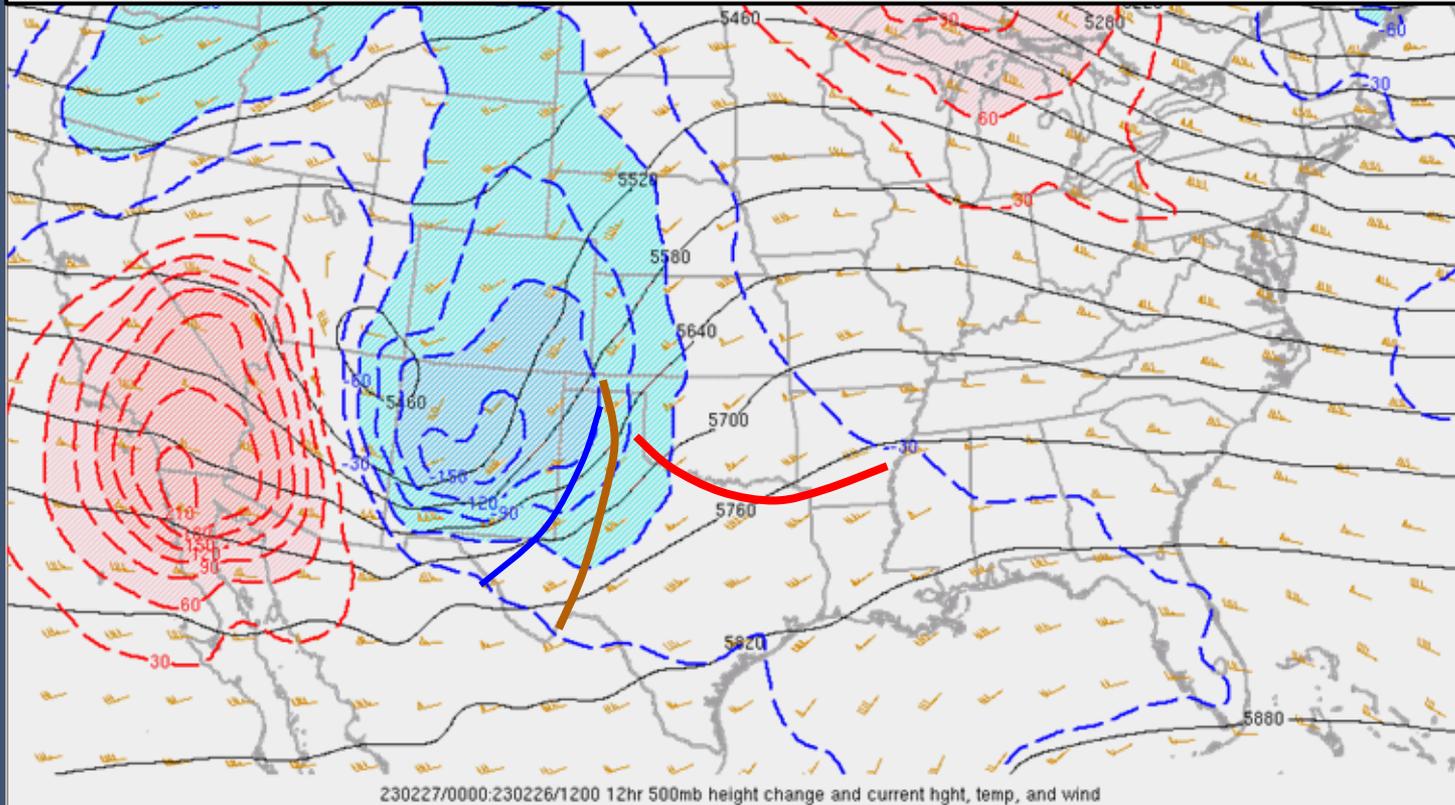
1) Very strong height falls aloft associated with the approach of a robust upper wave.

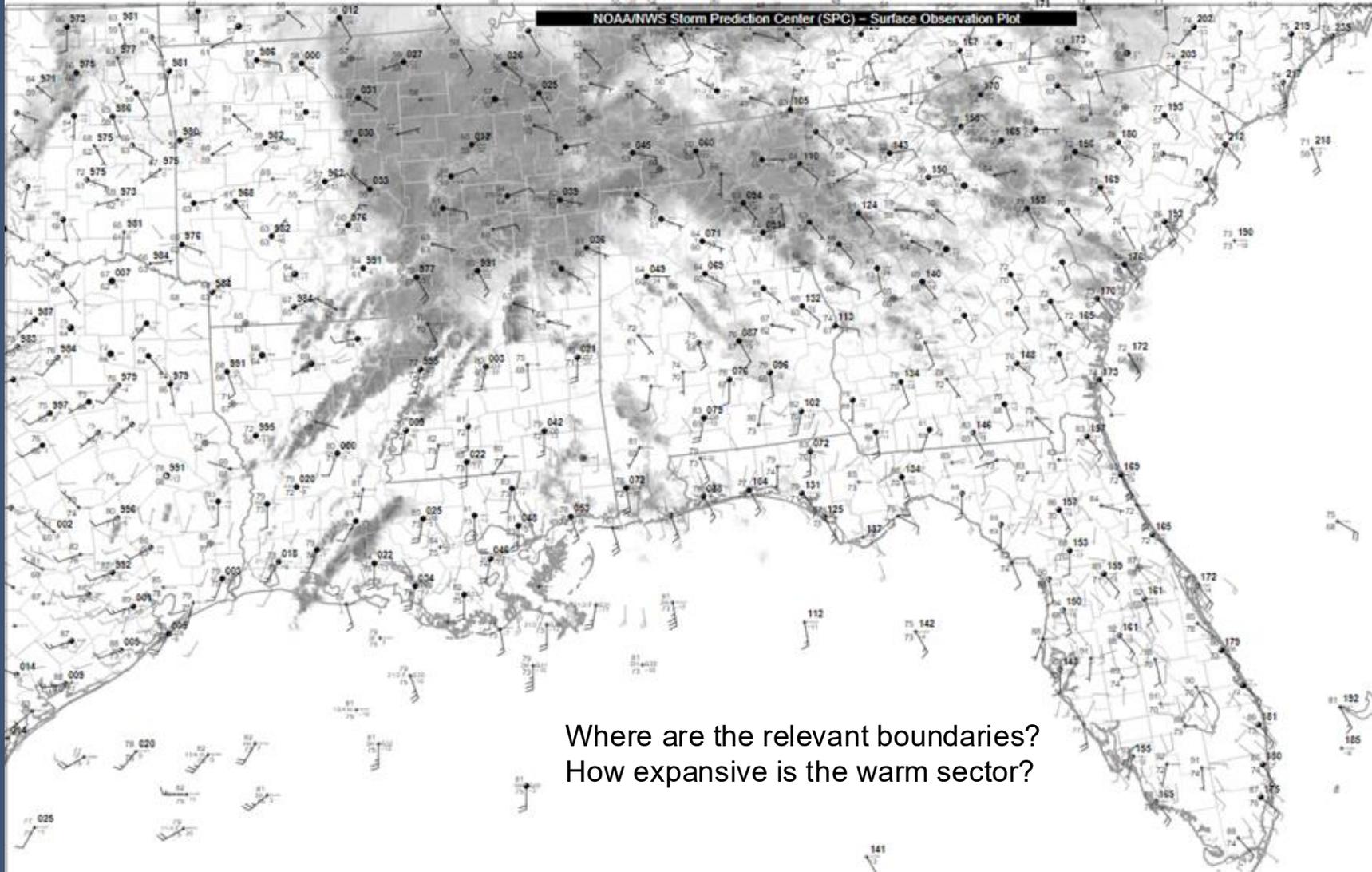
1) Strong ascent associated with an eastward-moving Pacific cold front

Both of these factors yielded very strong lift along the front, resulting in rapid upscale growth.

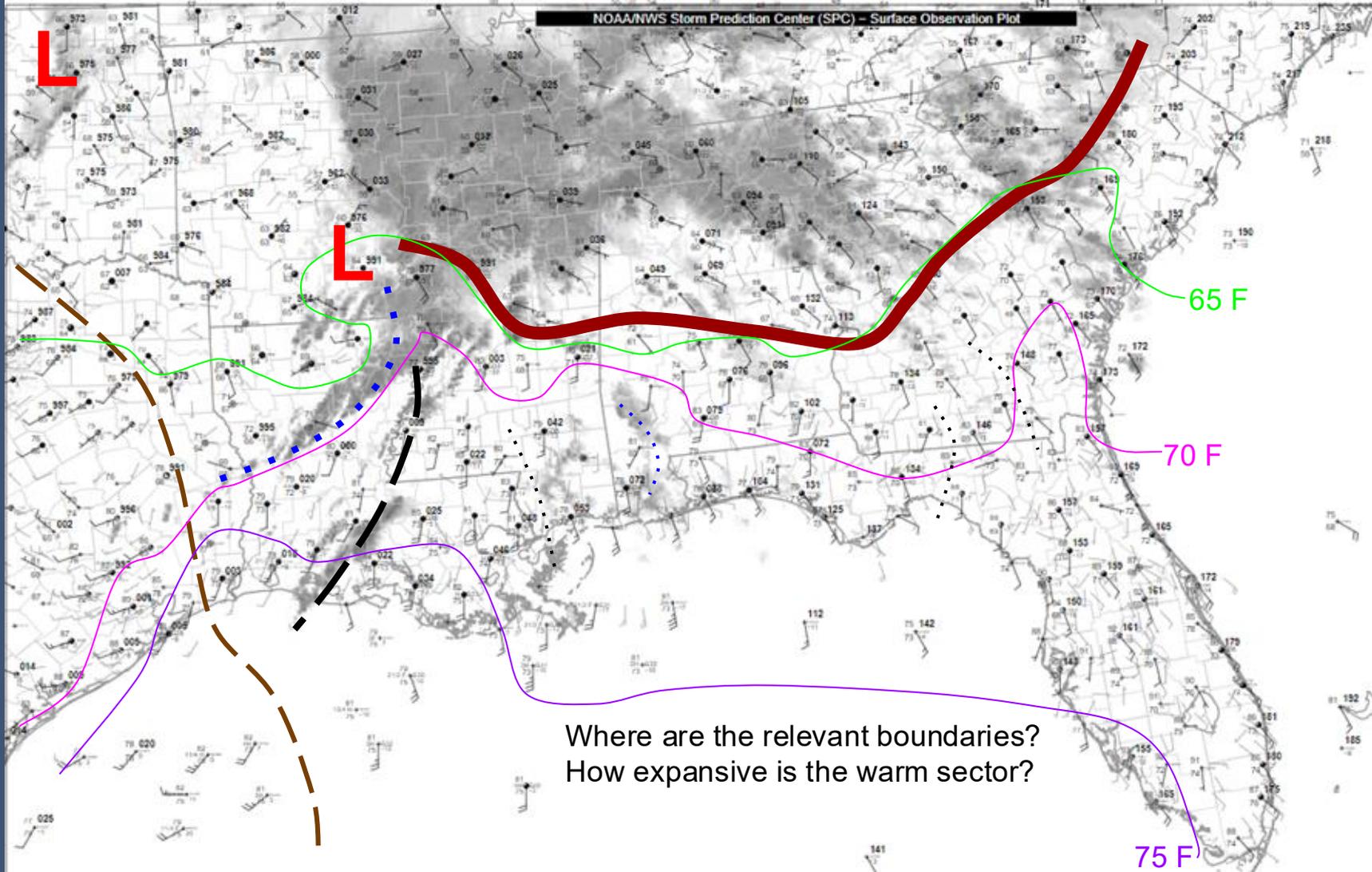


Moral of the story: these techniques work, but you have to take the entire synoptic regime into account and anticipate changes in time.



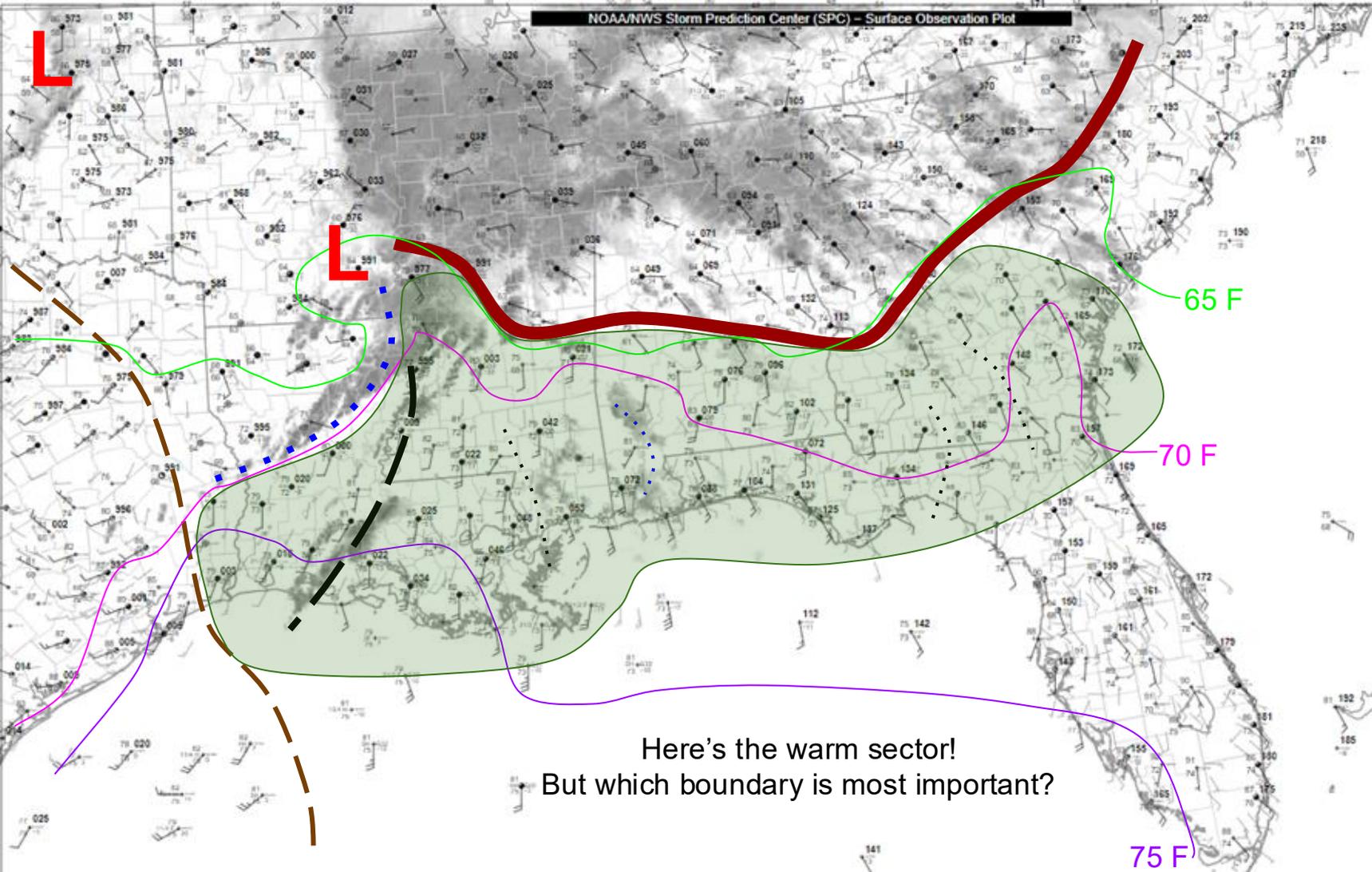


Where are the relevant boundaries?  
How expansive is the warm sector?



Where are the relevant boundaries?  
How expansive is the warm sector?

75 F

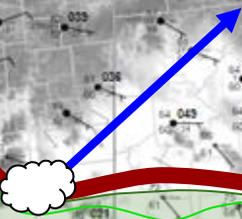


Here's the warm sector!  
But which boundary is most important?

75 F



Storm motion into the cooler air. No residence time in the surface-based warm sector.

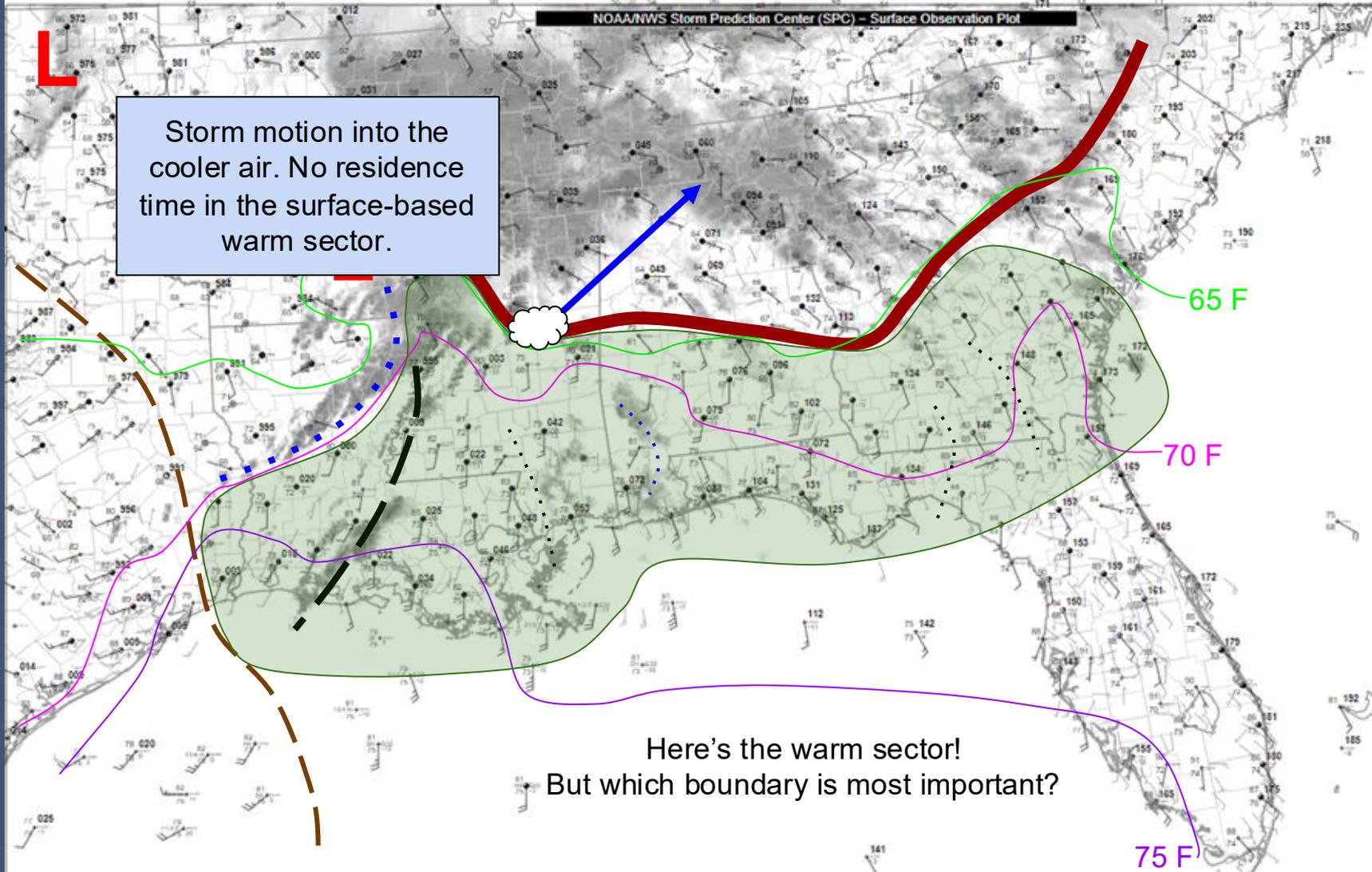


65 F

70 F

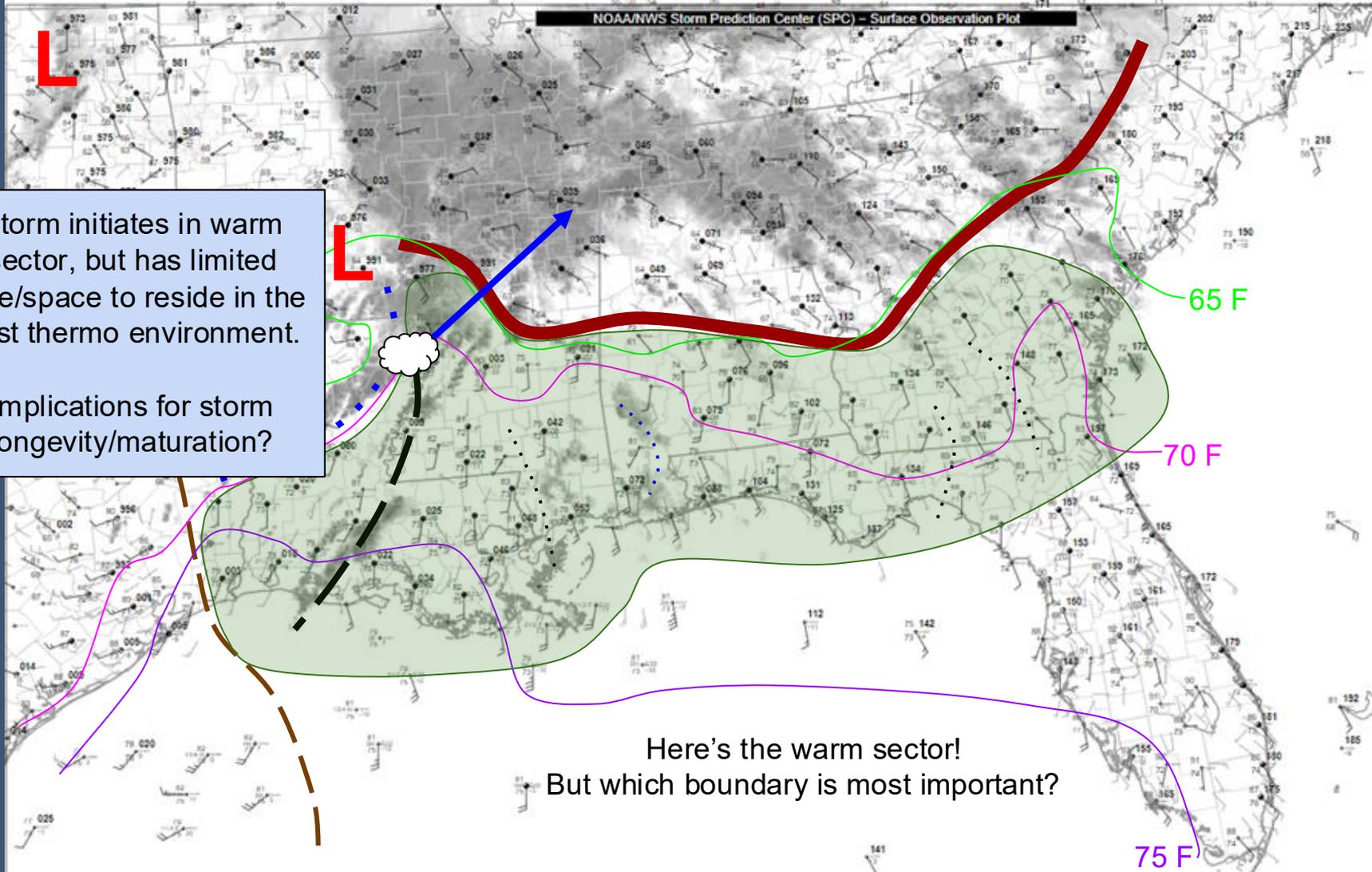
Here's the warm sector!  
But which boundary is most important?

