Impacts of Cold Pool Strength on Tornado Production in Quasi-Linear Convective Systems

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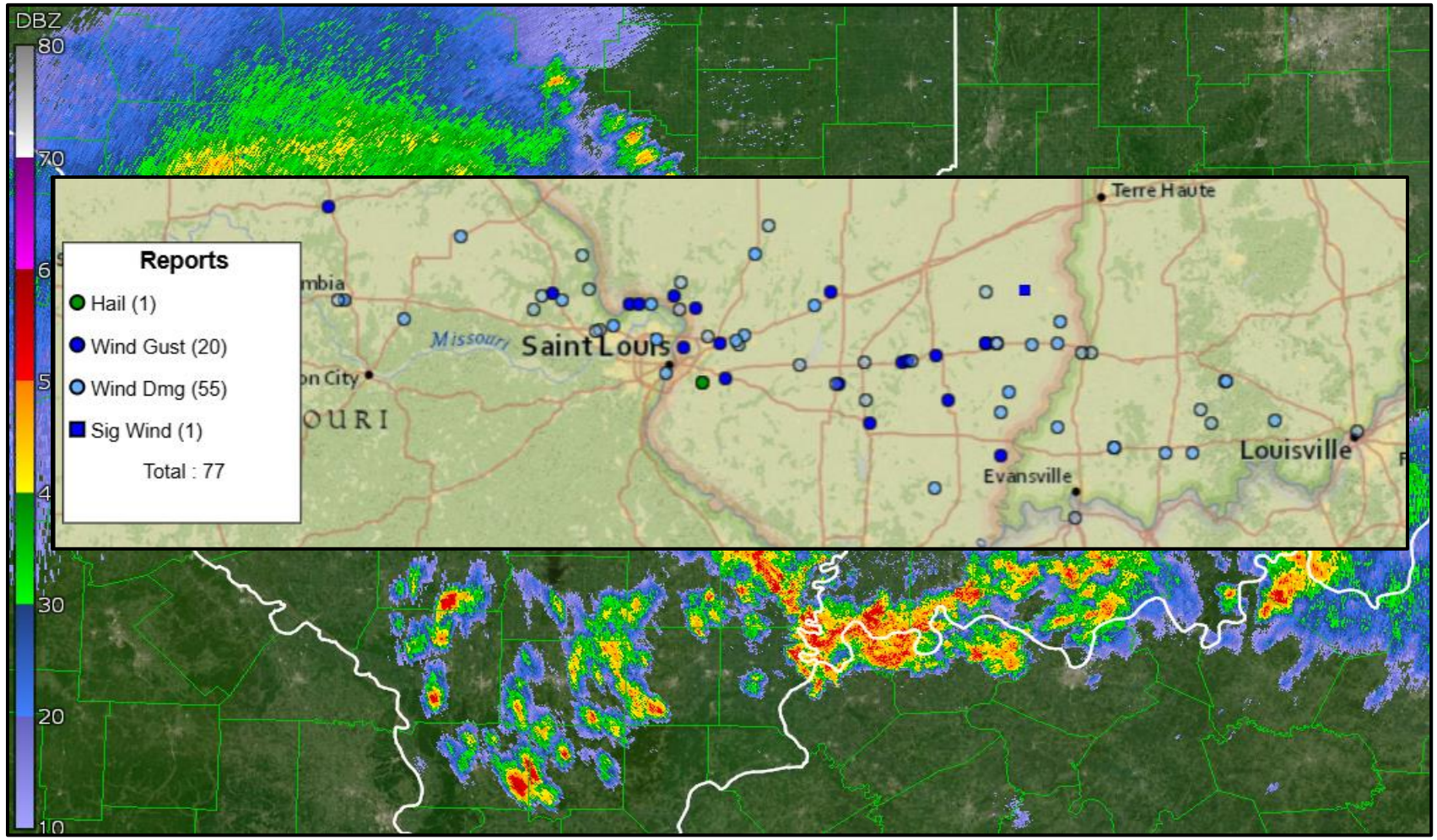
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What is a Quasi-linear Convective System (QLCS)?

- **Quasi-linear Convective System (QLCS):** A type of mesoscale convective system that features at least 35 dBZ of linear radar reflectivity for at least 75 kilometers along the long axis.
  - Squall lines
  - Bow echoes
  - Derechos
- QLCSs can be either **nontornadic** or **tornadic**.