75 F



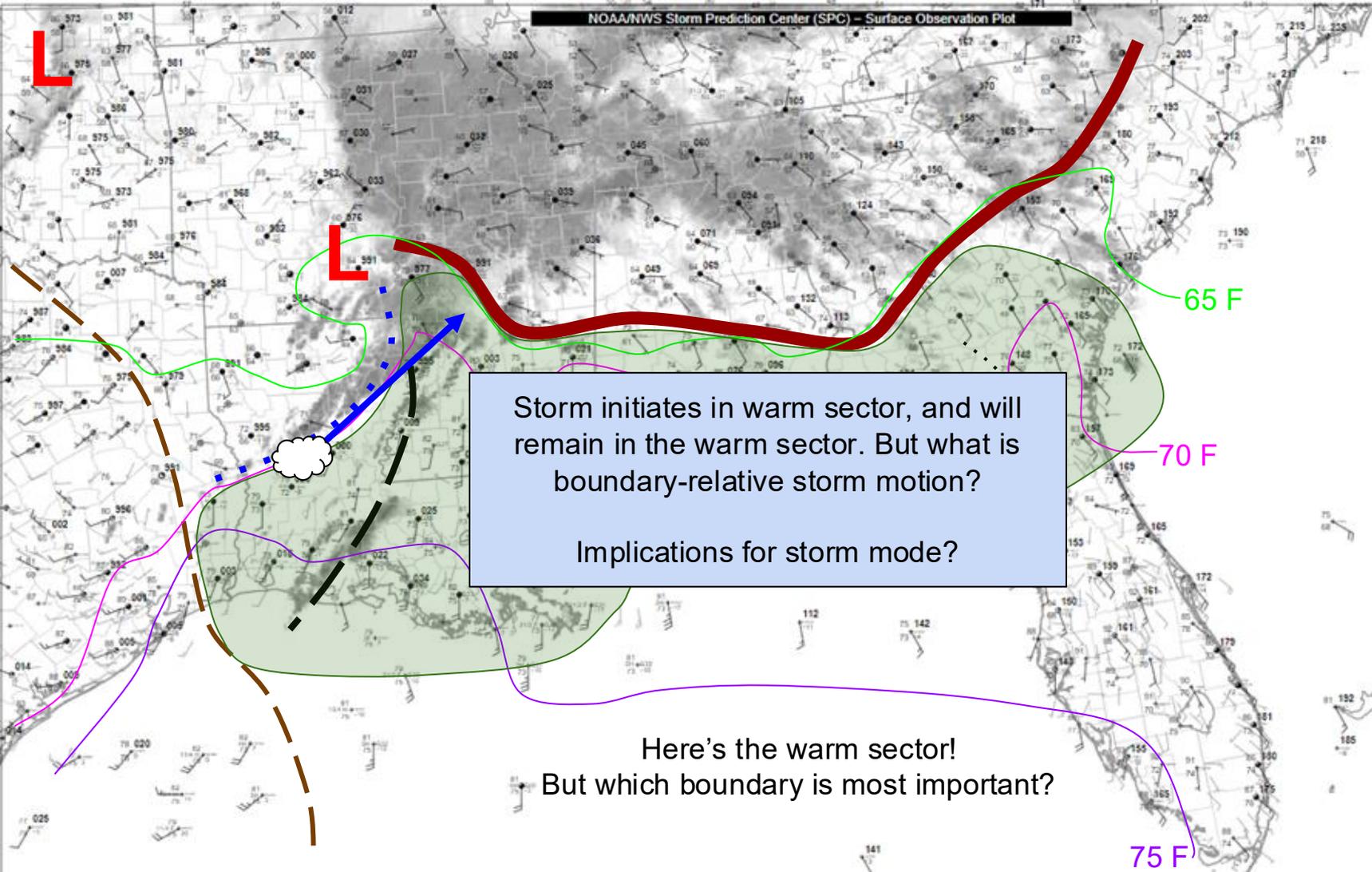
Storm initiates in warm sector, but has limited time/space to reside in the best thermo environment.

Implications for storm longevity/maturation?



Here's the warm sector!  
But which boundary is most important?

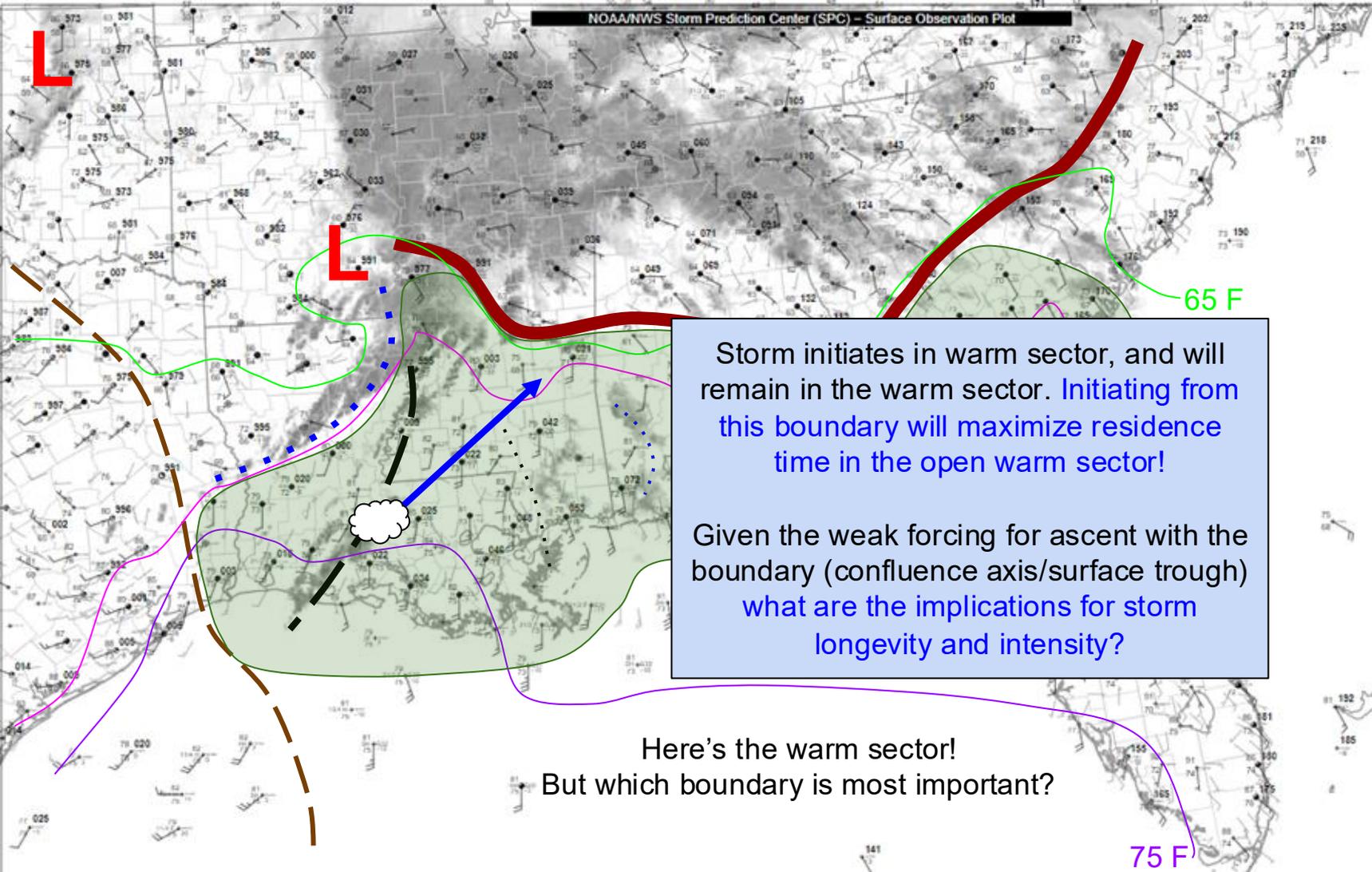
75 F



Storm initiates in warm sector, and will remain in the warm sector. But what is boundary-relative storm motion?  
Implications for storm mode?

Here's the warm sector!  
But which boundary is most important?

75 F

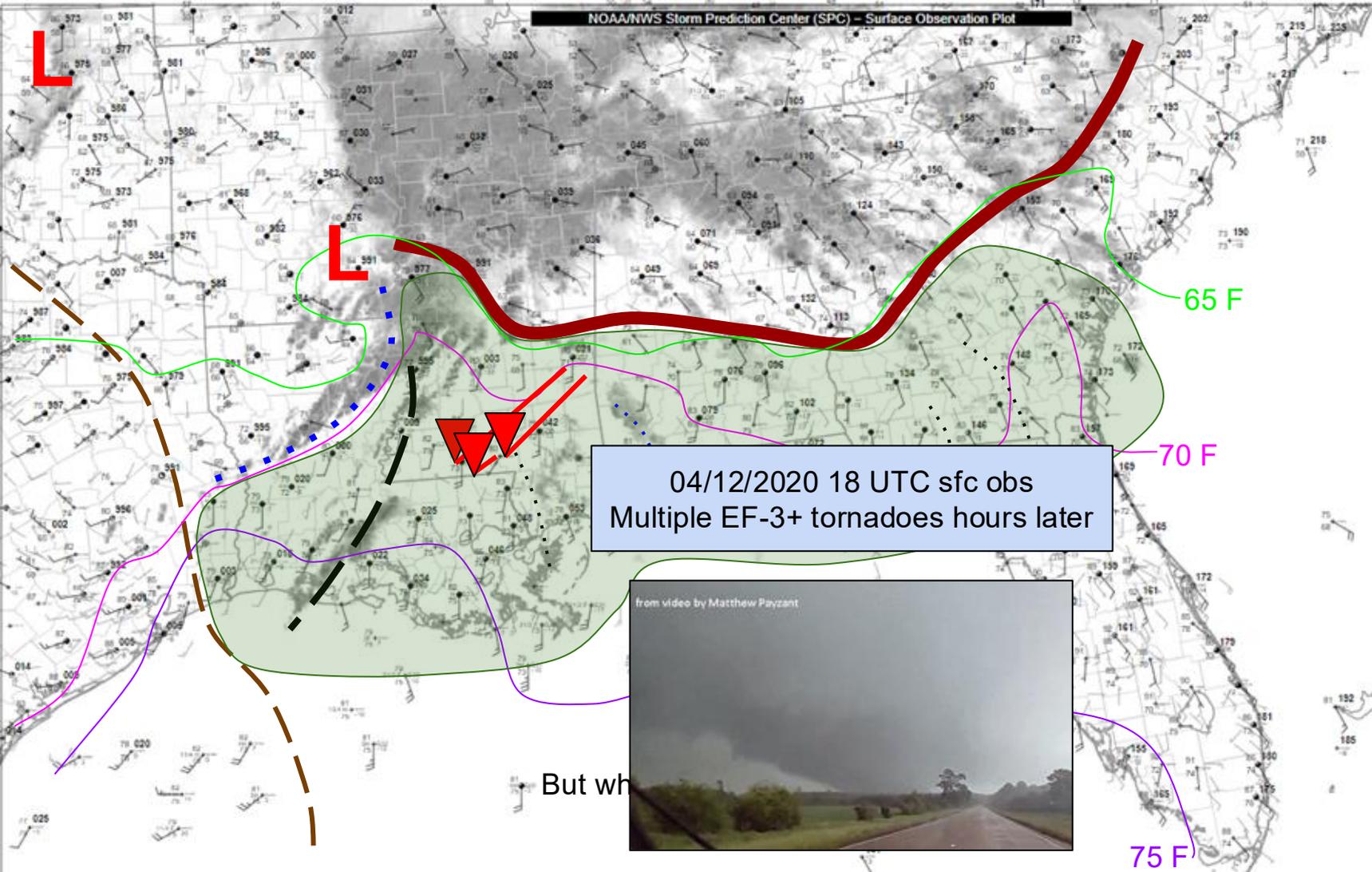


Storm initiates in warm sector, and will remain in the warm sector. Initiating from this boundary will maximize residence time in the open warm sector!

Given the weak forcing for ascent with the boundary (confluence axis/surface trough) what are the implications for storm longevity and intensity?

Here's the warm sector!  
But which boundary is most important?