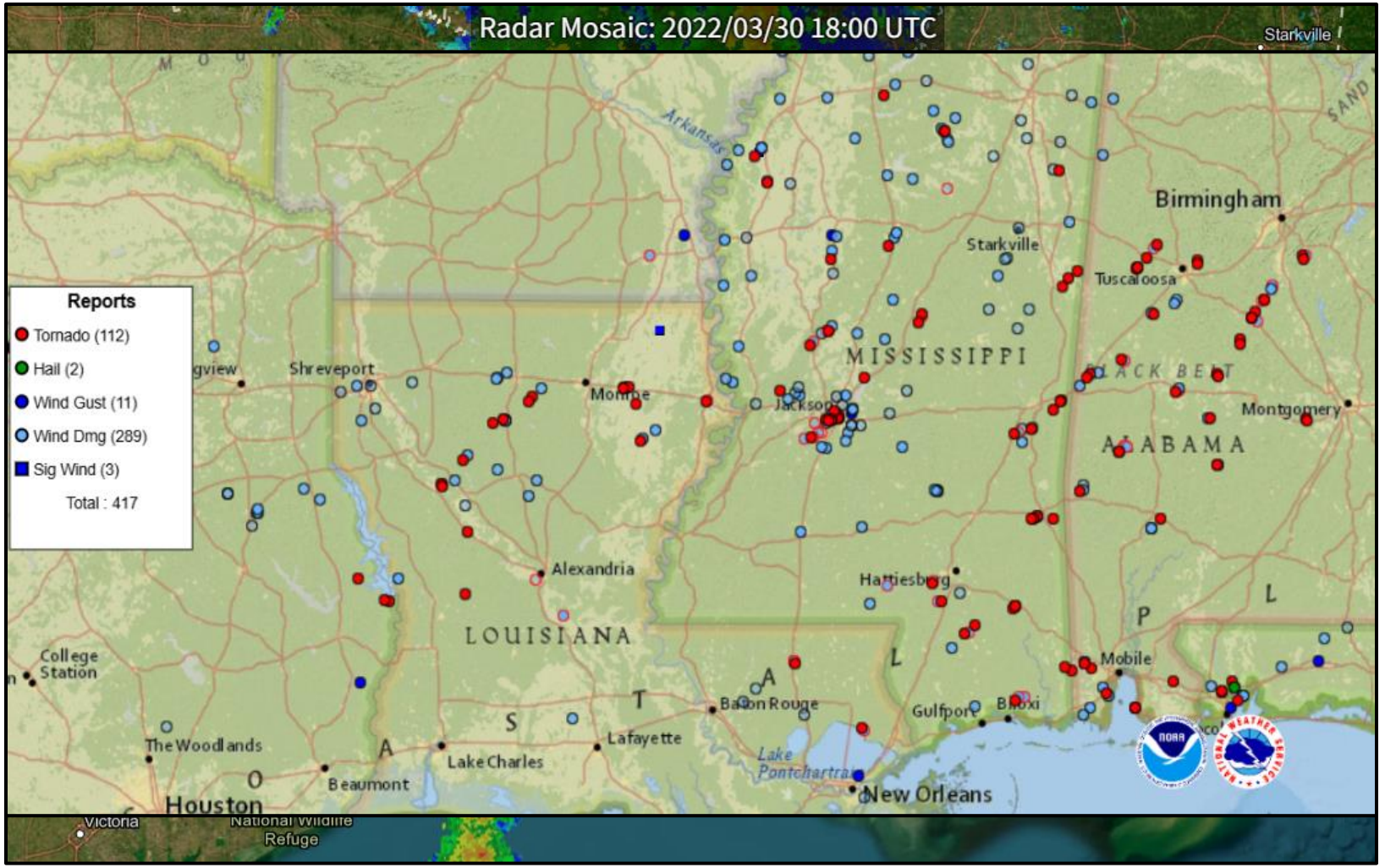
Nontornadic QLCS Example

- KVWX (Evansville, IN) at 1037 UTC on July 23, 2017 (convective day 7/22/17)
- Bow echo developed after thunderstorms grew upscale east of St. Louis
- Swath of severe wind reports produced
- Nontornadic event
- These types of QLCSs are very common in the central U.S. during the late spring and summer (May – September)



Tornadic QLCS Example

- Event: March 30, 2022
- Radar mosaic features a frontally-forced QLCS tracking across the Deep South
- 50 QLCS tornadoes produced
  - EF0: 14
  - EF1: 31
  - EF2: 5
- QLCS tornado outbreaks are not uncommon in the Southeast from October-May



Objectives of This Study

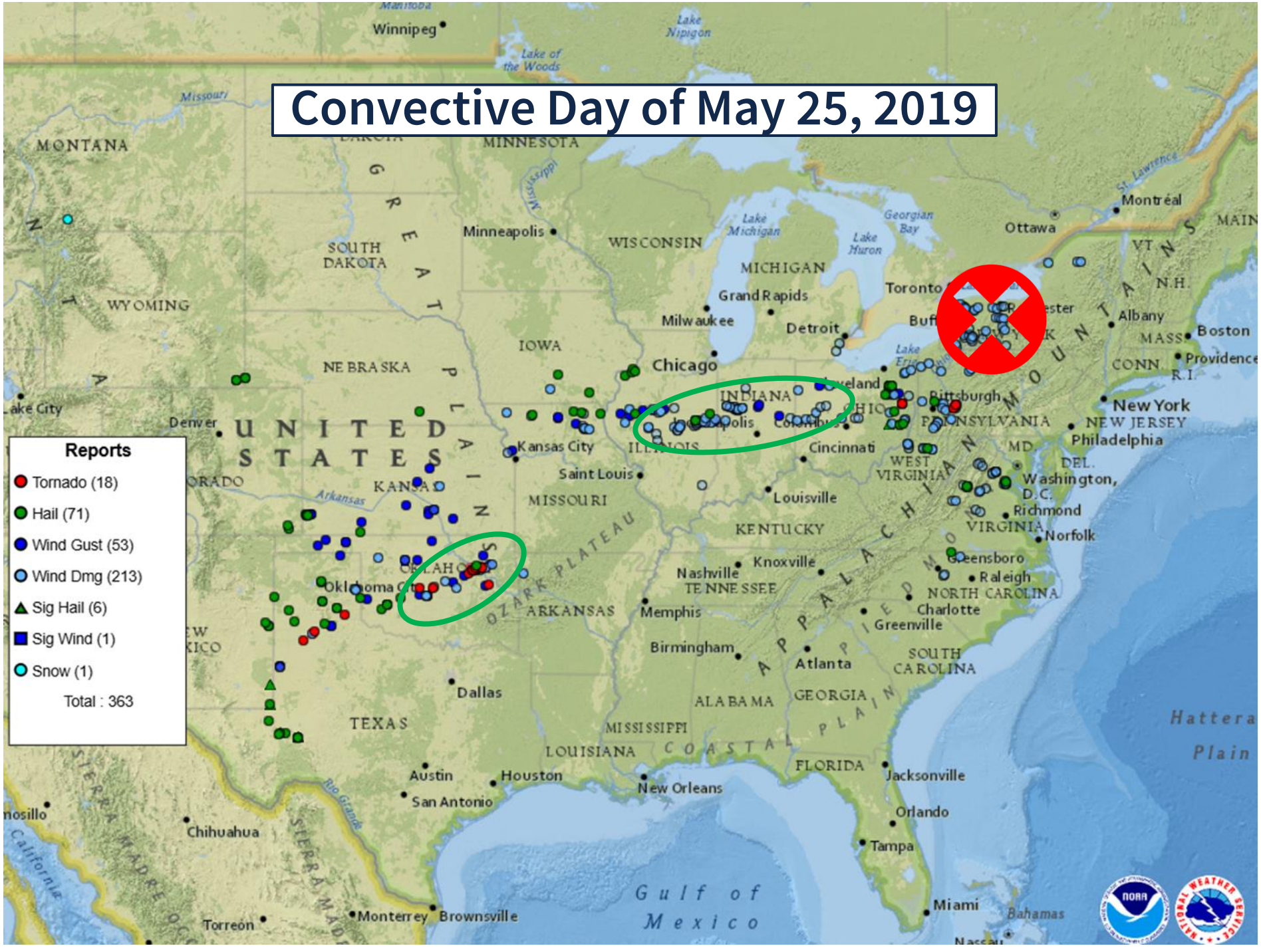
- Recent studies have investigated cold pool properties within tornadic and nontornadic QLCSs and their influence on QLCS tornadogenesis.
- Most previous studies of QLCS cold pools have been limited to case studies and data from field projects.
- To fill the gap, this study compiles a large dataset of tornadic and nontornadic QLCSs and analyzes the cold pool properties of each.
- **Disclaimer:** This study does **not** analyze the thermodynamic properties of QLCS mesovortices.
- Rather, this study analyzes the surface thermodynamic **environment** before, during, and after the passage of a QLCS over surface stations to determine cold pool strength.