75 F

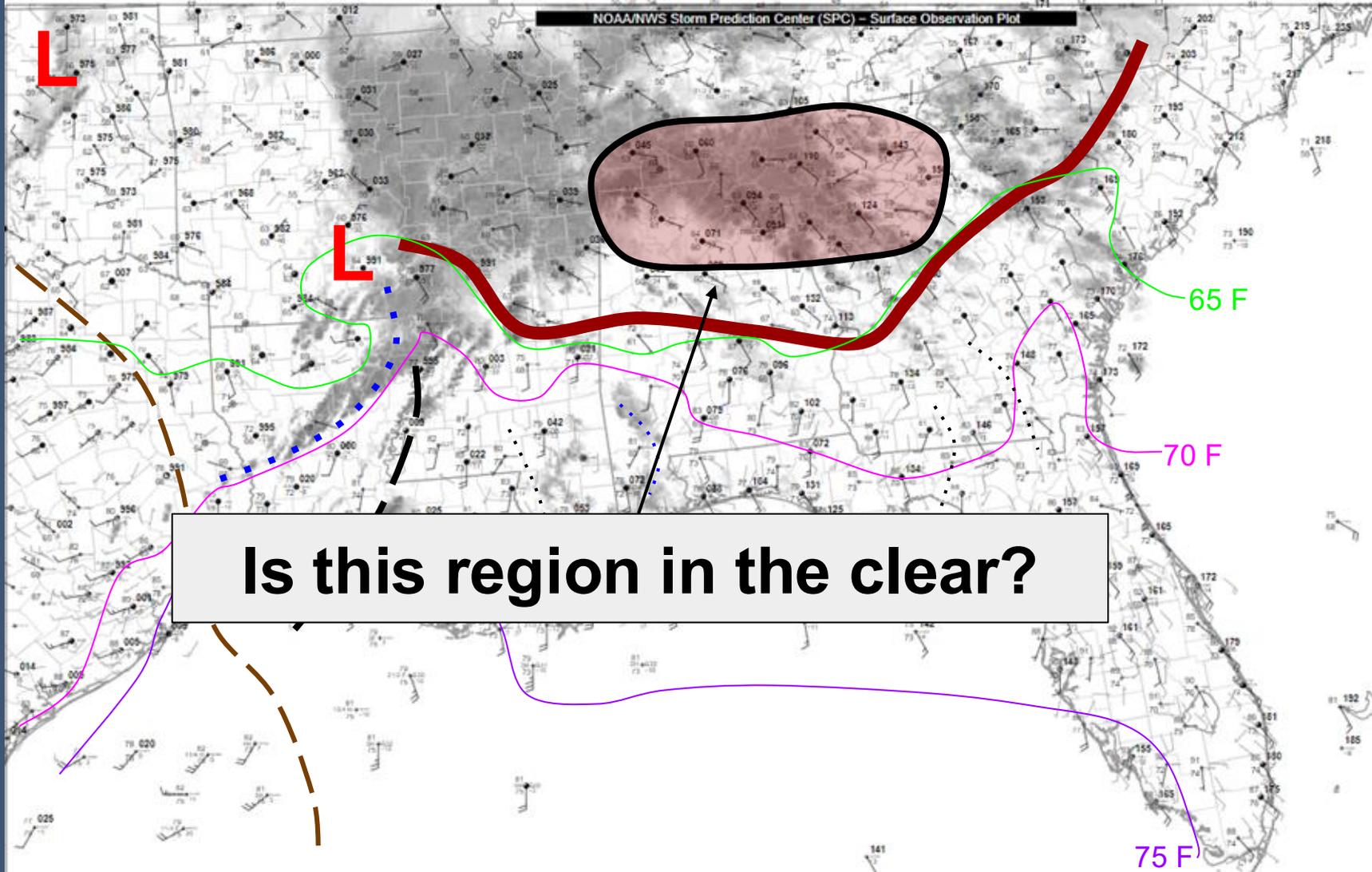


04/12/2020 18 UTC sfc obs  
Multiple EF-3+ tornadoes hours later



But wh

75 F

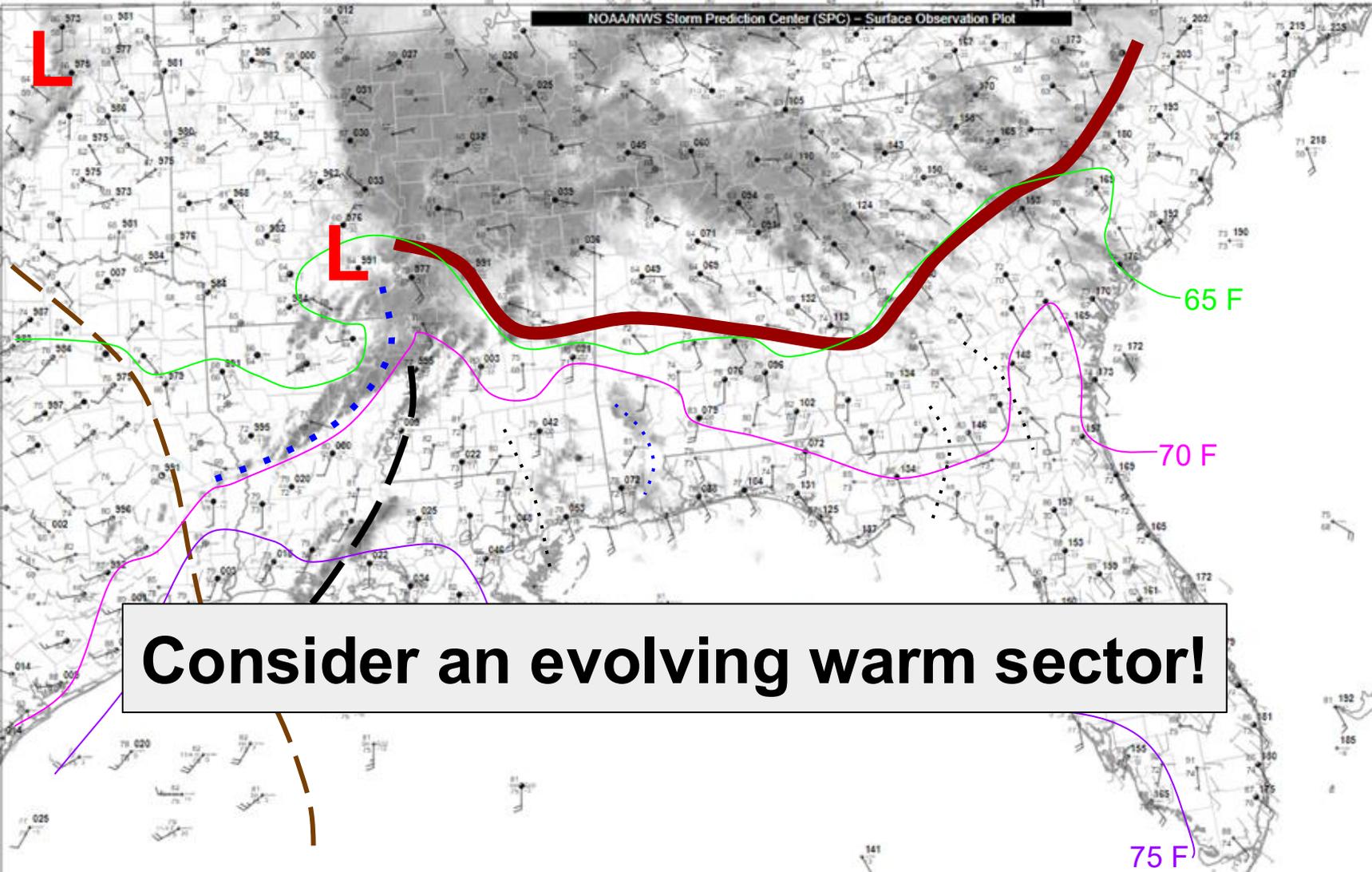


**Is this region in the clear?**

65 F

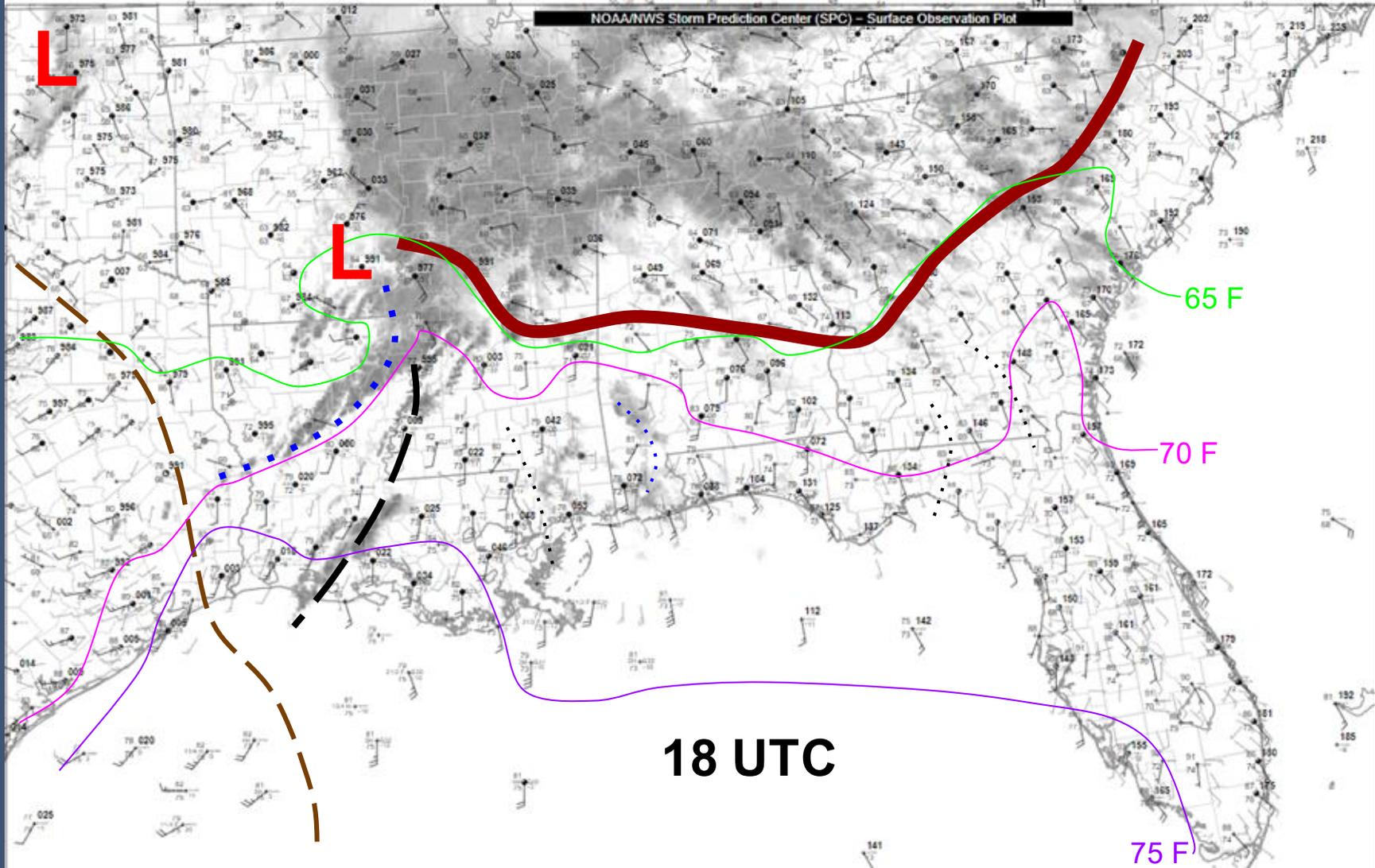
70 F

75 F



**Consider an evolving warm sector!**

75 F

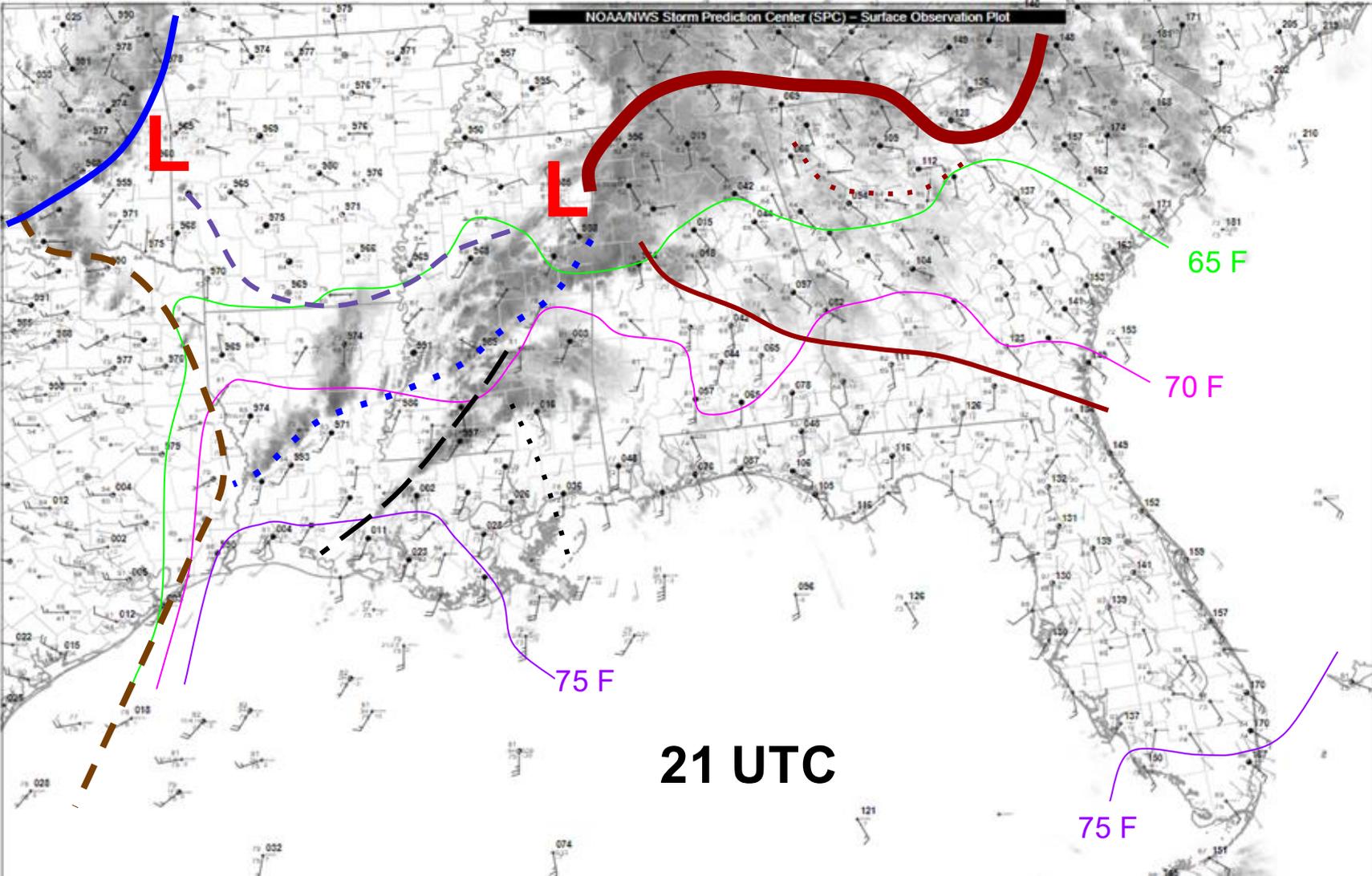


18 UTC

65 F

70 F

75 F



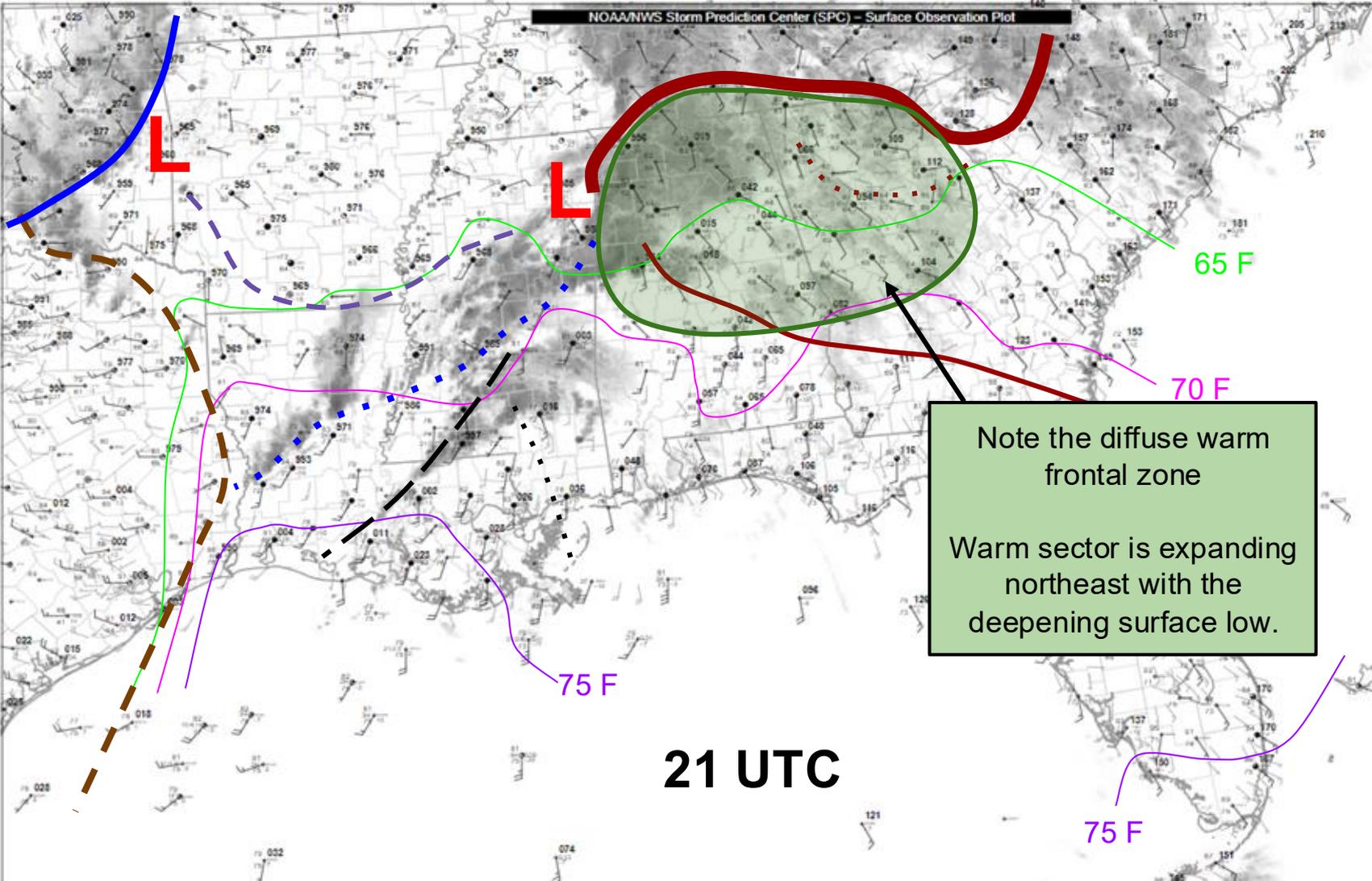
21 UTC

65 F

70 F

75 F

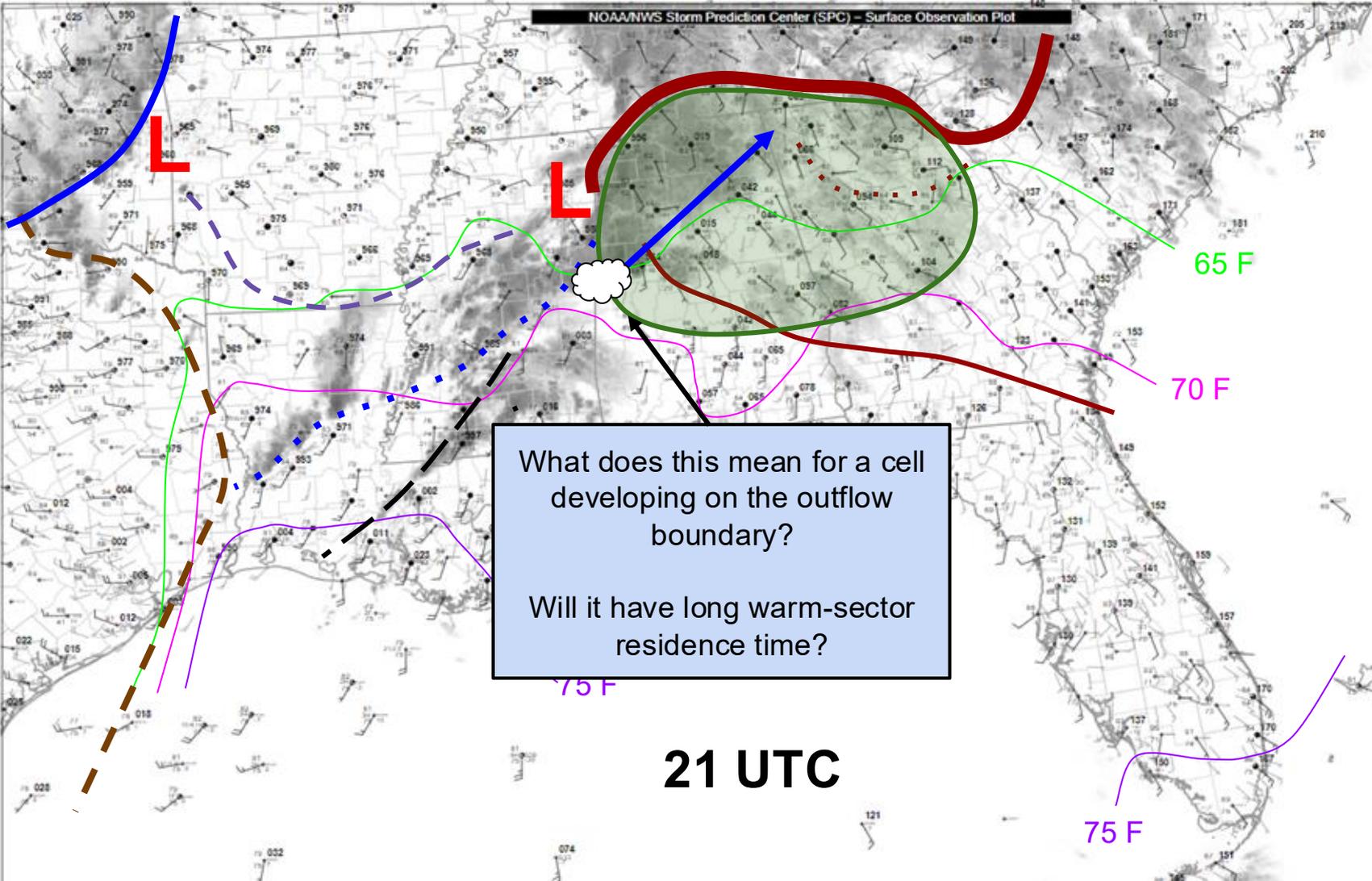
75 F



Note the diffuse warm frontal zone  
Warm sector is expanding northeast with the deepening surface low.

21 UTC

75 F



What does this mean for a cell developing on the outflow boundary?

Will it have long warm-sector residence time?

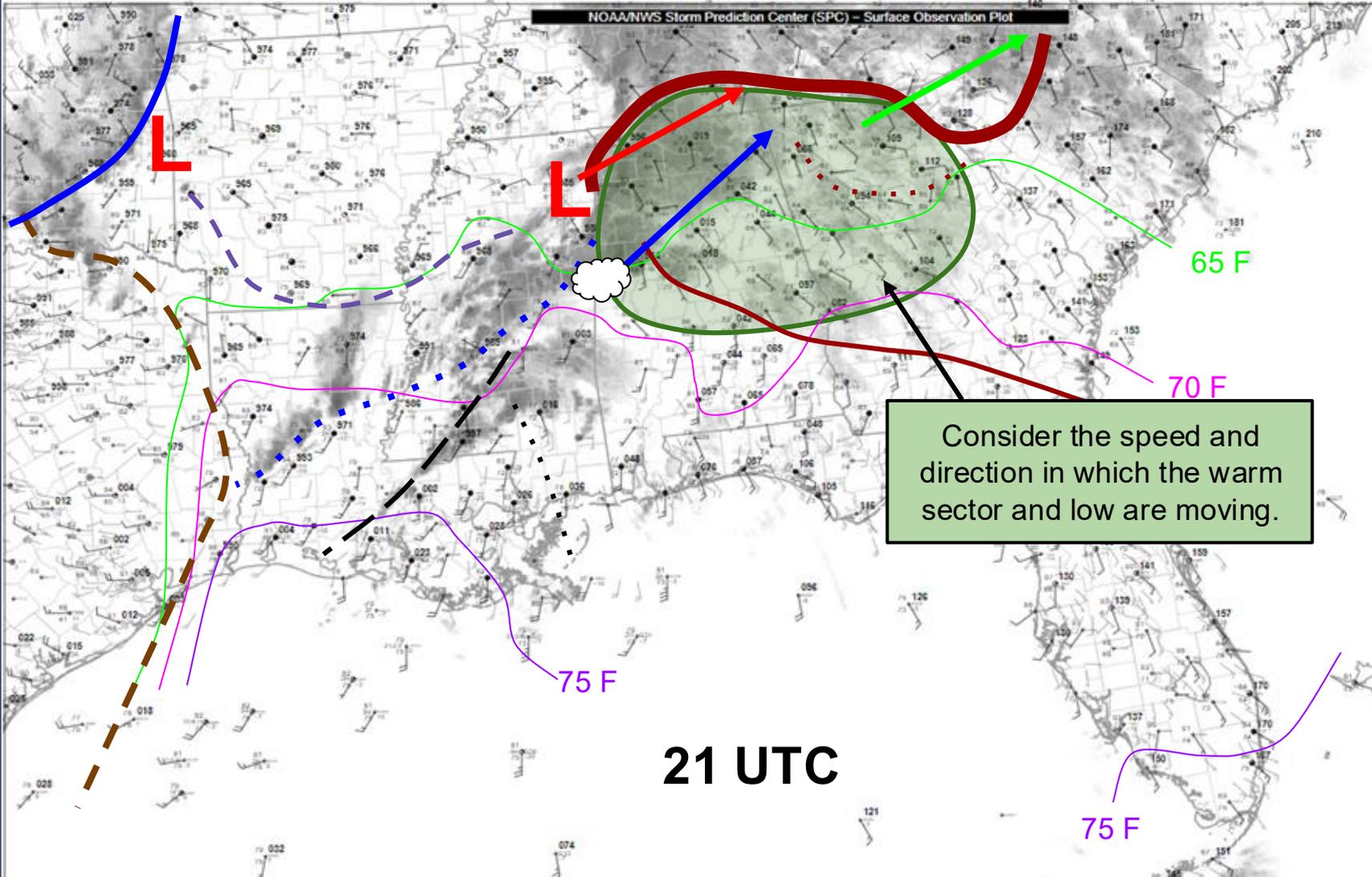
**21 UTC**

75 F

65 F

70 F

75 F



65 F

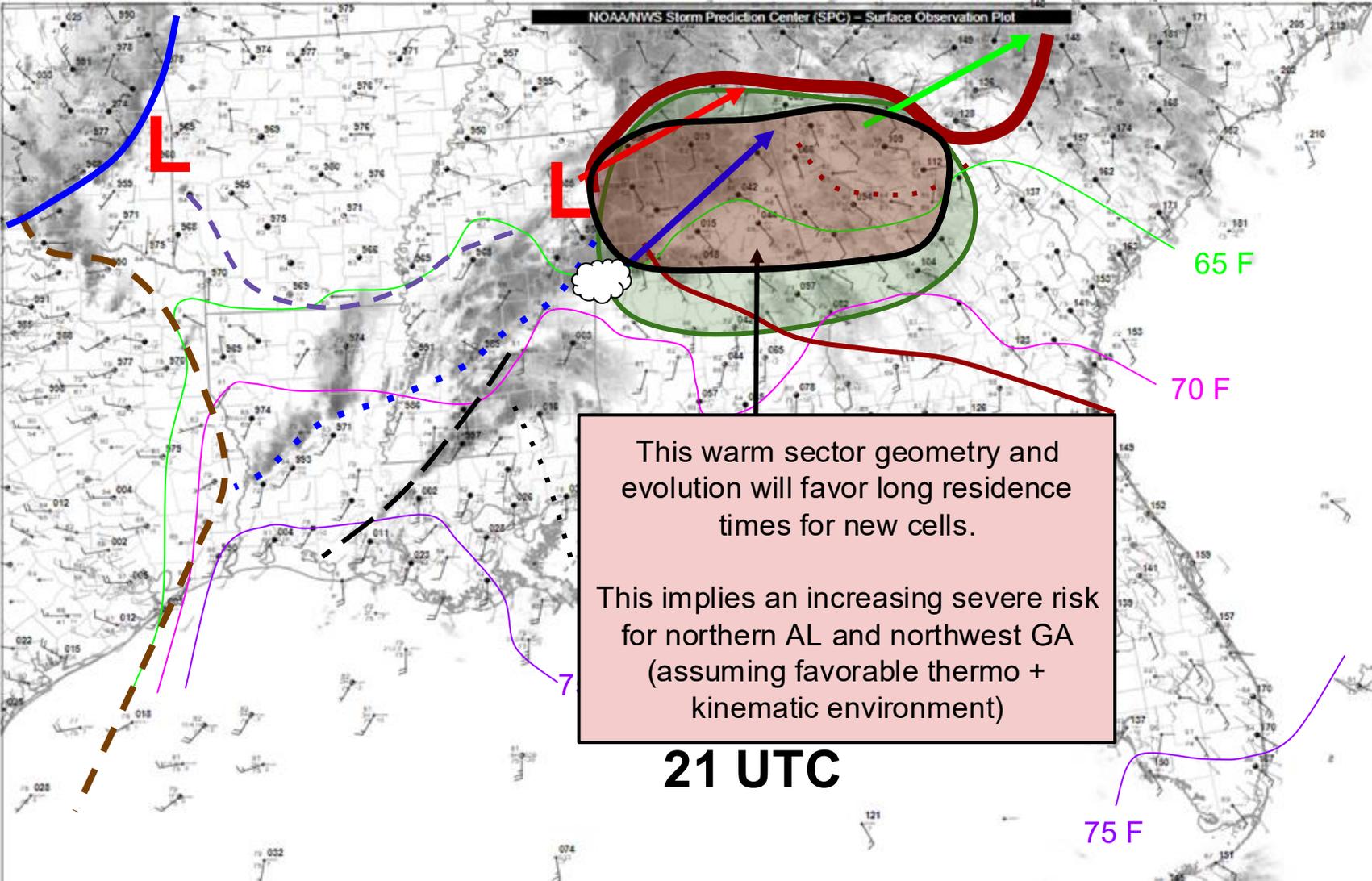
70 F

75 F

75 F

Consider the speed and direction in which the warm sector and low are moving.