Hypotheses

1. **More buoyant cold pools lead to increased tornado production in QLCSs.**
2. **Cold pool buoyancy is a less effective indicator of tornado production in QLCSs than vertical wind shear.**

Methods, Step 1: Find Severe QLCSs

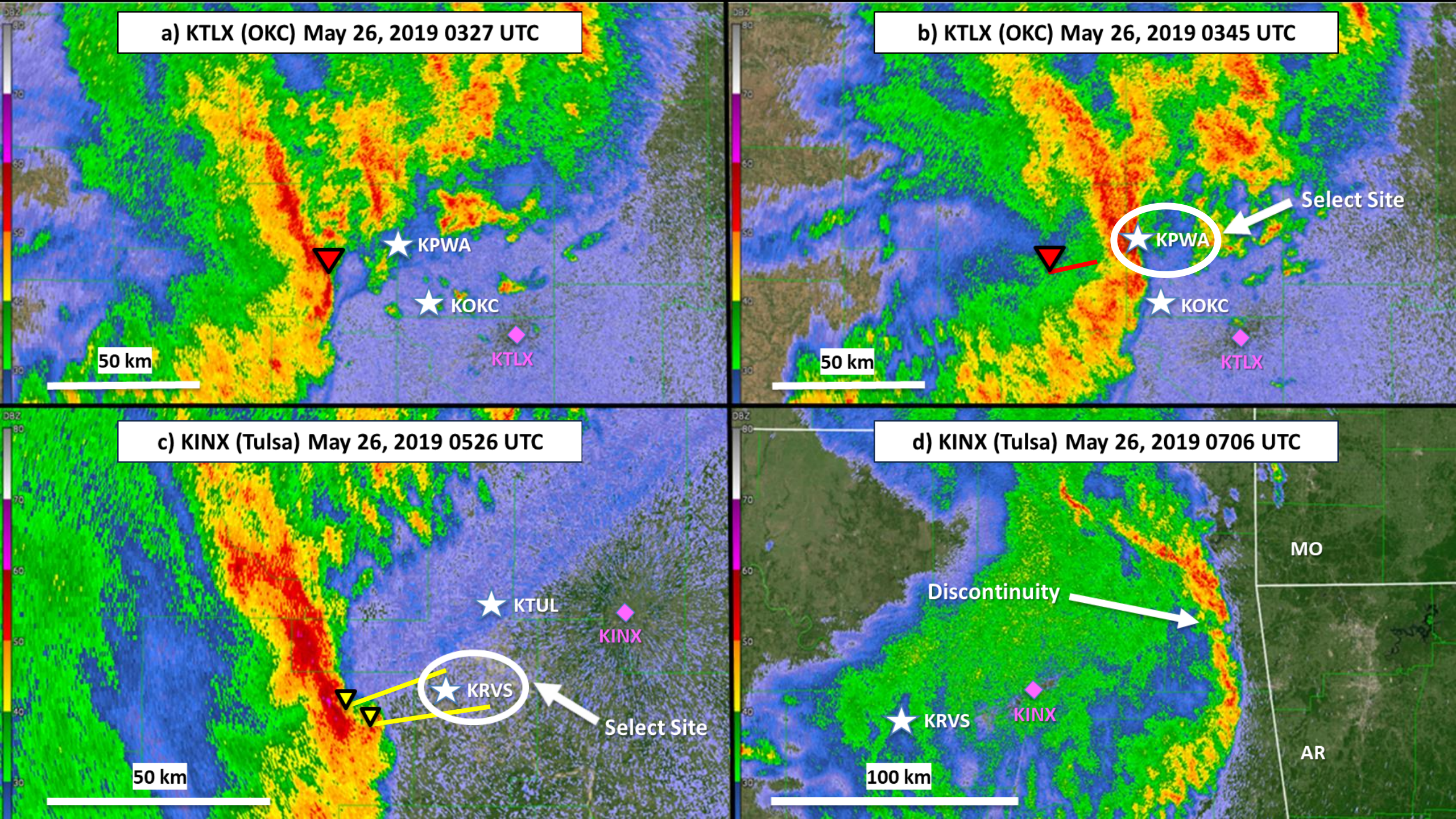
- Obtain a dataset of **severe QLCSs from 2017-2022.**
- **Severe QLCS:** a QLCS that tracked ≥100 km with severe wind reports along most of its track.
- Using the SPC storm reports database, filter convective days (1200 to 1159 UTC) with >200 severe wind reports
- Identify convective days with swaths of severe wind reports
- For a given convective day, analyze the radar mosaic to verify that a QLCS caused one or more swaths of severe wind reports
- Any QLCS that satisfies these criteria is a *potential* case.


Convective Day of May 25, 2019
Reports
Tornado (18)
Hail (71)
Wind Gust (53)
Wind Dmg (213)
Sig Hail (6)
Sig Wind (1)
Snow (1)
Total : 363
Winnipeg
Lake Nipigon
Lake of the Woods
Missouri
MONTANA
MINNESOTA
Minneapolis
WISCONSIN
Lake Michigan
Lake Huron
Georgian Bay
Ottawa
Montréal
St. Lawrence
SOUTH DAKOTA
WYOMING
MICHIGAN
Grand Rapids
Toronto
Milwaukee
Detroit
Albany
Boston
IOWA
NEBRASKA
Chicago
Providence
Denver
INDIANA
Cleveland
Pittsburgh
New York
UNITED STATES
Kansas City
ILLINOIS
Cincinnati
PENNSYLVANIA
NEW JERSEY
Philadelphia
Saint Louis
WEST VIRGINIA
MD.
DEL.
Washington, D.C.
KANSAS
MISSOURI
Louisville
Richmond
KENTUCKY
VIRGINIA
Norfolk
Arkansas
Knoxville
Nashville
TENNESSEE
Raleigh
NORTH CAROLINA
Memphis
Charlotte
ARKANSAS
Greenville
Birmingham
Atlanta
SOUTH CAROLINA
Dallas
ALABAMA
GEORGIA
TEXAS
MISSISSIPPI
LOUISIANA
FLORIDA
Jacksonville
Austin
Houston
New Orleans
San Antonio
Orlando
Chihuahua
Tampa
Gulf of Mexico
Miami
Bahamas
Torreon
Monterrey
Brownsville
Nassau

Methods, Step 2: Analyze Each QLCS

- Radar criteria:
  - Must be within 250 km of a WSR-88D site.
  - Must exhibit at least 35 dBZ for a length of ≥ 75 km along the long axis on the 0.5° scan.
  - Must track ≥ 100 km and remain intact along the path.
- Select ASOS (at least 100 km apart) along the trajectory of each QLCS
- ASOS must be within either 50 km of a QLCS tornado track (classified as a **tornadic** QLCS environment) or a severe wind report (classified as a **nontornadic** QLCS environment).
  - If a QLCS tornado was rated ≥EF2, a site within 50 km of its track is classified as **significantly tornadic**.
- **Priority given to ASOS nearest a QLCS tornado track or near a stronger wind gust.**

Let's look at an example case…


a) KTLX (OKC) May 26, 2019 0327 UTC
KPWA
KOKC
KTLX
50 km
b) KTLX (OKC) May 26, 2019 0345 UTC
Select Site
KPWA
KOKC
KTLX
50 km
c) KINX (Tulsa) May 26, 2019 0526 UTC
KTUL
KINX
KRVS
Select Site
50 km
d) KINX (Tulsa) May 26, 2019 0706 UTC
Discontinuity
MO
KRVS
KINX
AR
100 km

Methods, Step 3: Calculate Cold Pool Buoyancy

- Virtual potential temperature perturbation, or θ_v', quantifies cold pool buoyancy.
- As θ_v' becomes less negative, cold pool buoyancy increases.
- Calculate θ_v' from 1-minute ASOS data from the IEM (formulas from Bolton 1980)

$$\theta = T\left(\frac{P_0}{P}\right)^{R_d/c_p}$$

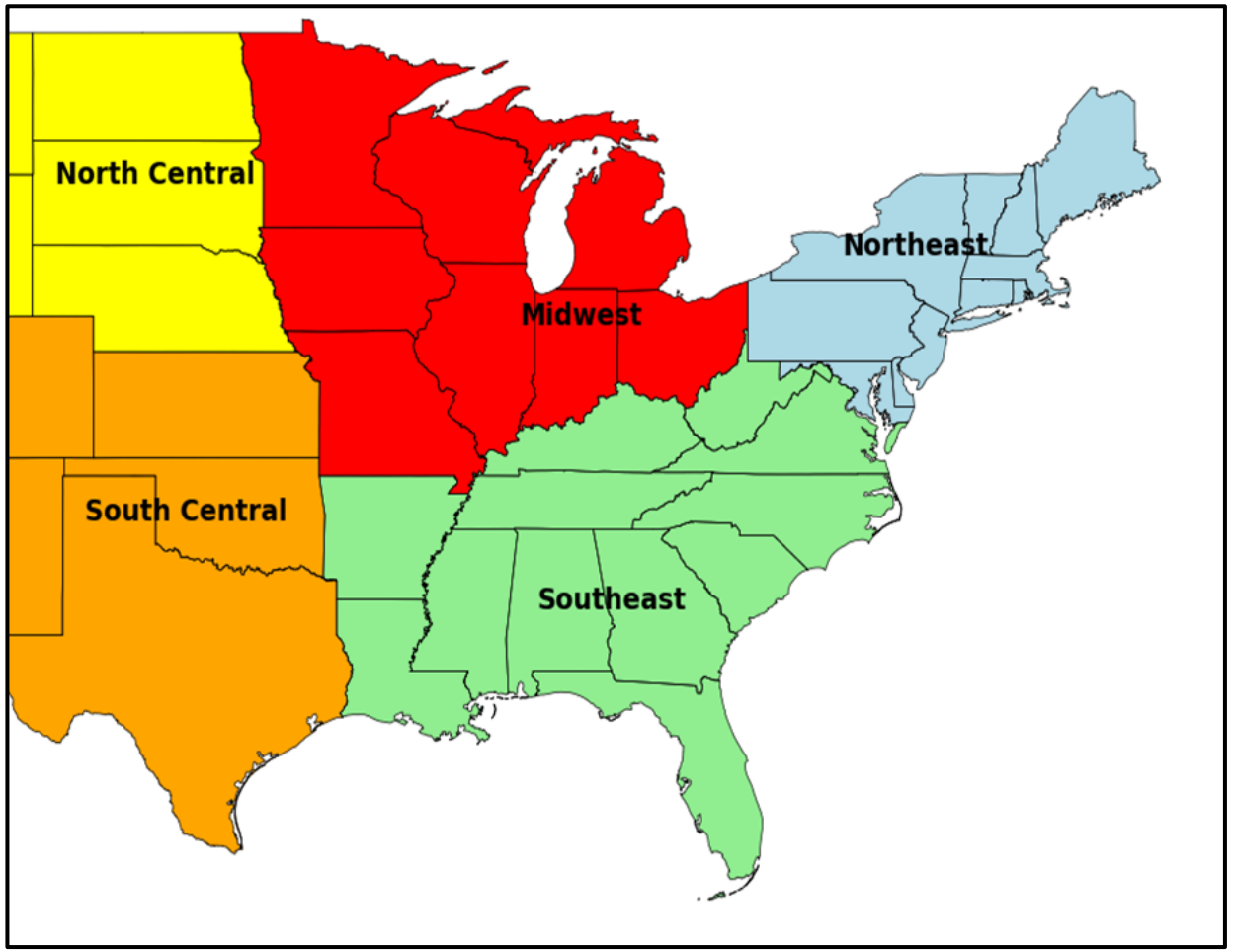
$$\theta_v \approx \theta(1 + 0.61r)$$

- $\theta_v' = \theta_{v,\text{ cold pool}} - \theta_{v,\text{ environment}}$
  - $\theta_{v,\text{ environment}}$: 30-minute average of the pre-QLCS environment base state
  - $\theta_{v,\text{ cold pool}}$: 30-minute average of the cold pool base state

Methods, Step 4: Classify Each ASOS Site

Season	Months
Cold	Oct-Feb
Spring	Mar-May
Warm	Jun-Sep

Time of Day	Definition
Morning	Sunrise - Noon
Daytime	Noon – 1 hour before sunset
Evening	1 hour before – 1 hour after sunset
Night	1 hour after sunset to sunrise