21 UTC

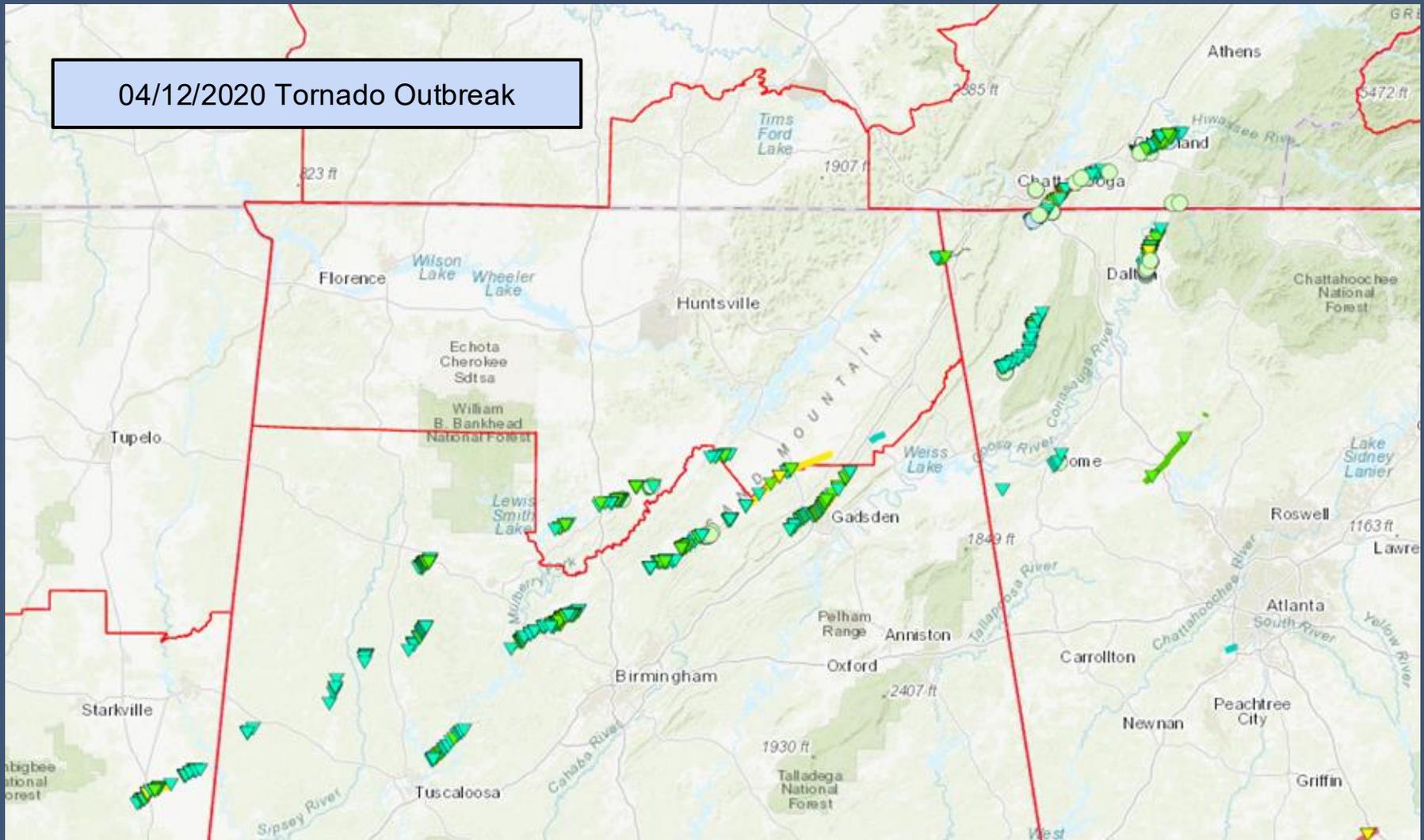


This warm sector geometry and evolution will favor long residence times for new cells.

This implies an increasing severe risk for northern AL and northwest GA (assuming favorable thermo + kinematic environment)

**21 UTC**

04/12/2020 Tornado Outbreak



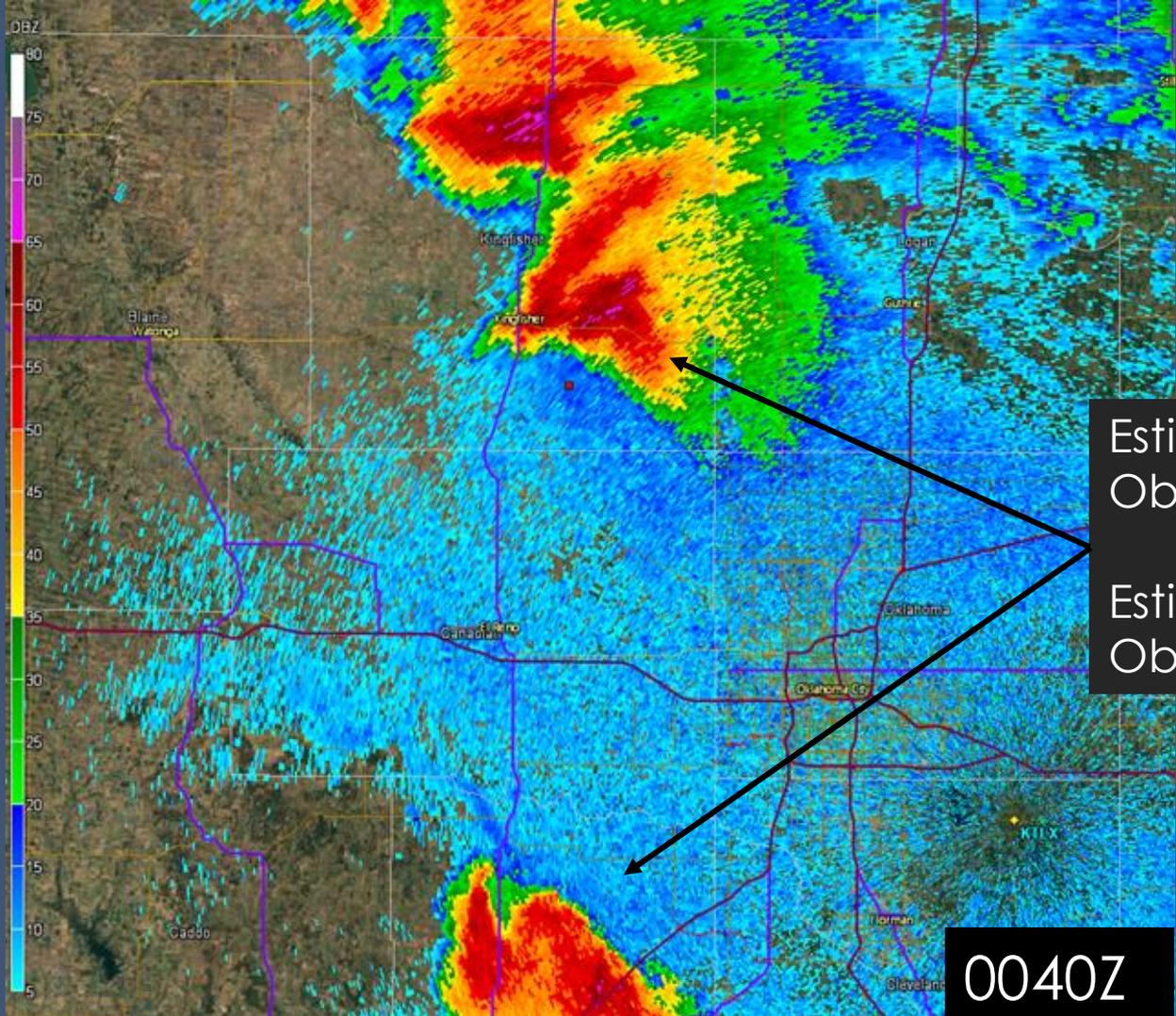
# Warm Sector Geometry and Residence Time Summary

- Careful surface analysis will help identify important features and warm sector geometry.
- Utilize observed and/or forecast storm motions and warm sector evolution to gauge whether or not a storm will:
  - Quickly become displaced out of the warm sector
  - Have a short residence time
  - Have a long residence time
- Longer residence times favor storm maturation, which implies a higher potential for impactful weather

# Storm Interactions: Good or Bad?

It's not always clear!

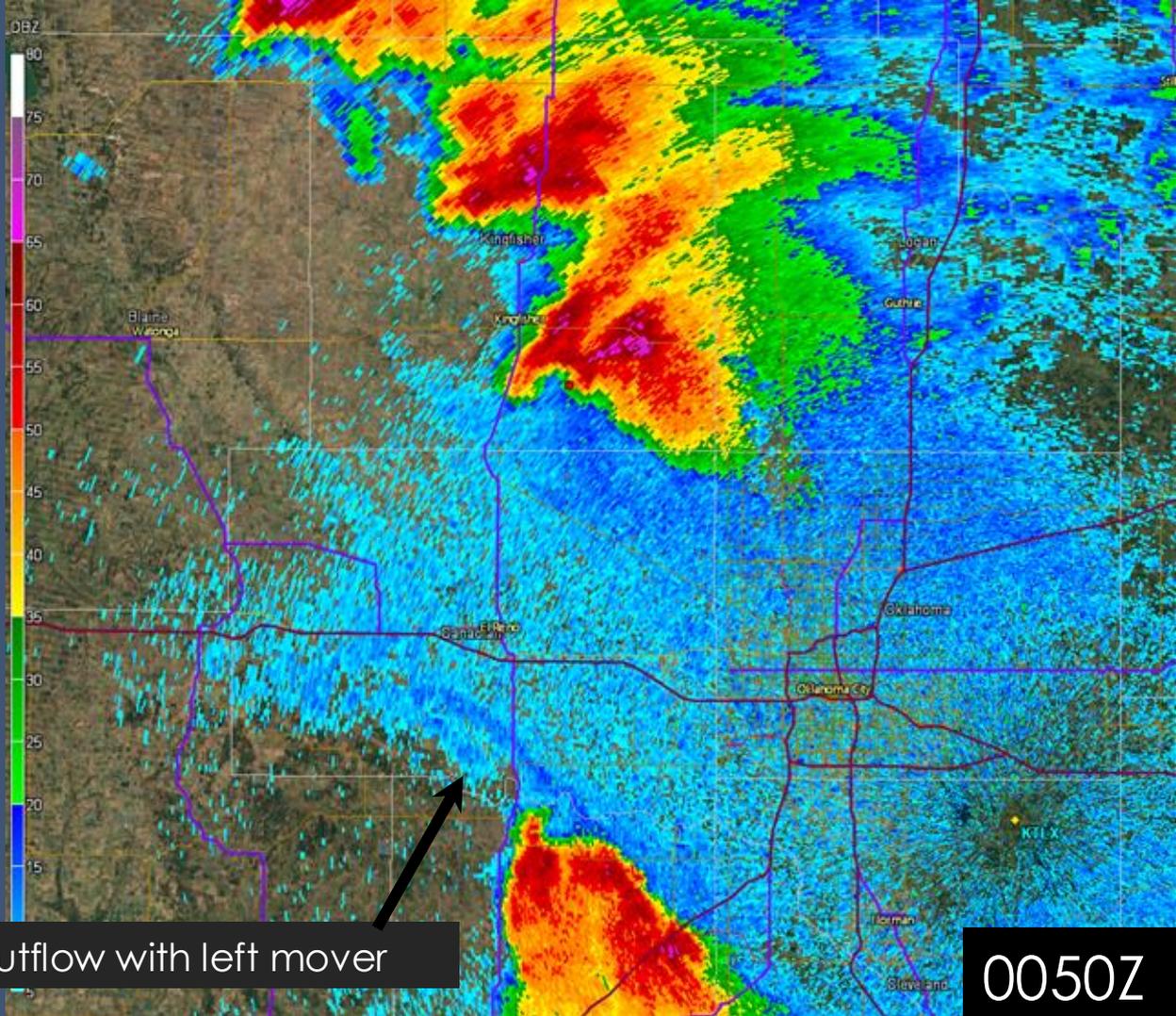




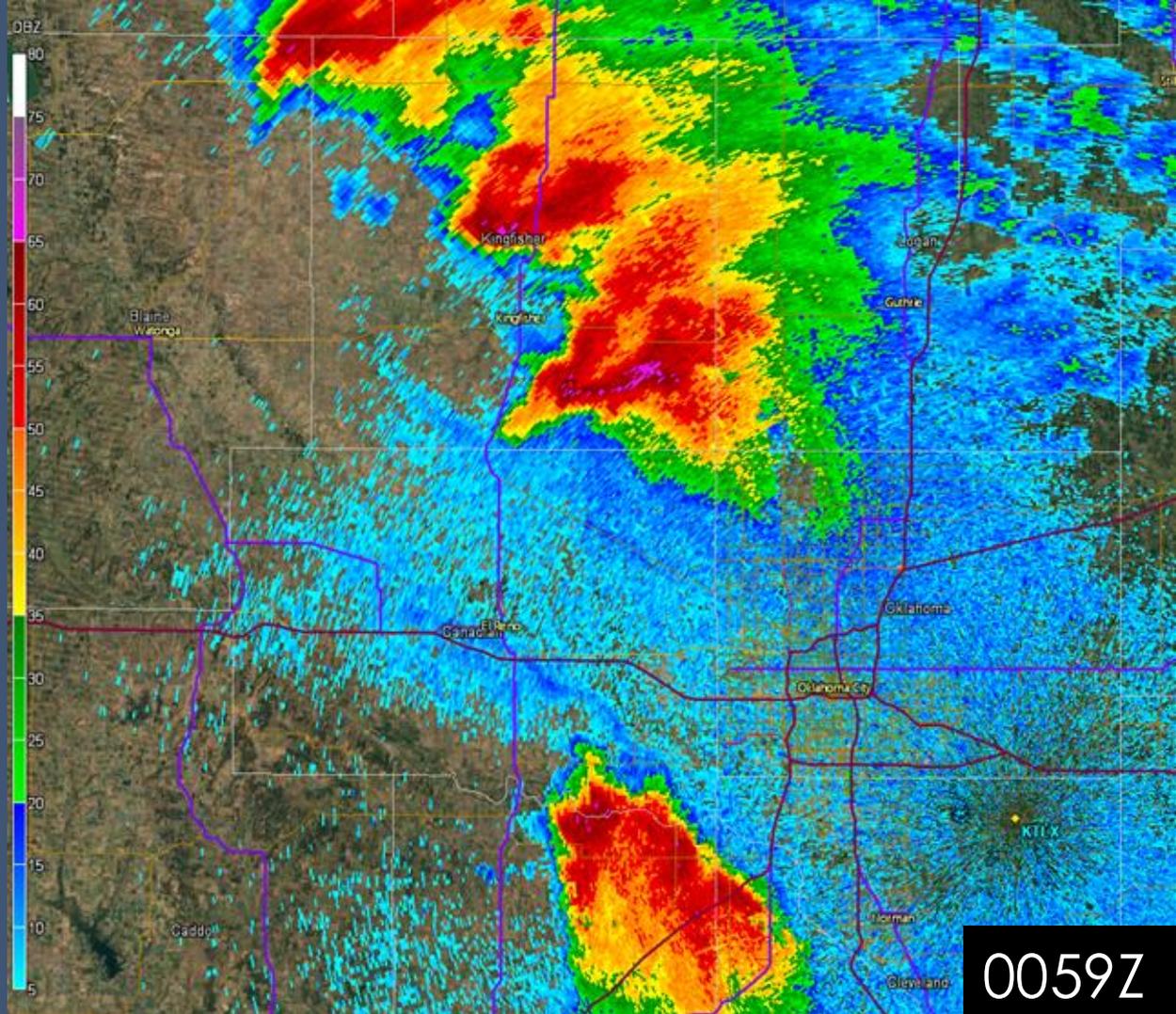
Estimated RM 328 @ 11 kt  
Observed RM 336 @ 15 kt

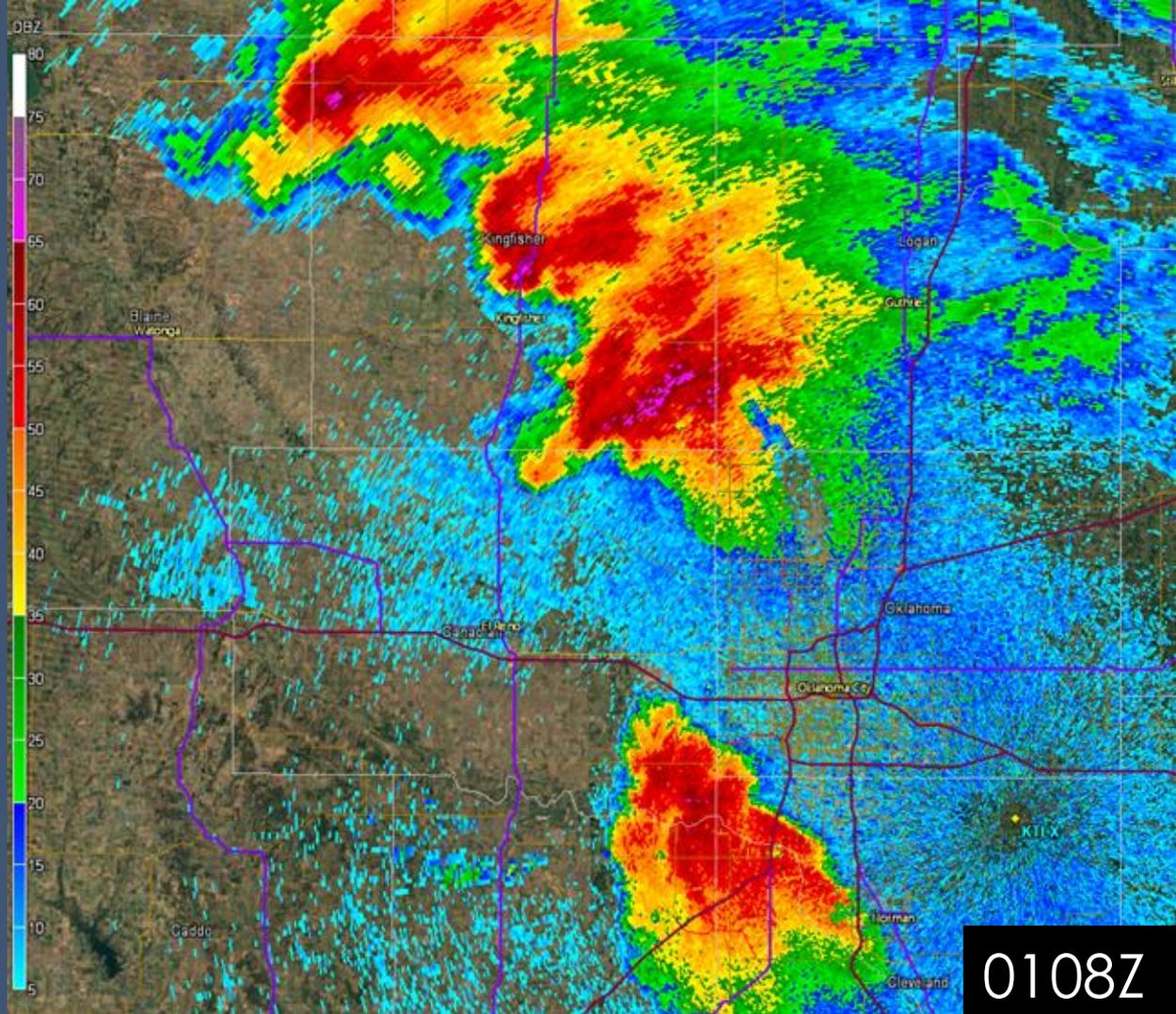
Estimated LM 231 @ 26 kt  
Observed LM 230 @ 29 kt