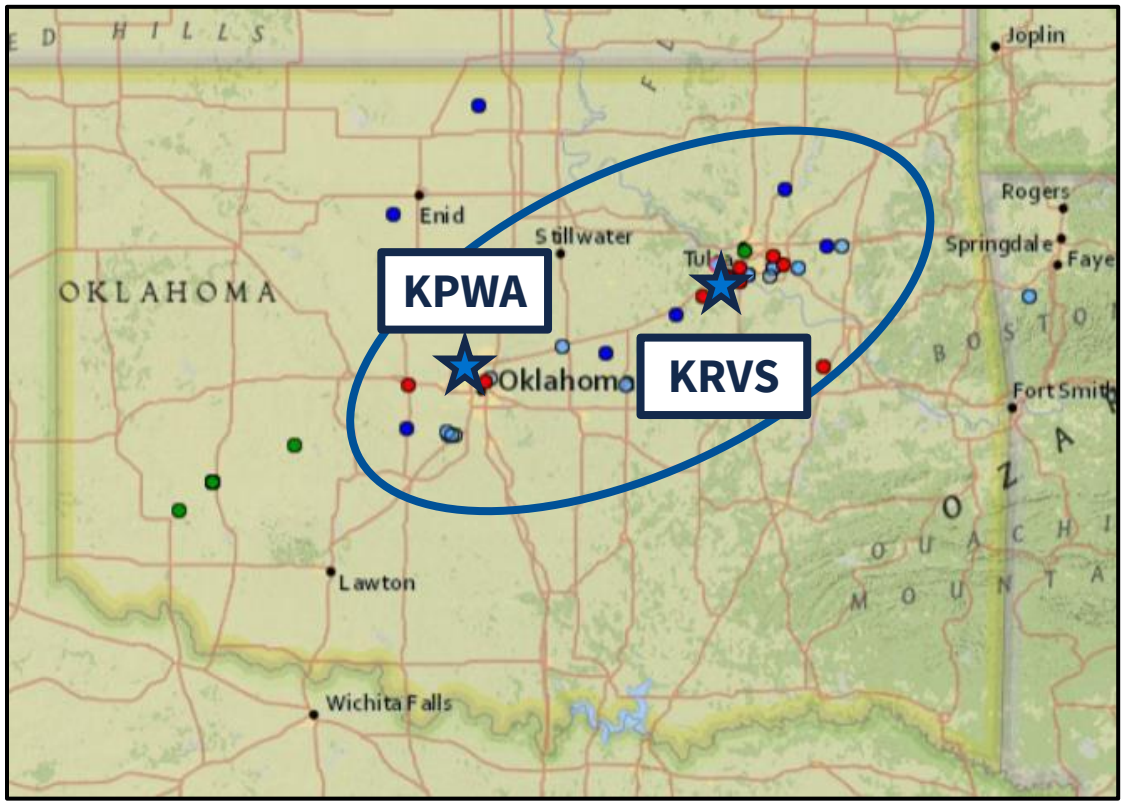
Methods, Step 5: Categorize Each QLCS Based on Tornado Production

Category	Number of QLCS Tornadoes
0	Nontornadic
1	1-4 EF0/EF1
2	5-10 EF0/EF1 and/or 1-2 EF2+
3	11-20 EF0/EF1 and/or 3-5 EF2+
4	>20 EF0/EF1 and/or >5 EF2+

Example: The Oklahoma Tornadic QLCS of May 25, 2019

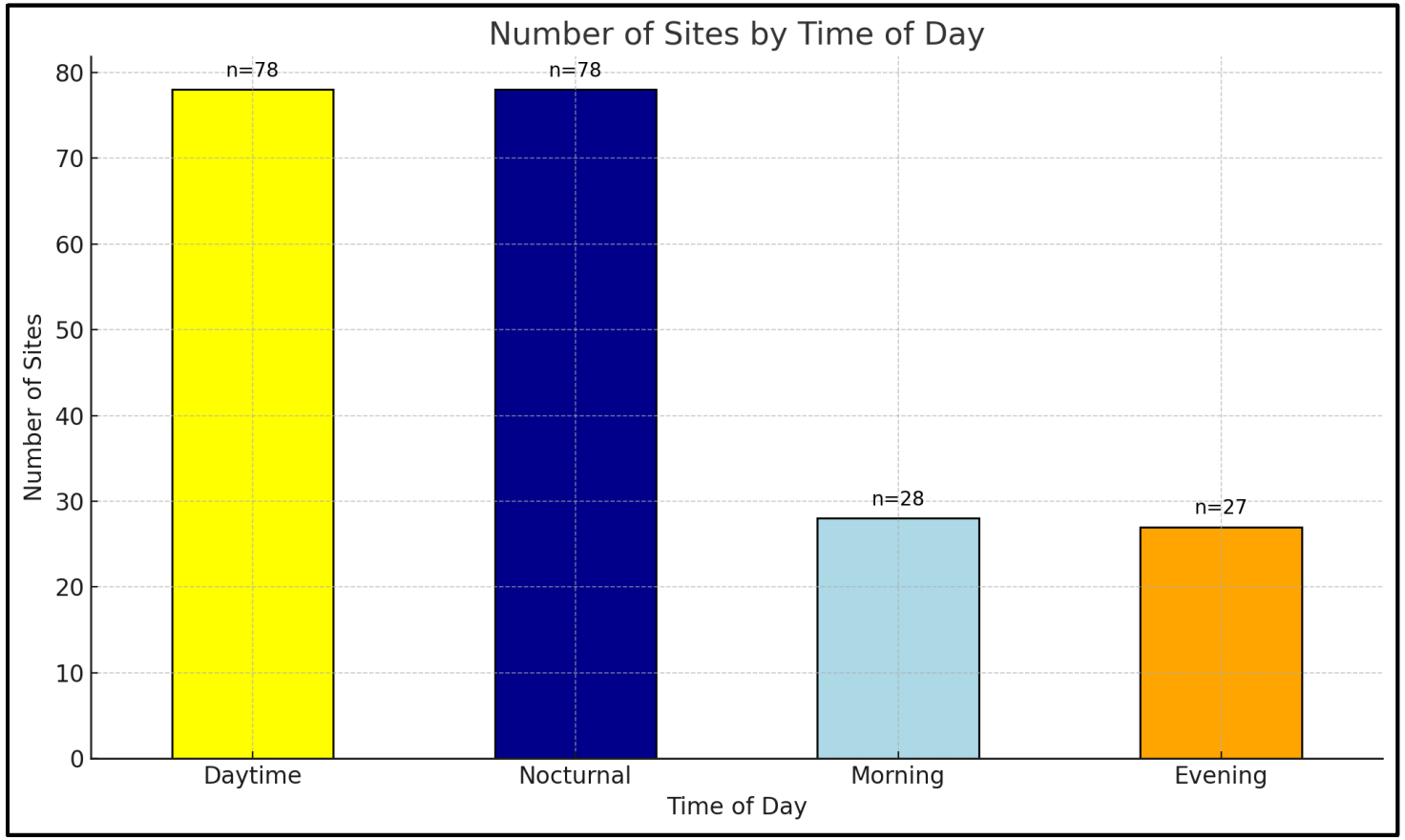
- Tornadic QLCS: 8 EF0s, 4 EF1s, and 1 EF3
- Category 3
- Calculated θ_v' at 2 ASOS sites

ASOS	KPWA (OKC)	KRVS (Tulsa)
θ_v' (K)	-6.43	-7.49
Storm Mode	Sig. Tornadic	Tornadic
Time of Day	Nocturnal	Nocturnal
Season	Spring	Spring
Region	South Central	South Central



Results: An Overview of All Cases

- **Total number of QLCS cases in this dataset: 90**
- 33 nontornadic QLCSs (Cat. 0)
- 57 tornadic QLCSs (Cat. 1-4)
- Most cases are warm season (June-September)
- 211 total ASOS sites
- Most sites sampled in the Southeast and Midwest regions
- Most sampled during the day & overnight

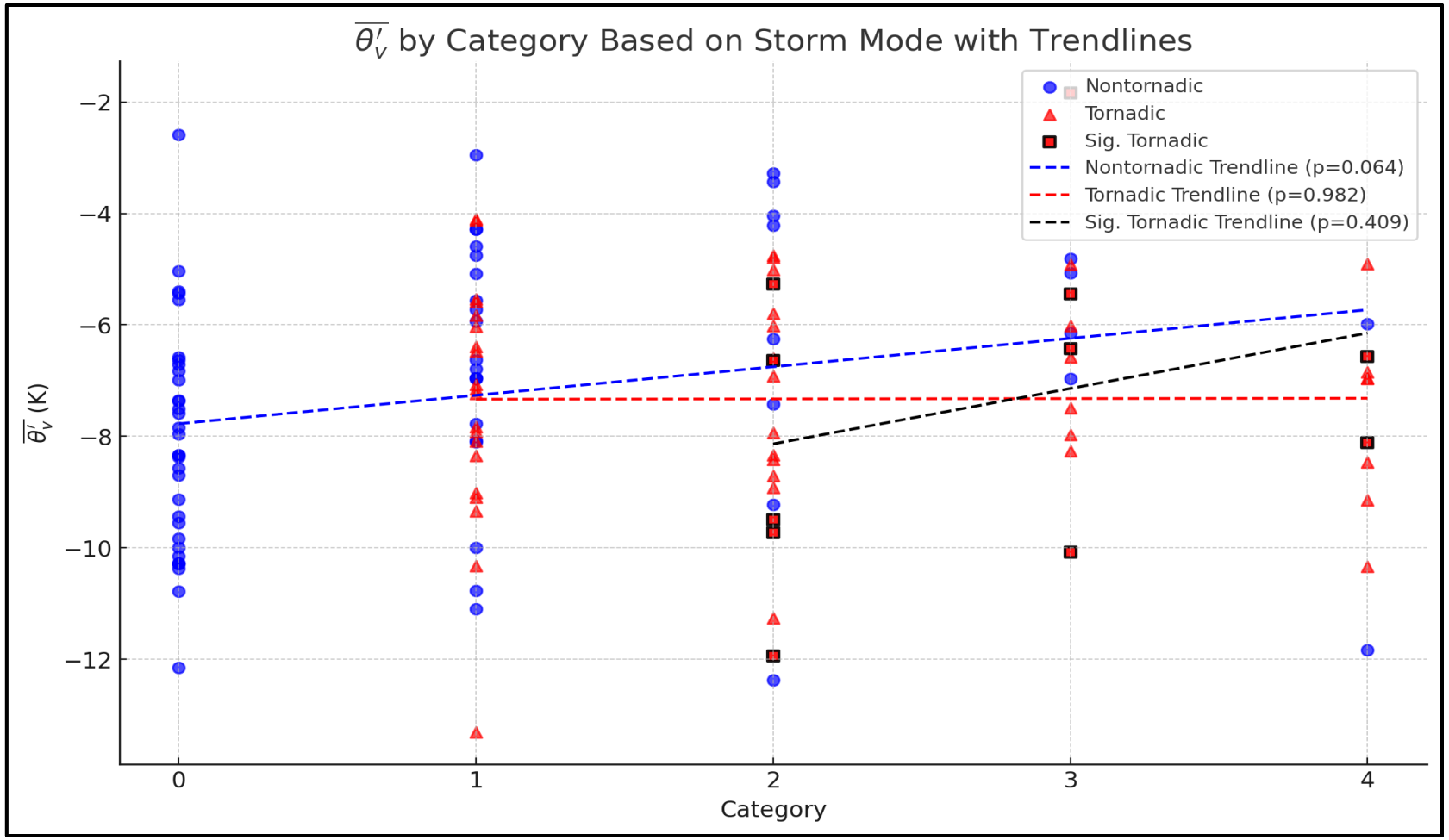


Results: An Overview of All Cases

For a QLCS with multiple stations of the same storm mode (nontornadic or tornadic), **θ_v' of those stations is averaged**.

This avoids skewing the plot because long-track cases have more sites than short-track cases.

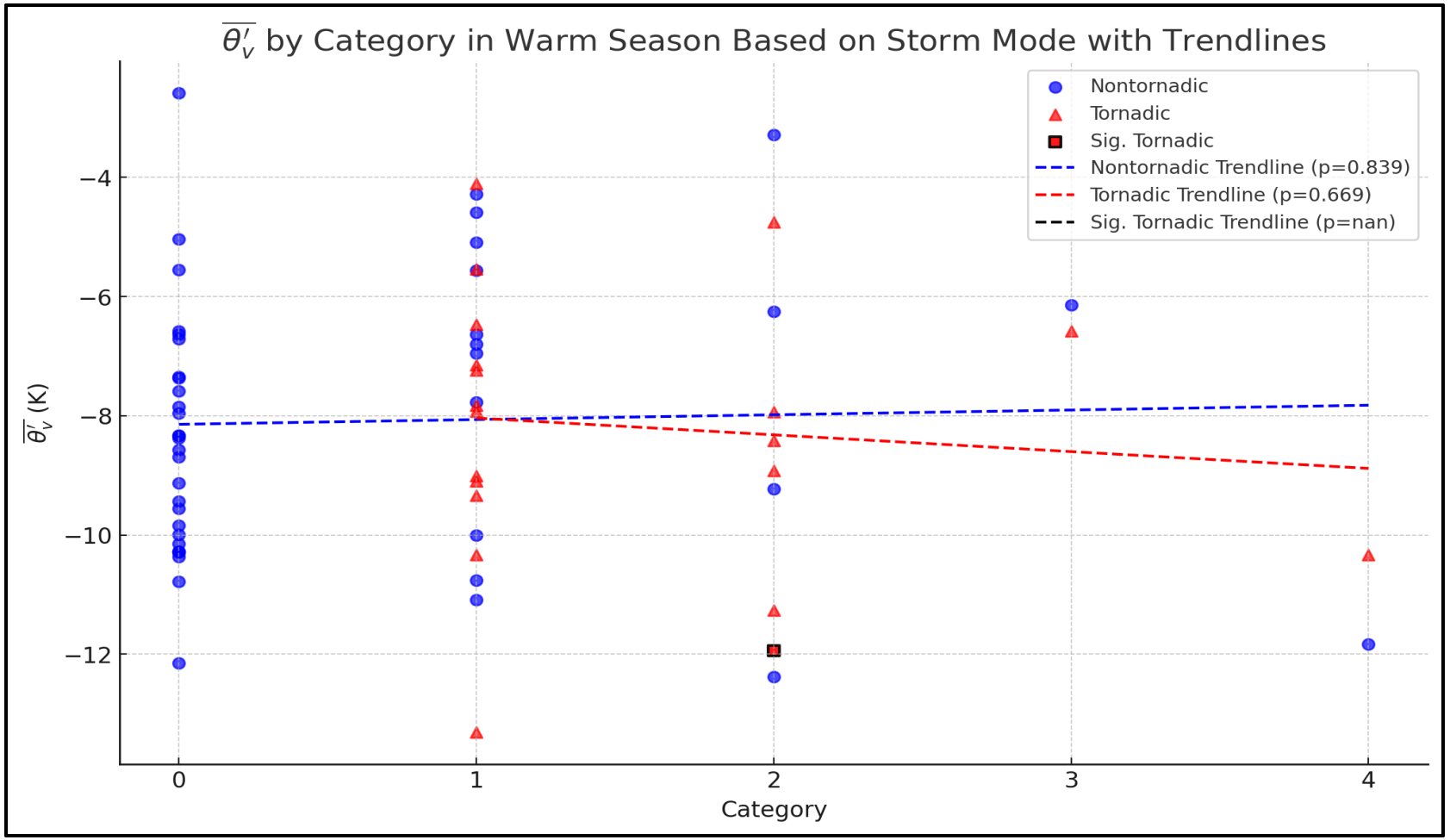
Overall trendline exhibits statistical significance (p=0.043).