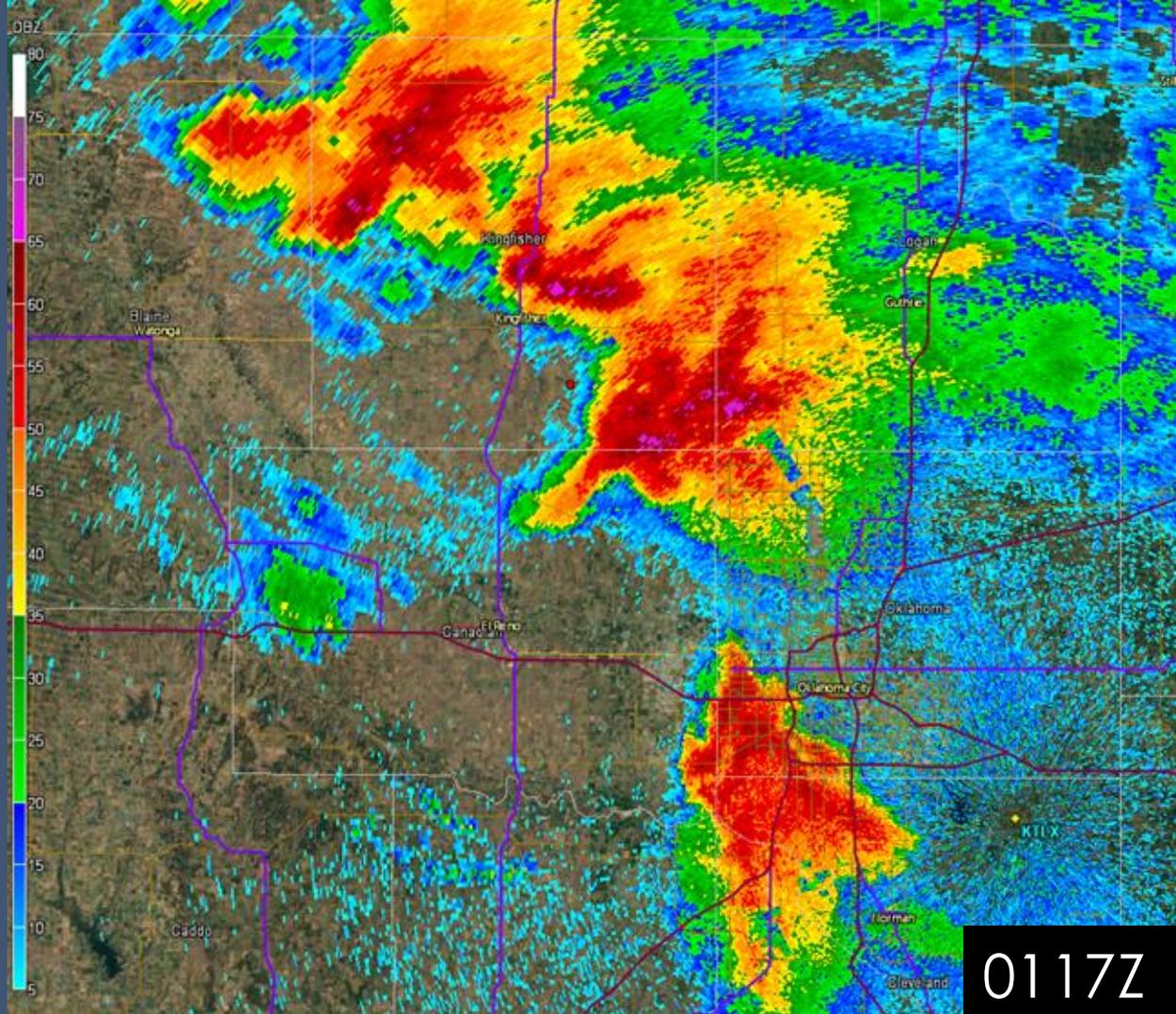
0040Z

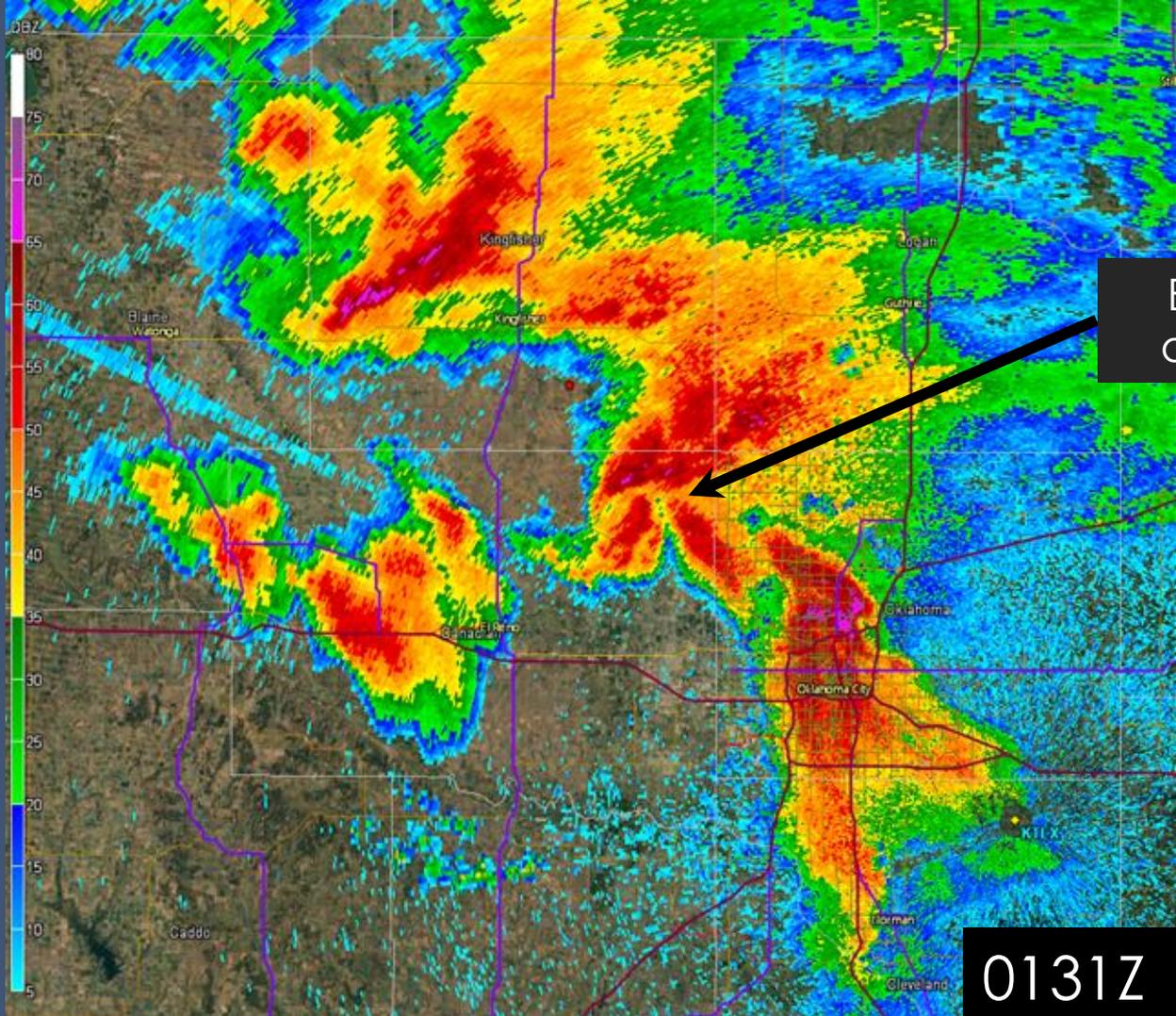


Outflow with left mover



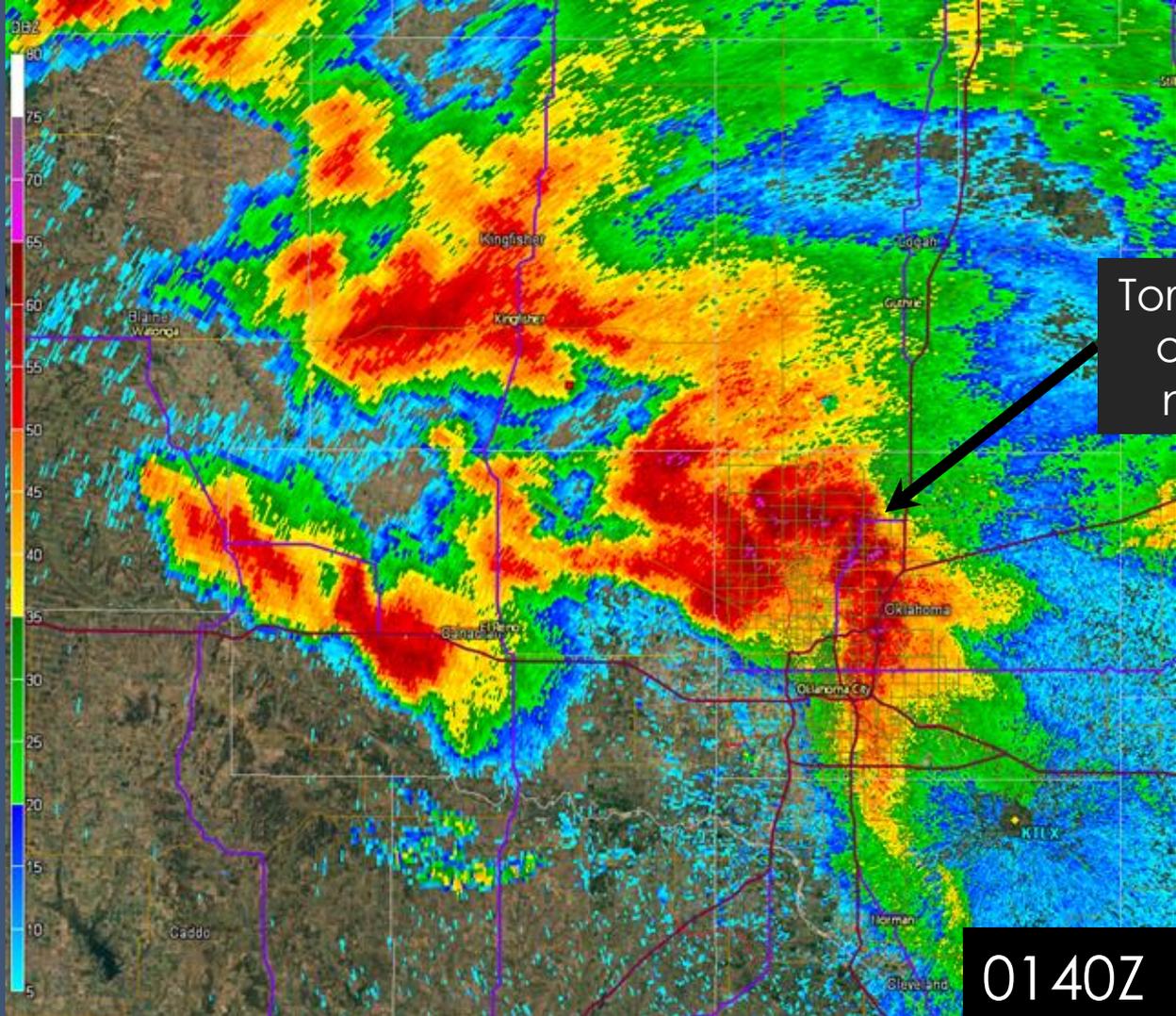






Brief tornado after  
outflow interaction

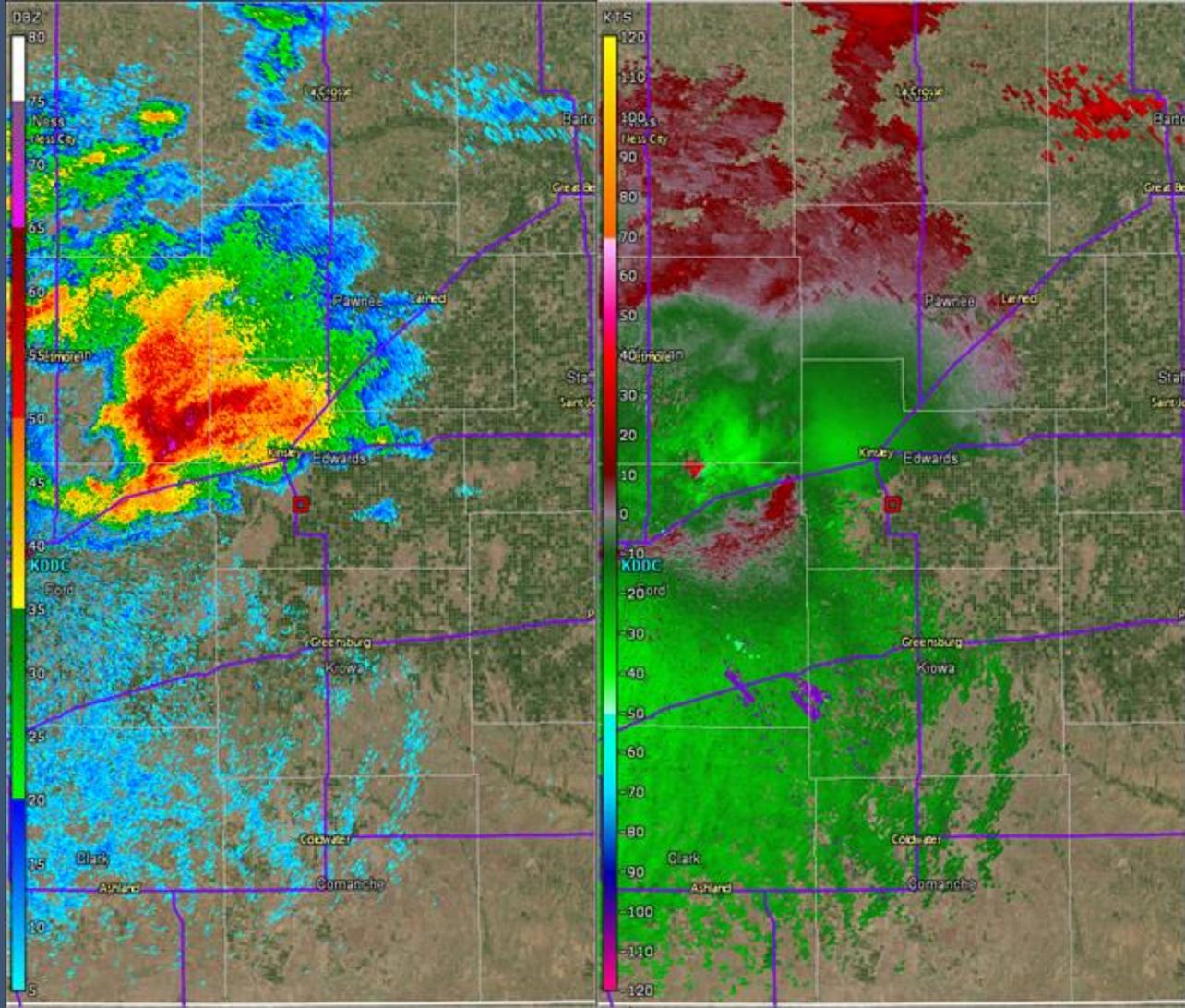
0131Z



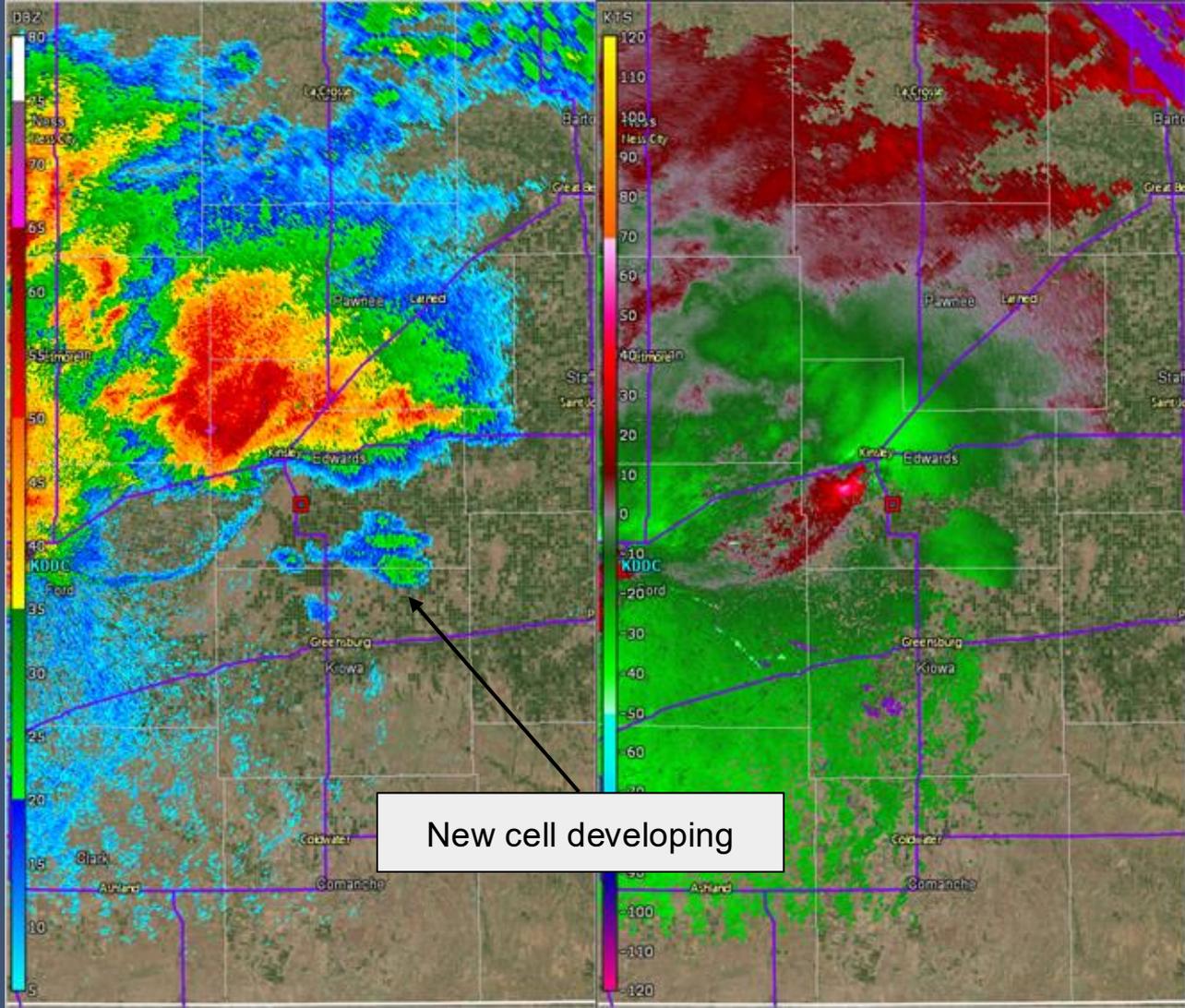
Tornado is gone, but lots of hail impacting the northern OKC metro

0140Z

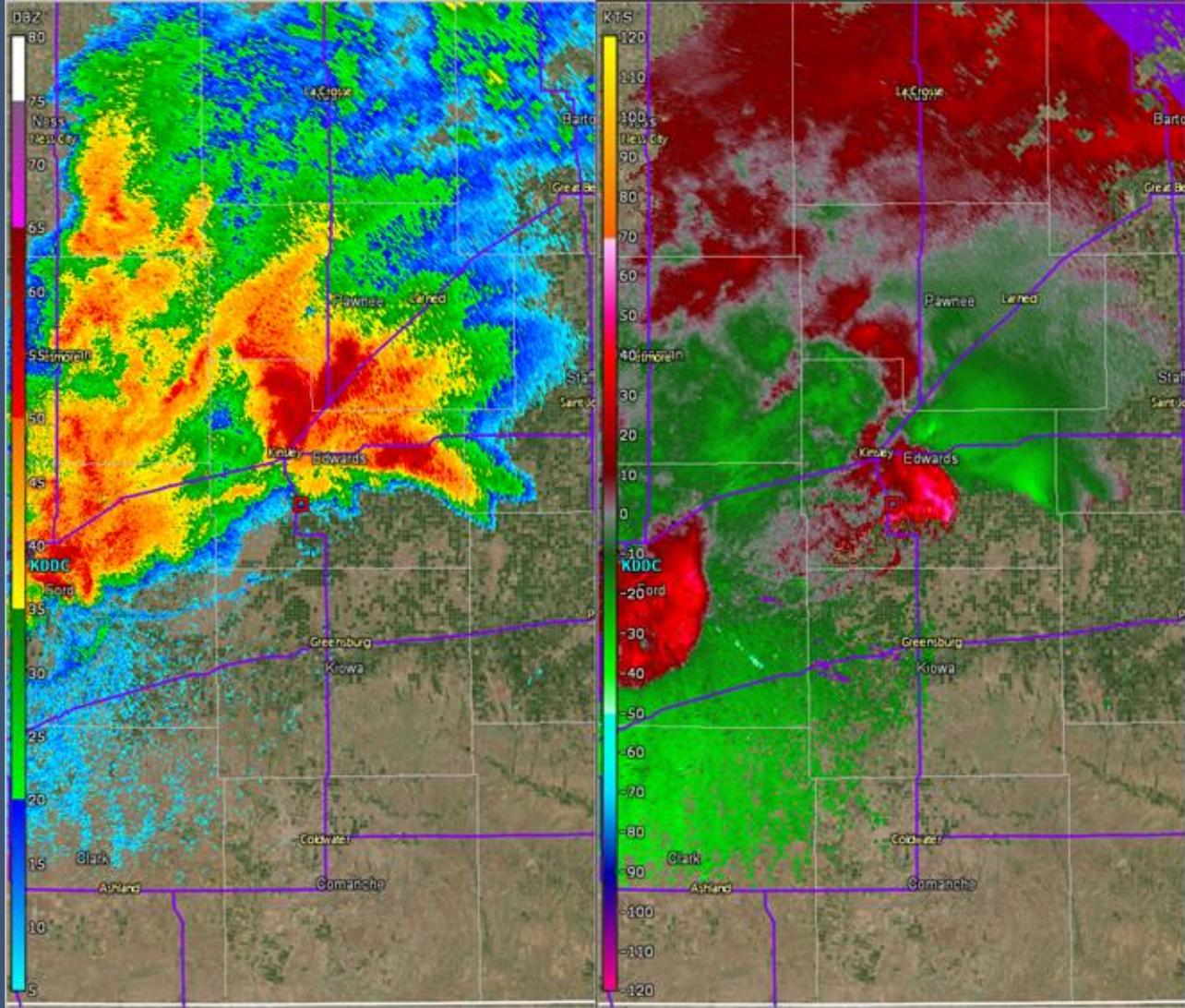




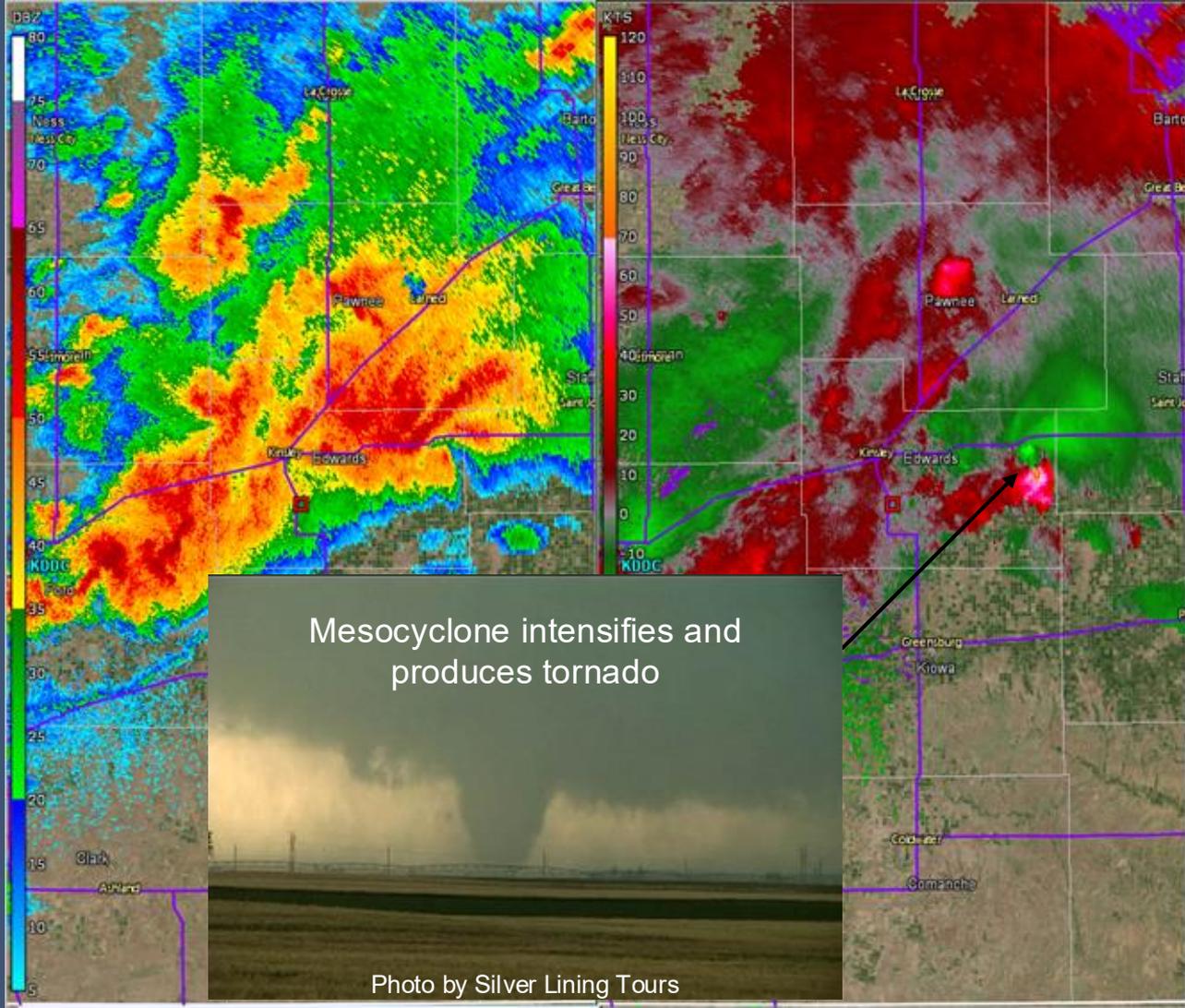












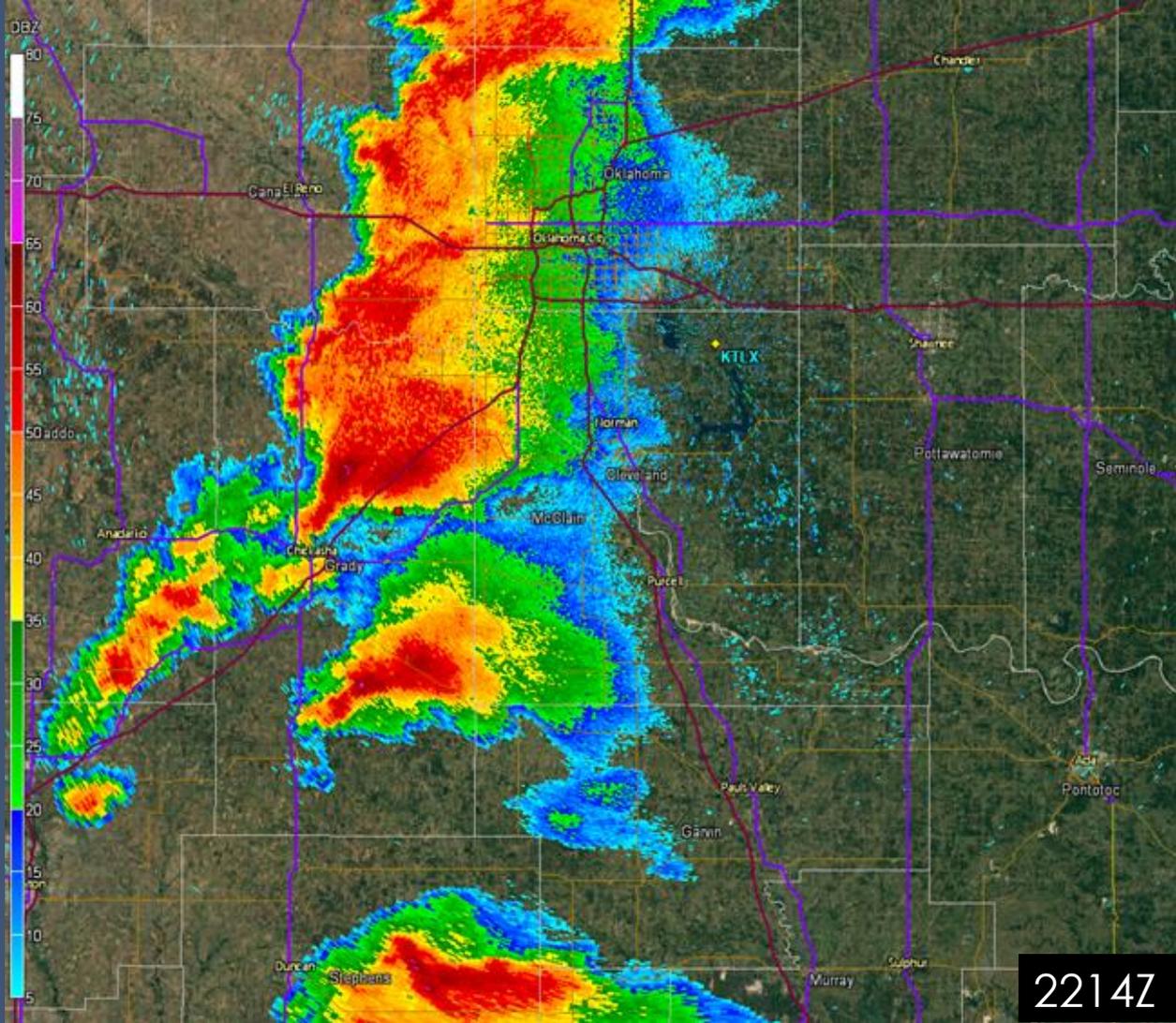
Mesocyclone intensifies and produces tornado