Warm Season (June – September)

Few strongly tornadic warm season cases available.

Many nontornadic and weakly tornadic warm season cases.

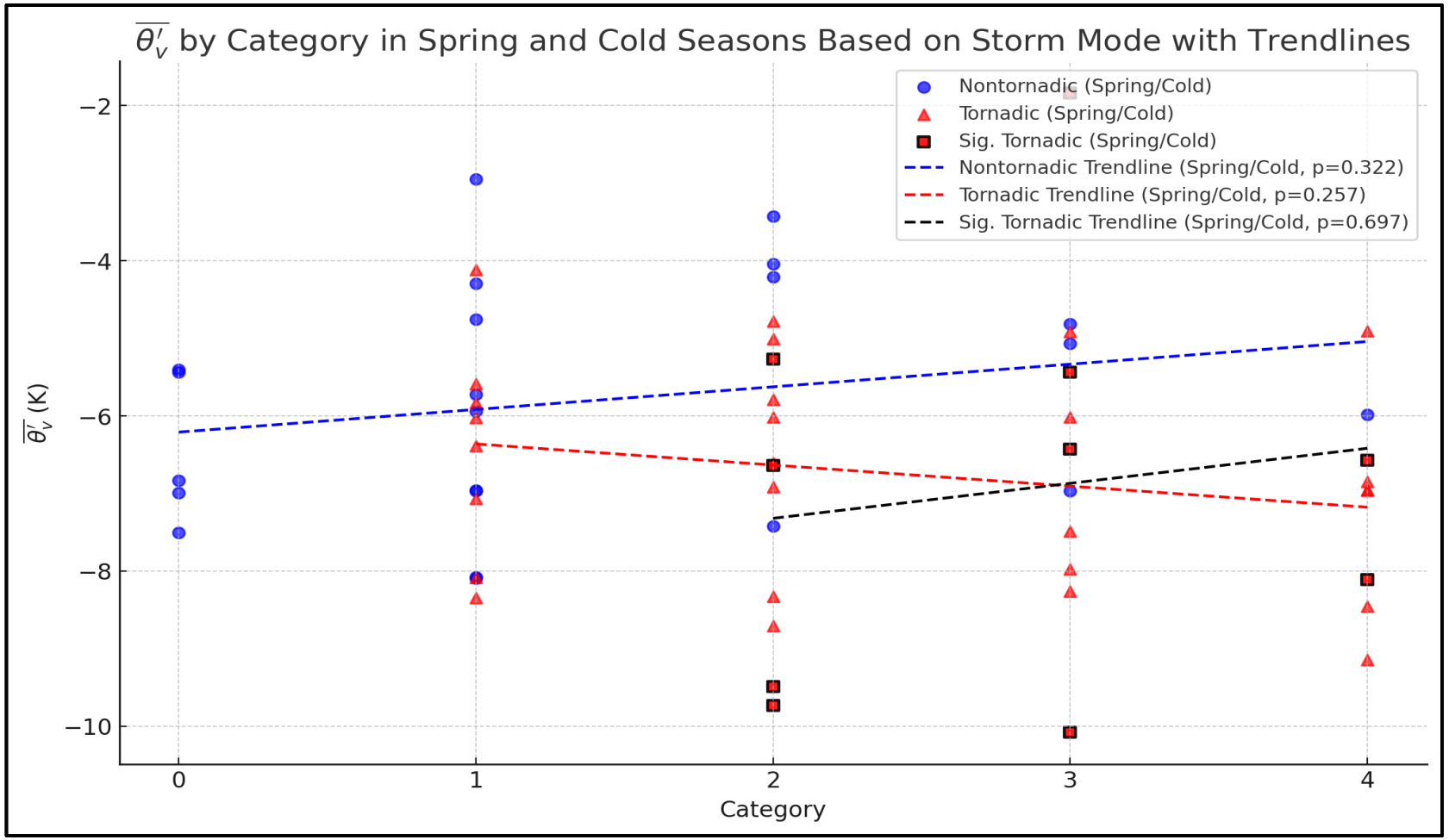


Cold and Spring Seasons (October – May)

Many of the cases sampled during this period are outbreaks.