Photo by Silver Lining Tours

# Storm Interactions: Good or Bad?

**I don't know, I see a positive trend here!**

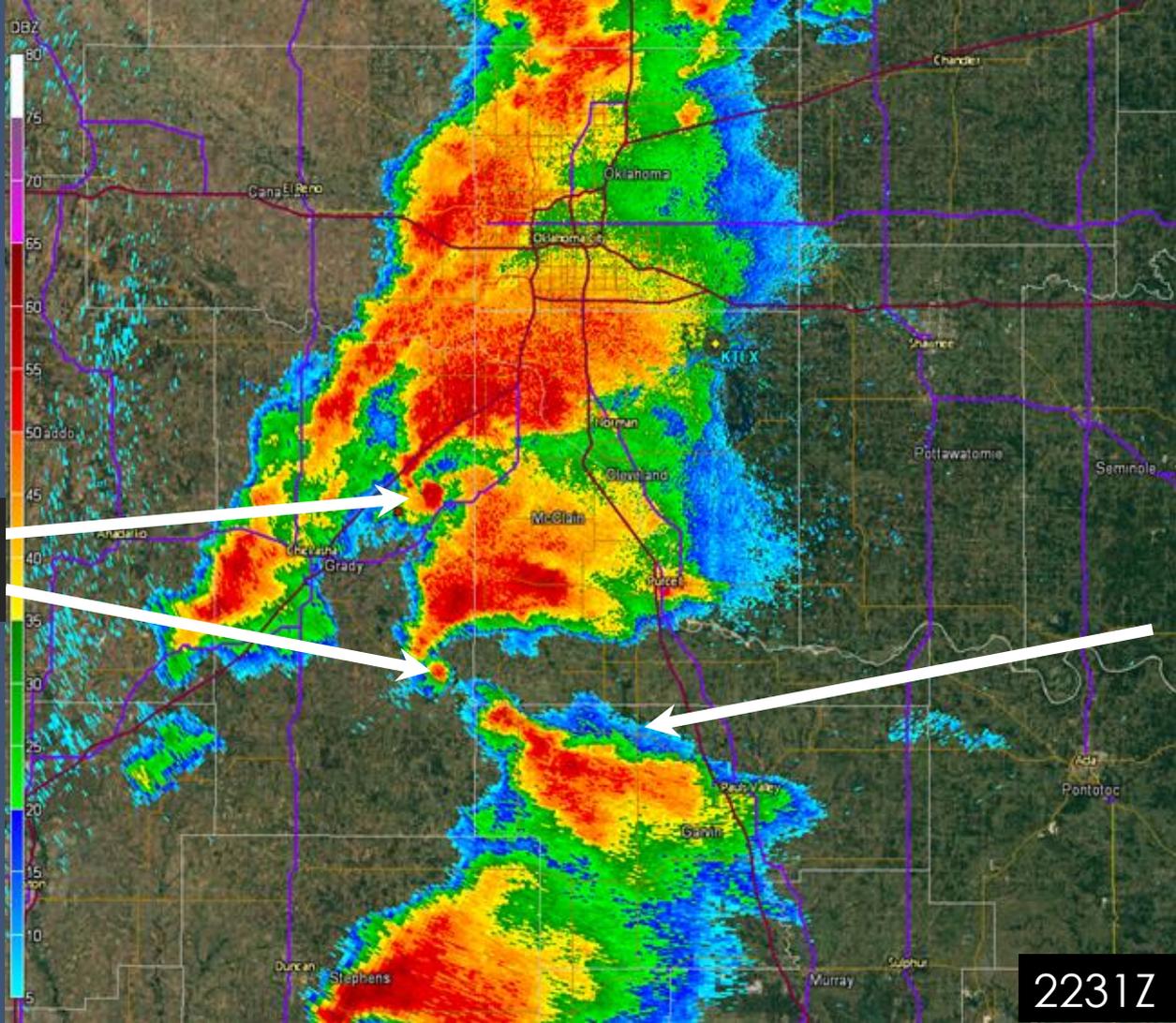




2214Z

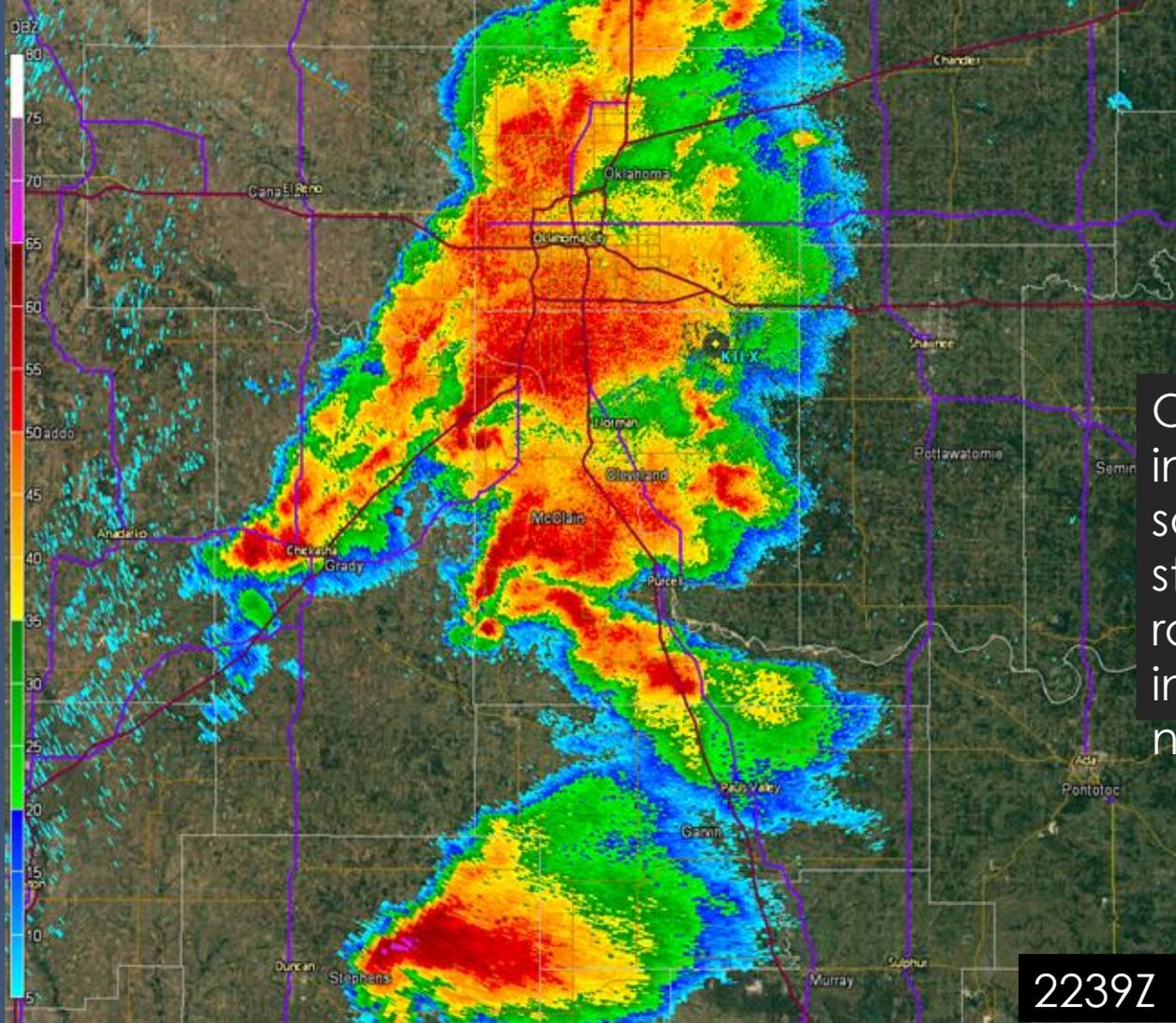


Damaging  
tornadoes



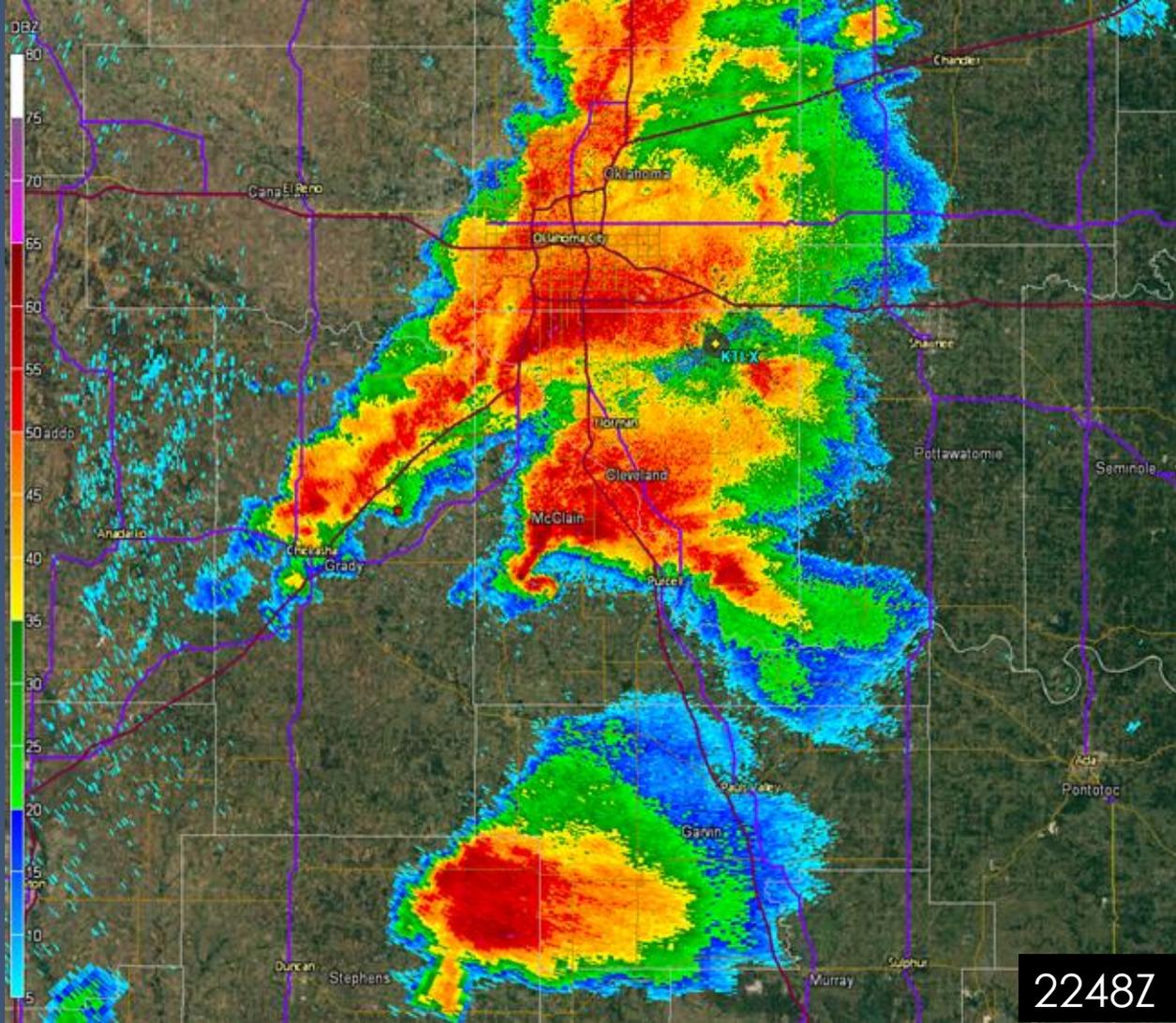
Remnant  
left mover

2231Z

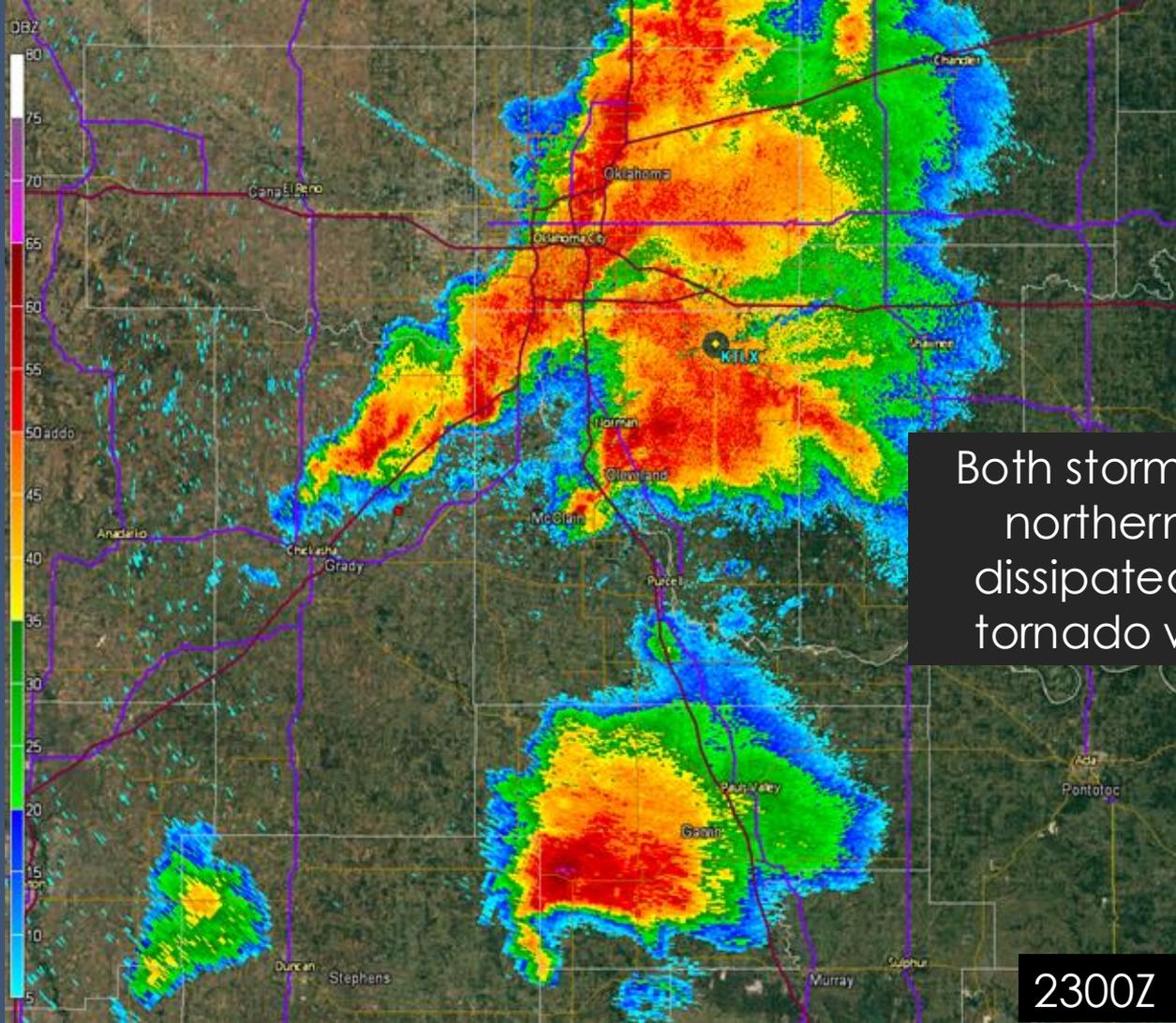


Outflow interacts with southern storm, which rains into inflow of northern storm

2239Z

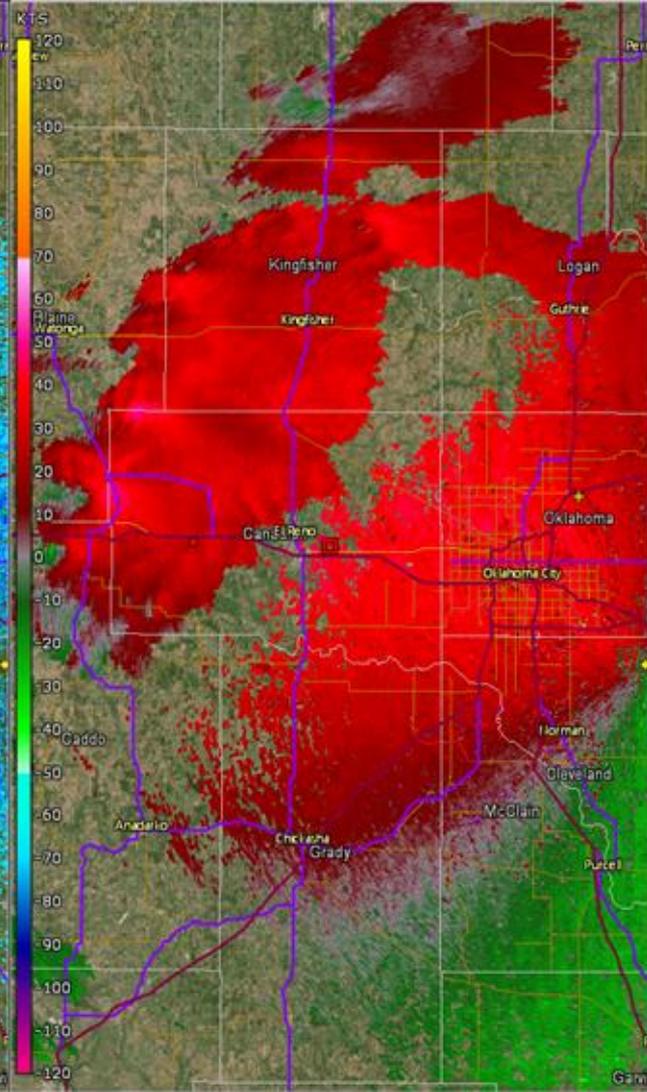
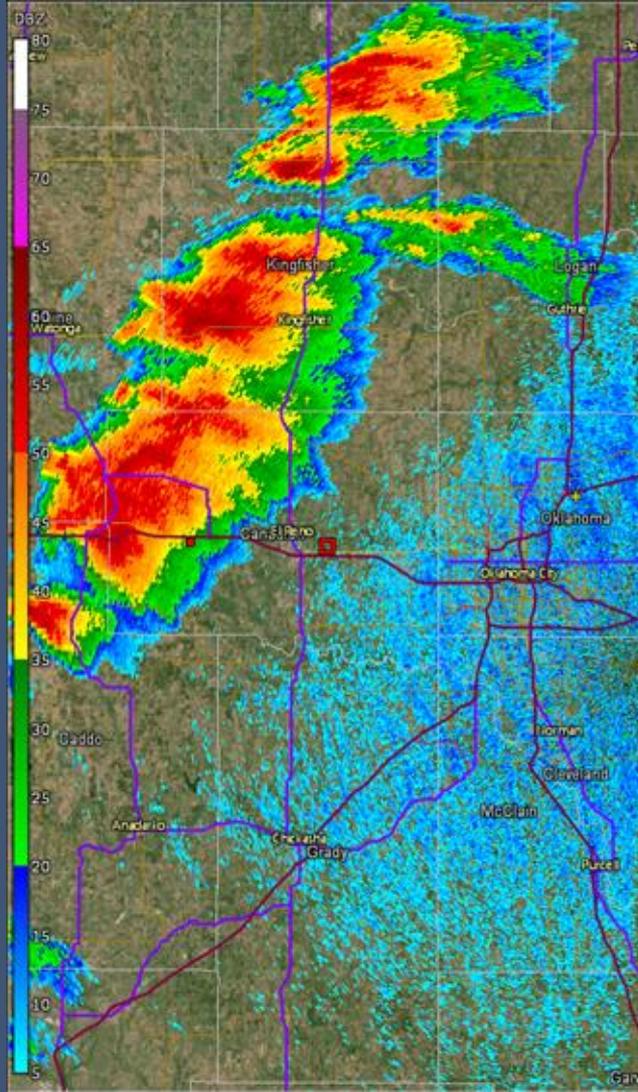


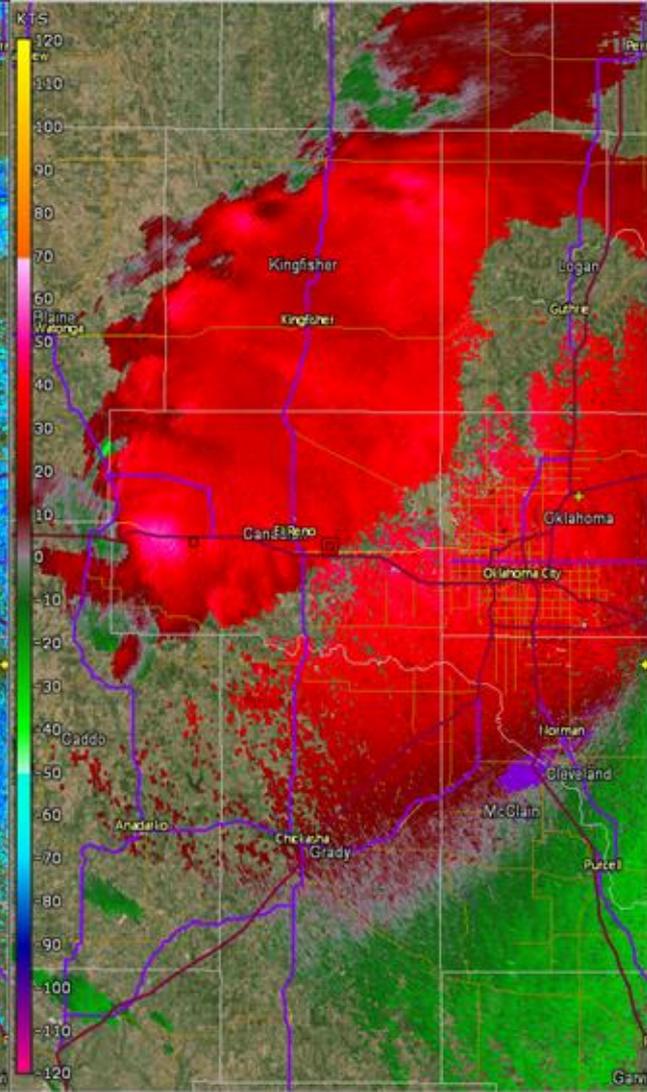
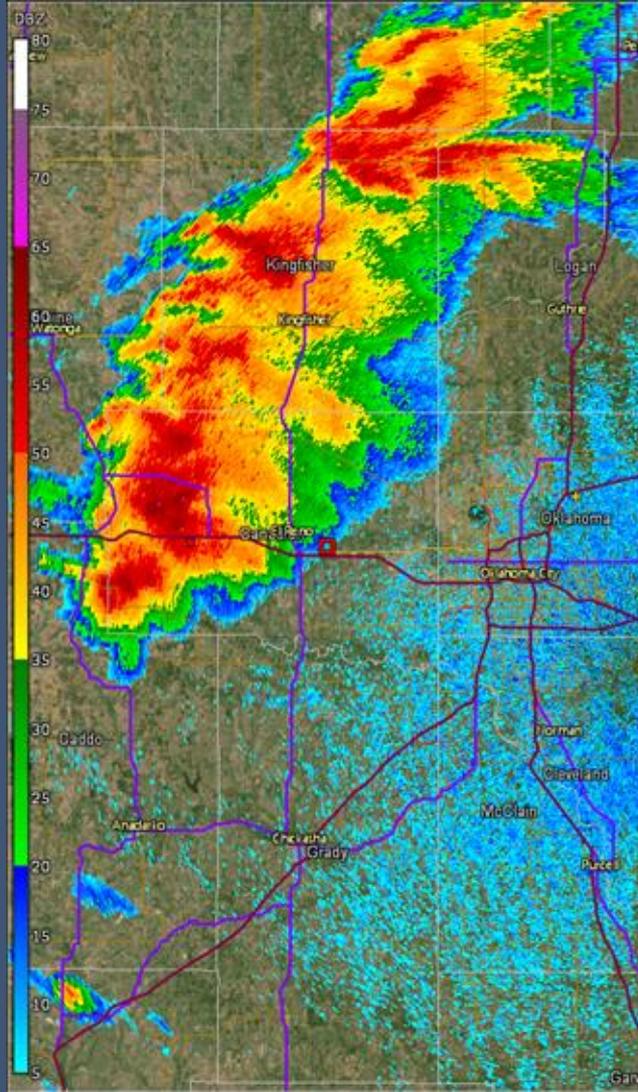
22487

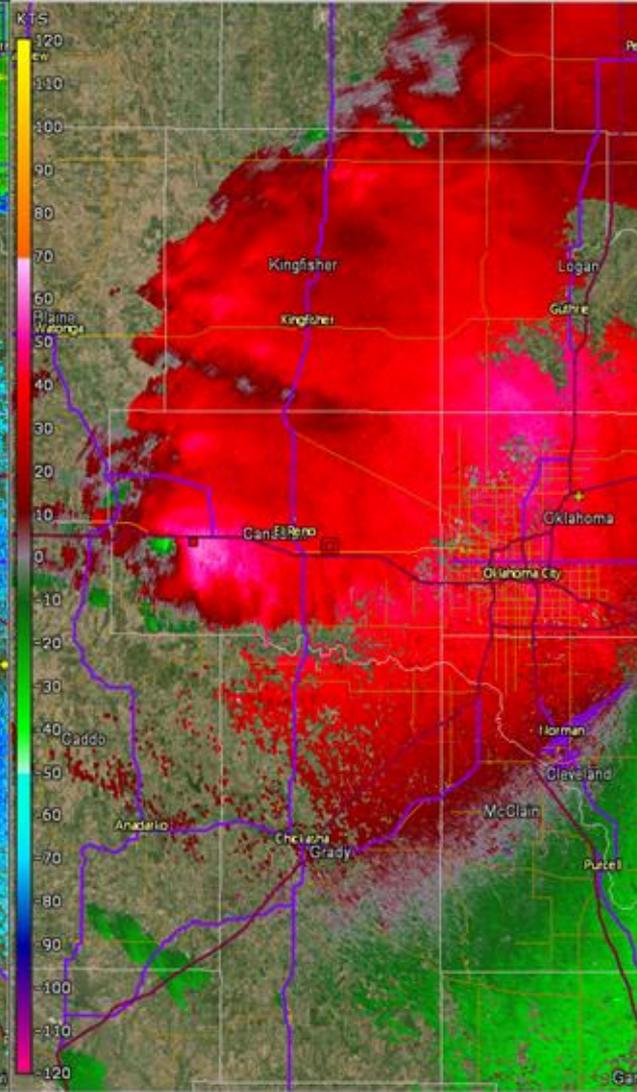
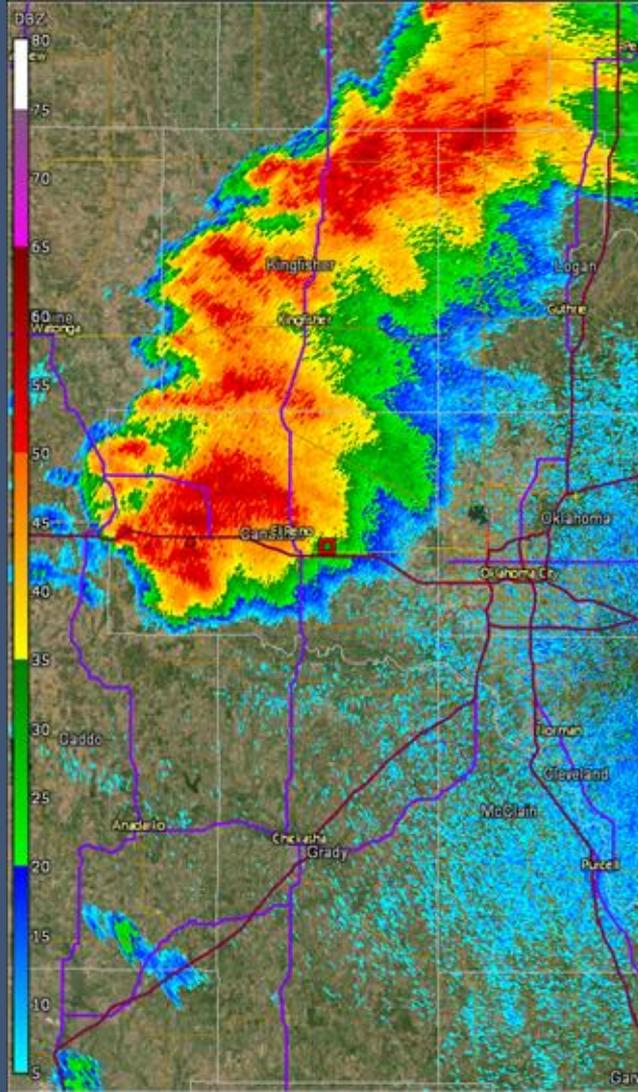


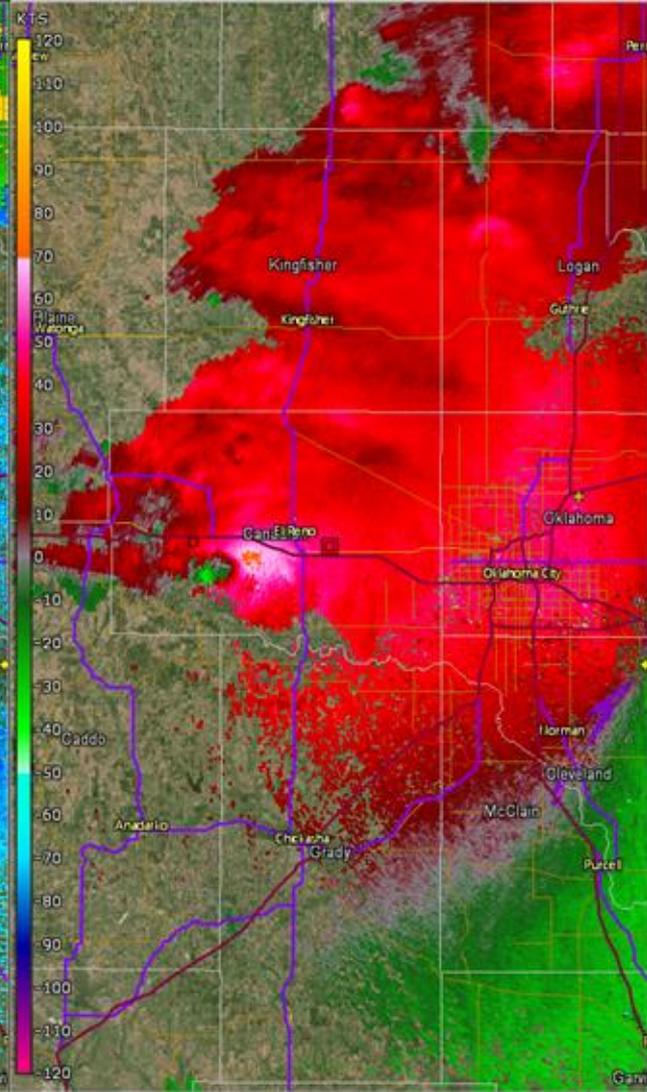
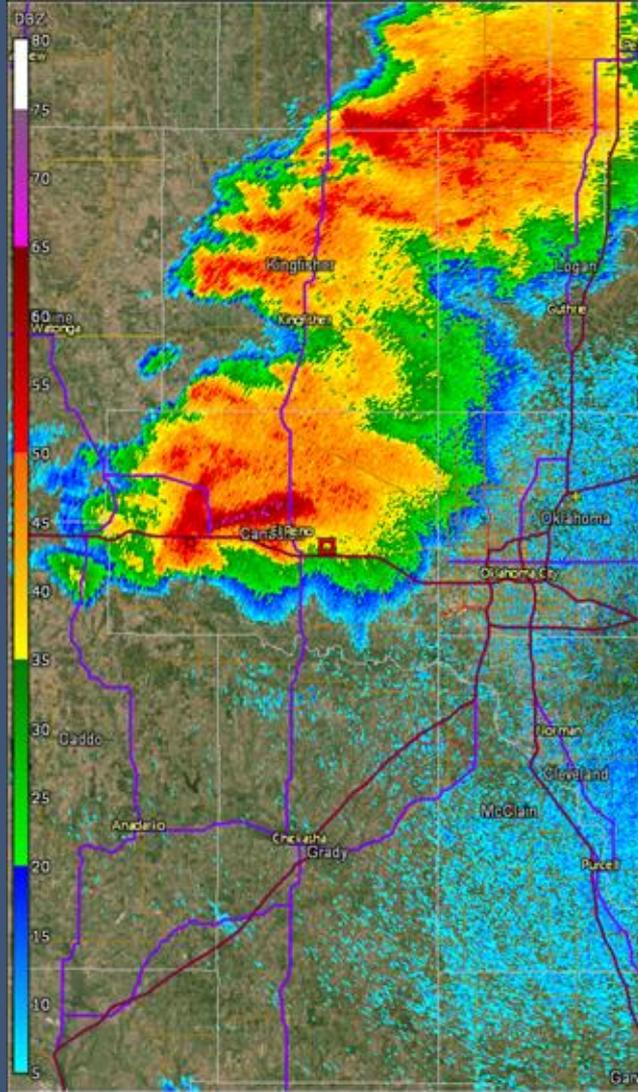
Both storms weaken – northern tornado dissipated, southern tornado weakening

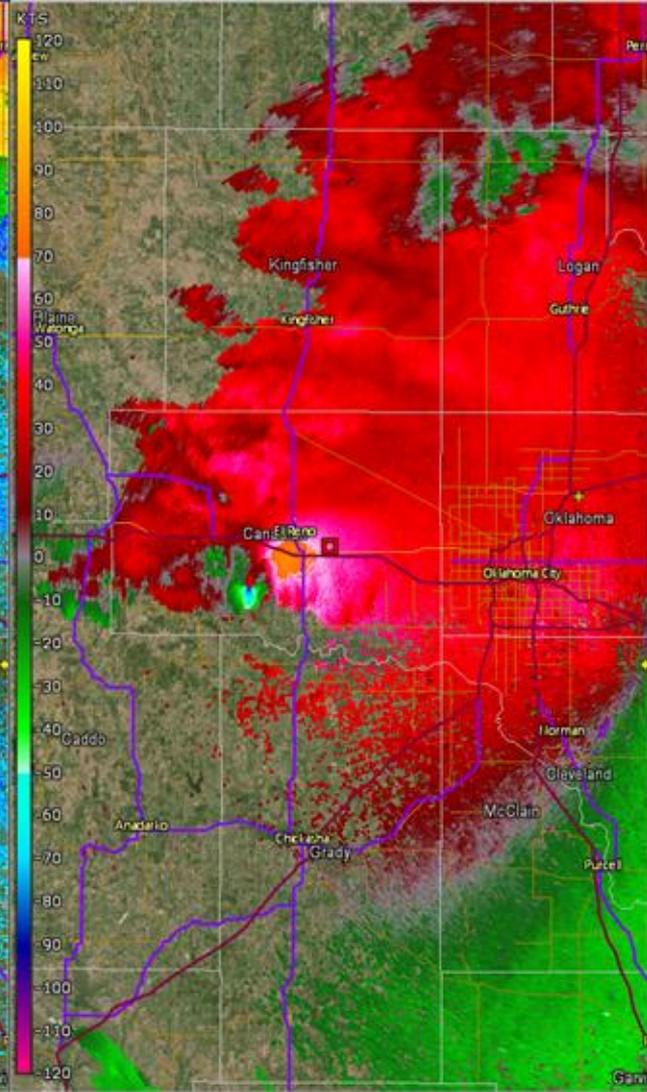
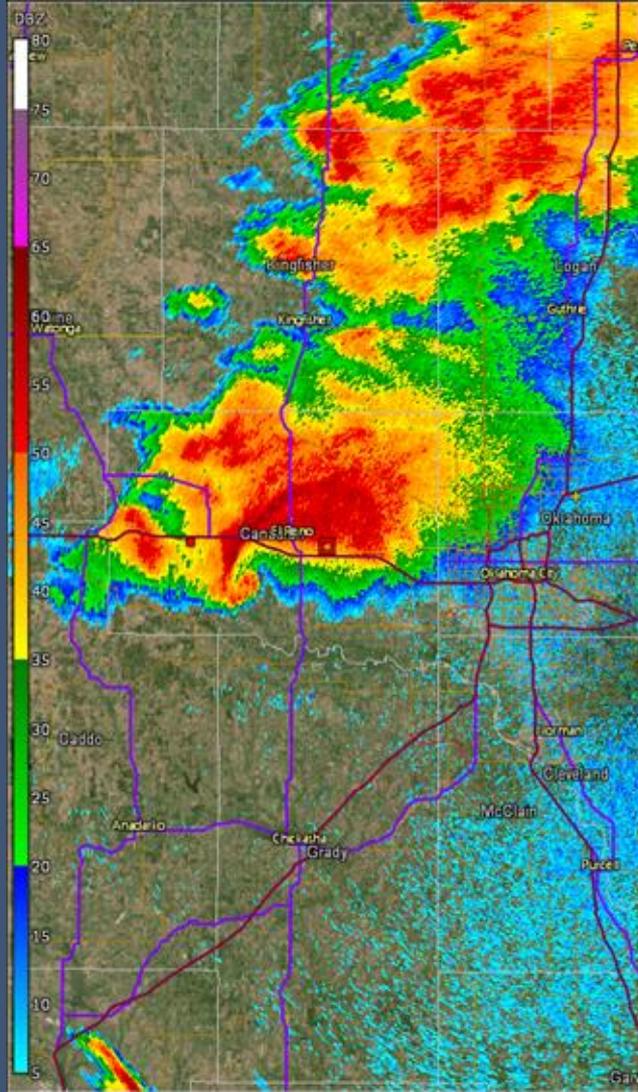
2300Z



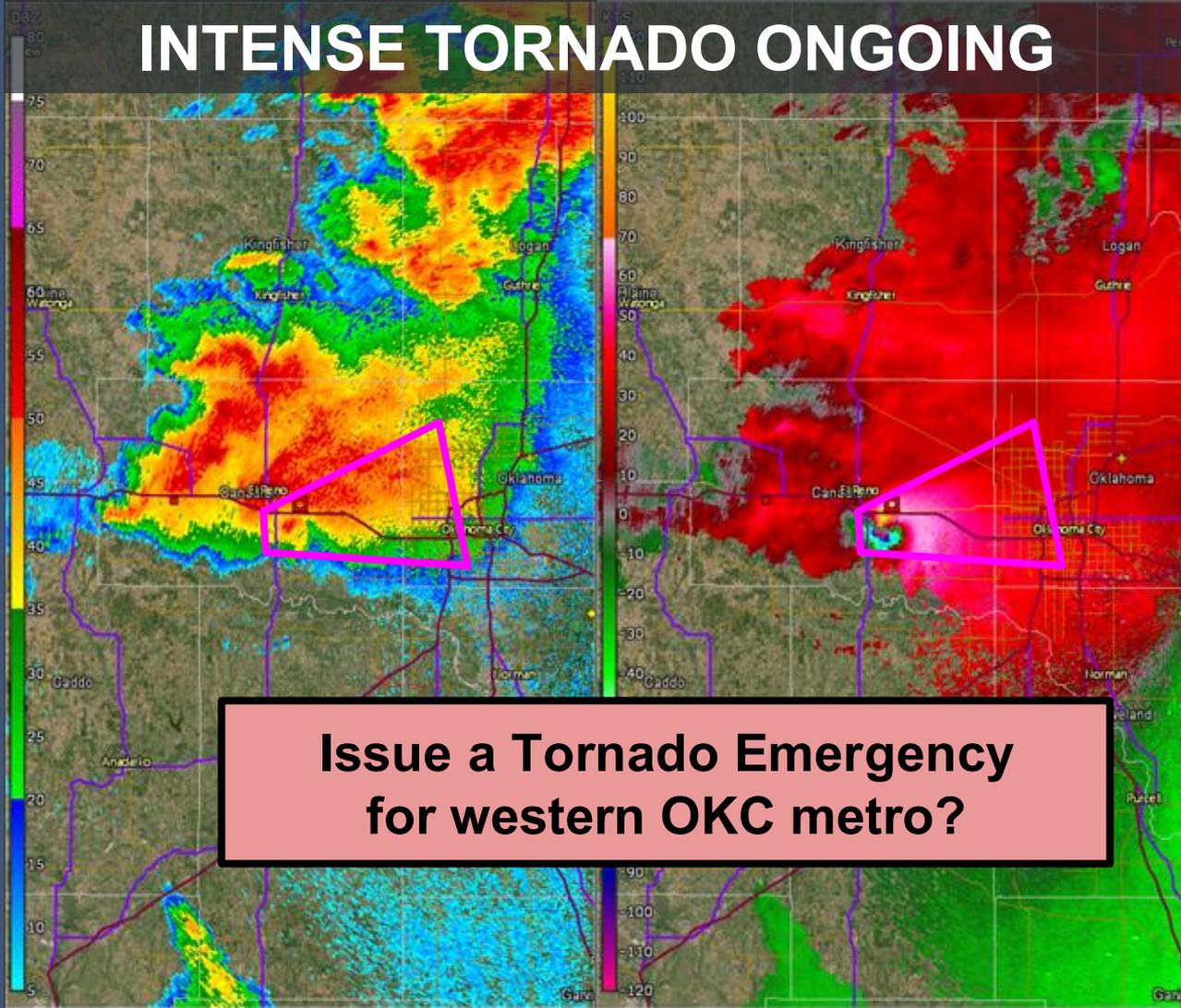




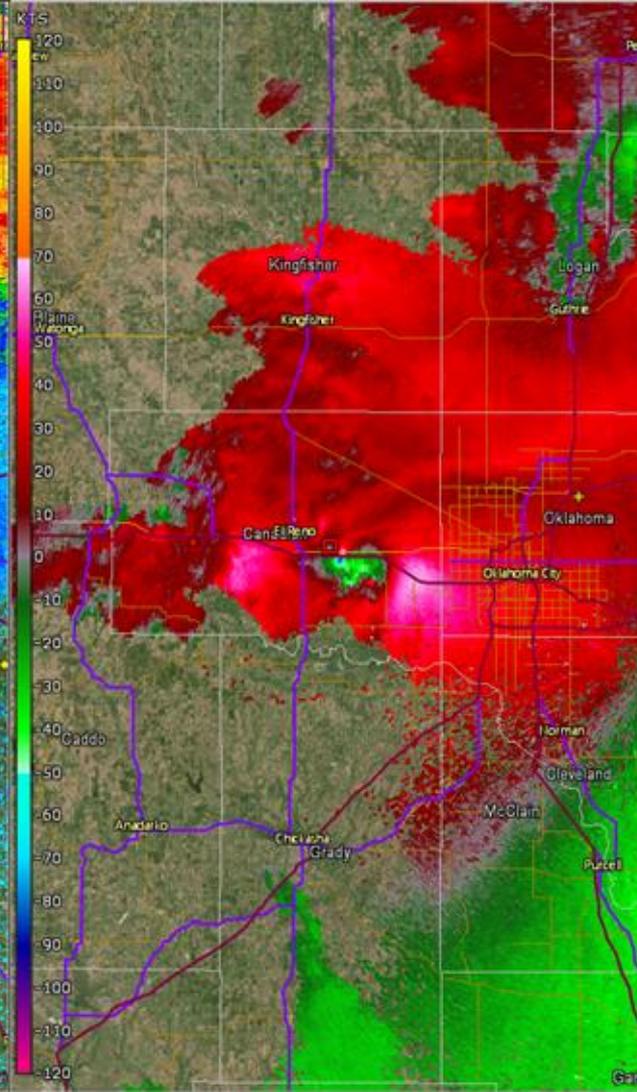
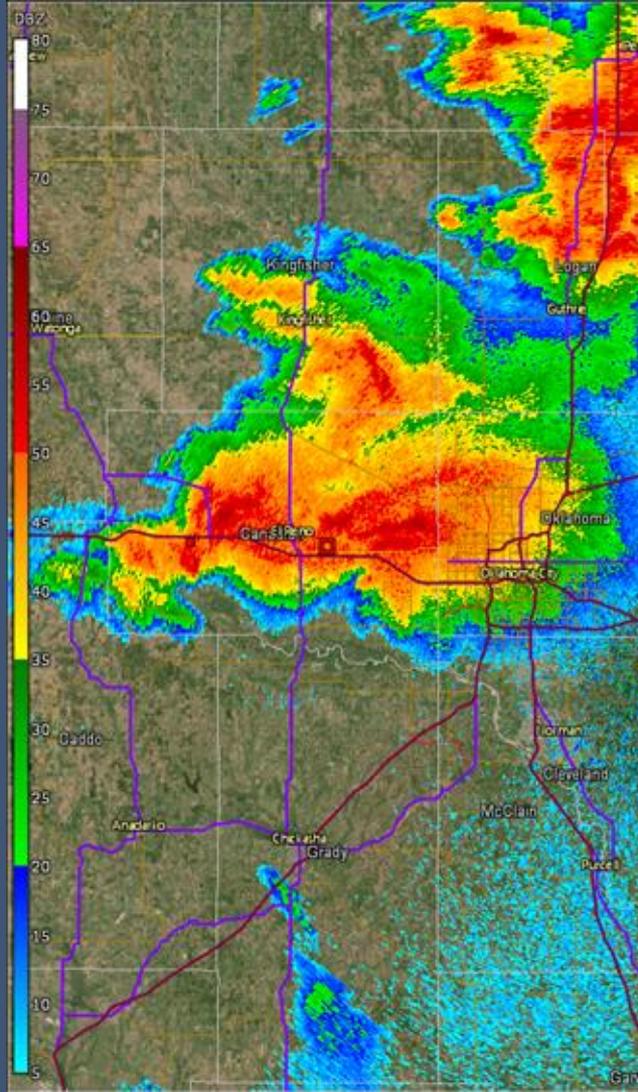


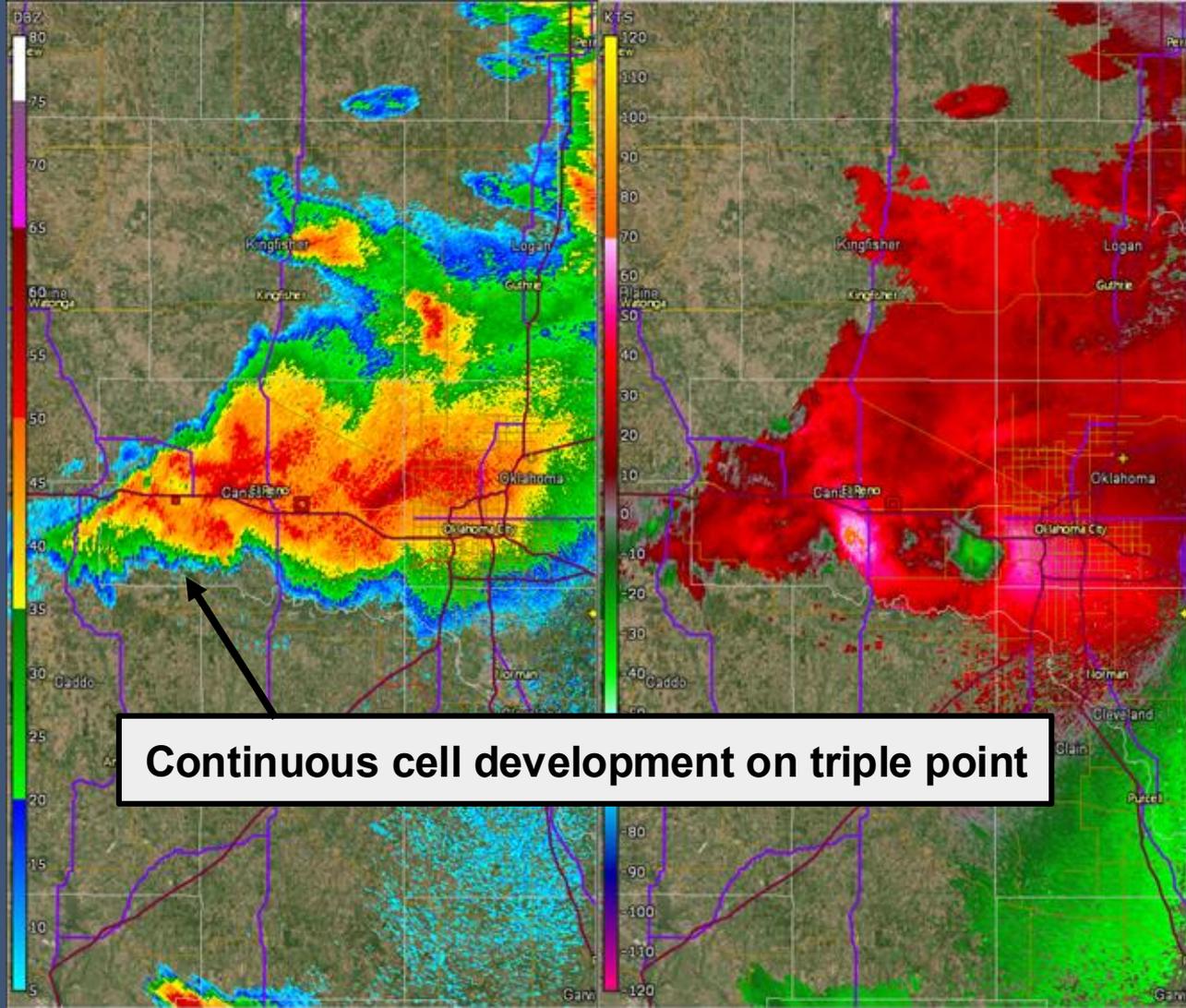


# INTENSE TORNADO ONGOING

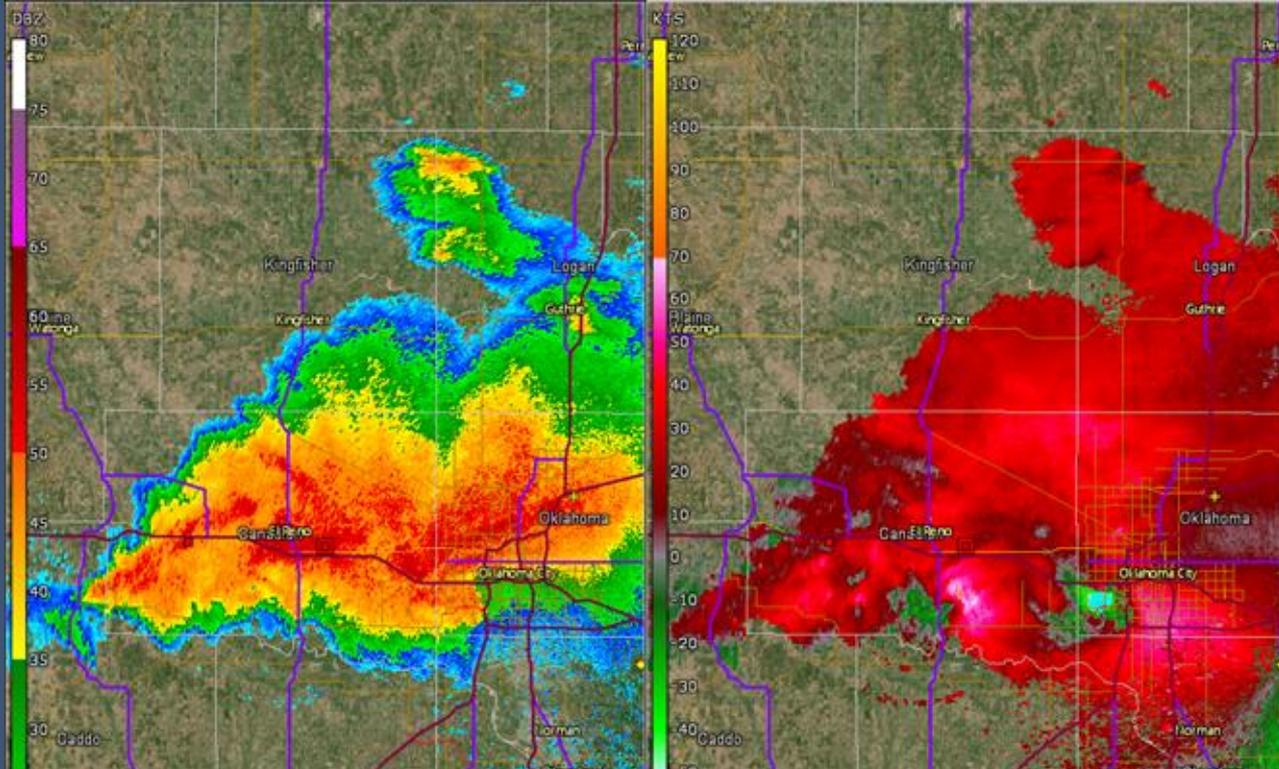


**Issue a Tornado Emergency  
for western OKC metro?**





**Continuous cell development on triple point**



**Onset of a deadly flash flood event in OKC  
(panic induced?)**

# Storm Interactions: What does the literature say?

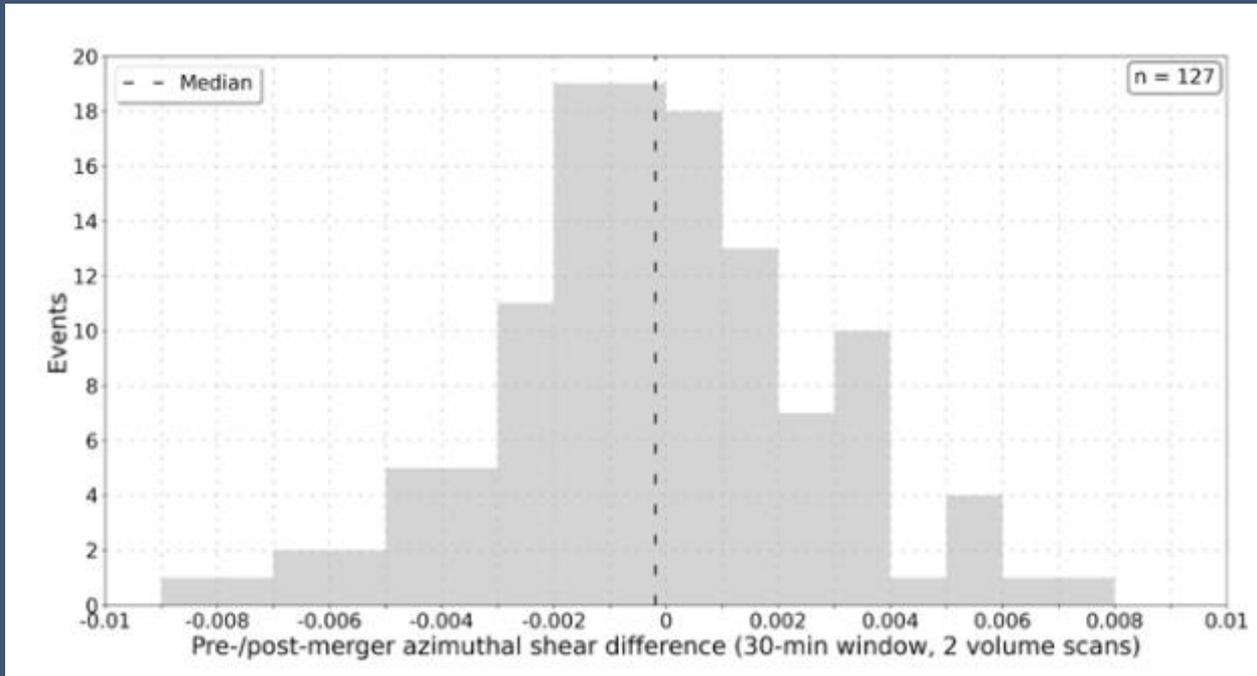


Figure 10 from Flournoy et al. 2020

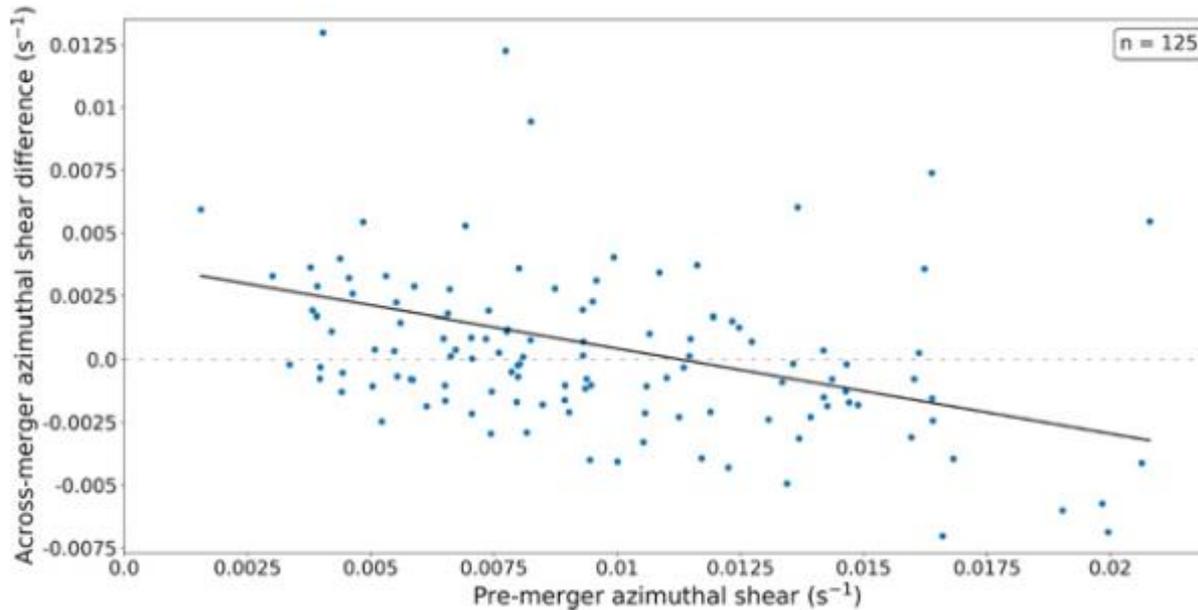
Flournoy et al. 2020 looked at 120+ instances of supercell mergers.

Found that there is no strong trend for constructive or destructive mergers.

This is consistent with previous studies.

Summary: It's not always clear!

# Storm Interactions: What does the literature say?



Flournoy et al. 2020 looked at 120+ instances of supercell mergers.

Did find some evidence that strong cells weaken and weak cells strengthen after mergers.

However, knowing which will occur will require a full environmental analysis!

Figure 11 from Flournoy et al. 2020

# Quick Recap

Storm Mode

Storm Interactions

Linear Extrapolation

Warm Sector Geometry

All very important  
for anticipating  
the correct  
hazards!