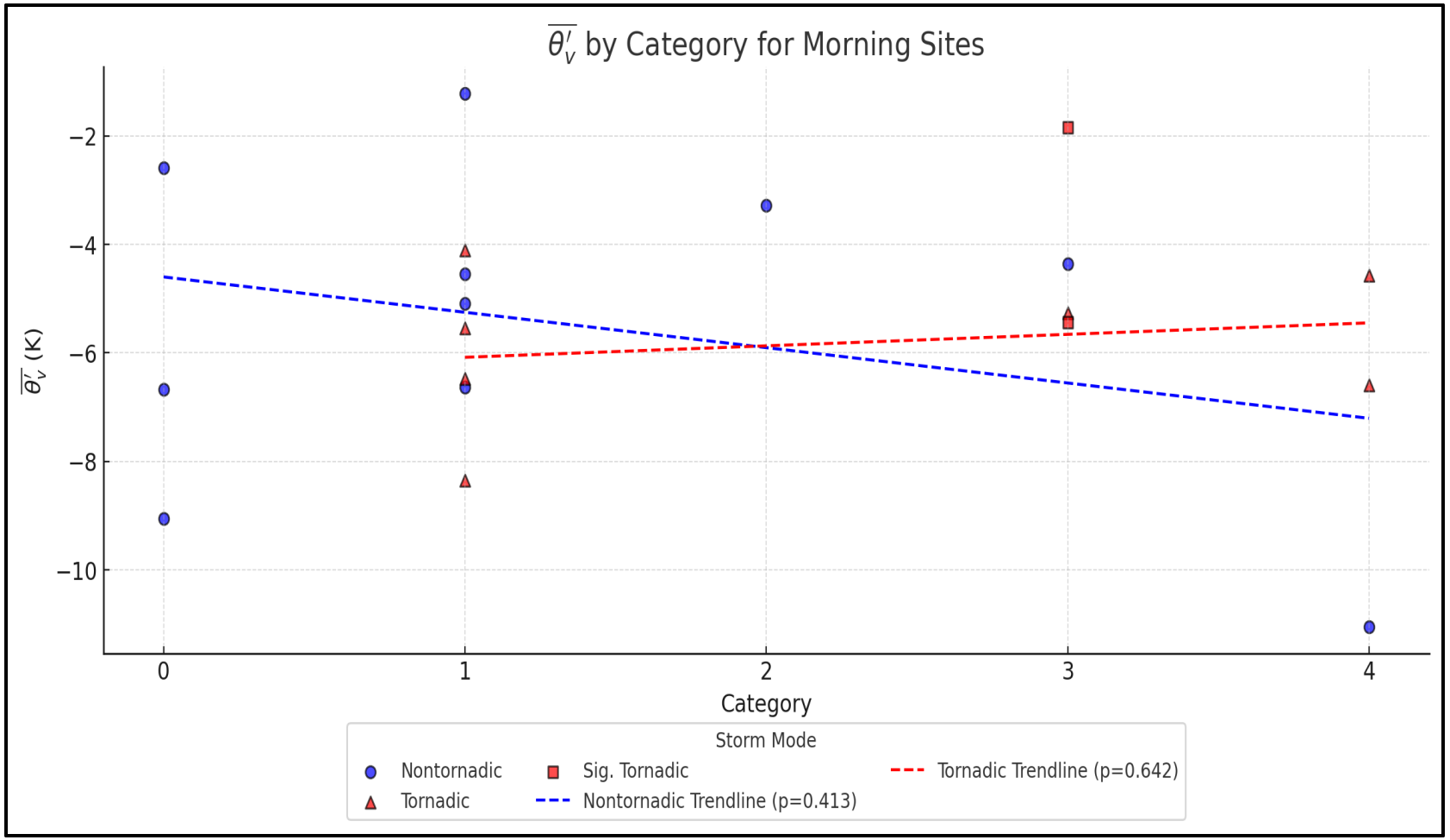
Because many cold and spring season cases feature strong synoptic forcing, **vertical wind shear likely has a much greater influence on tornado production than cold pool buoyancy from Oct-May**.

No statistically significant conclusions drawn here.



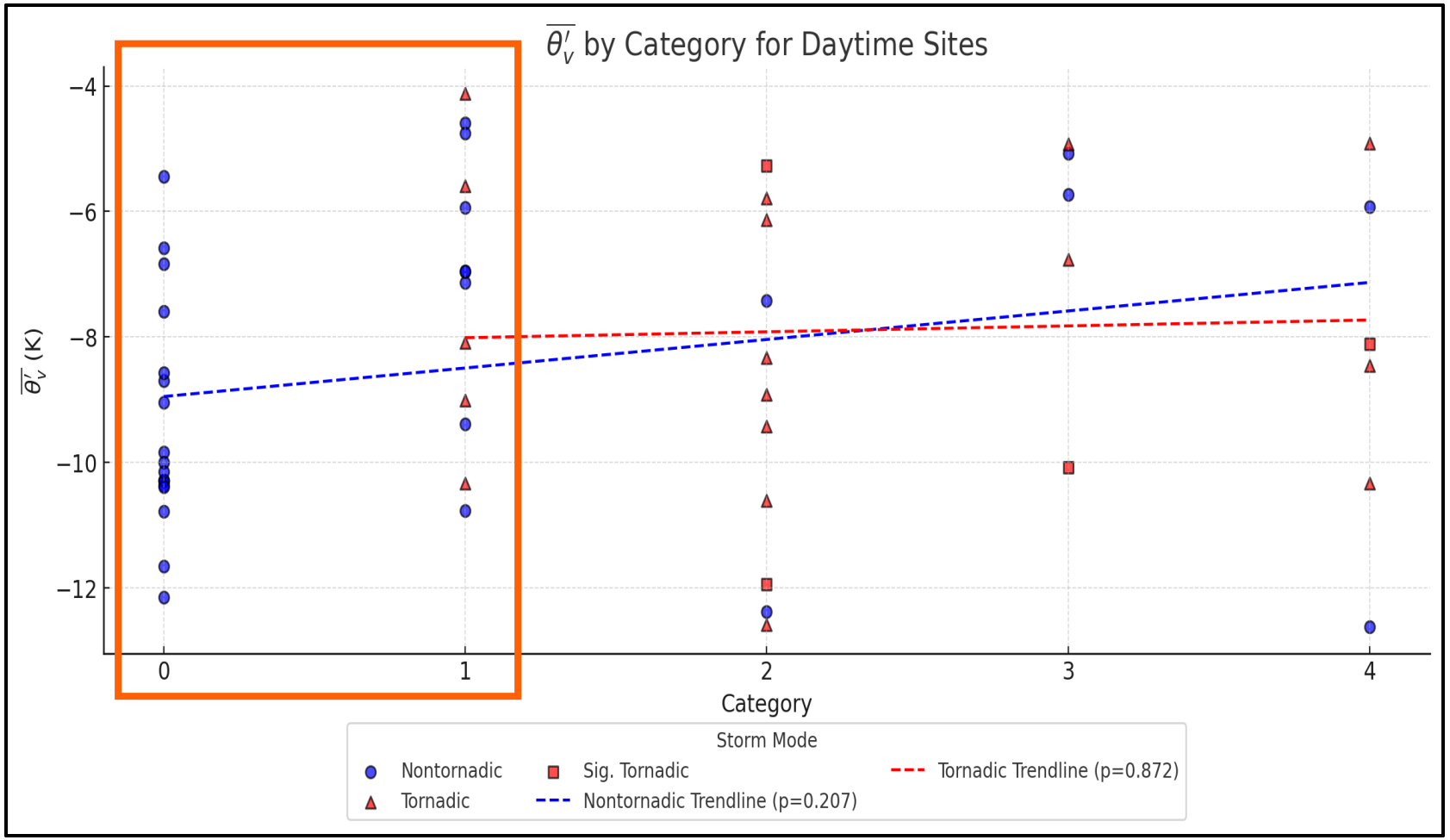
Time of Day Analysis: Morning (Sunrise-Noon)

Currently, this sample size is too small to draw conclusions from.



Time of Day Analysis: Daytime (Noon – 1 hr before sunset)

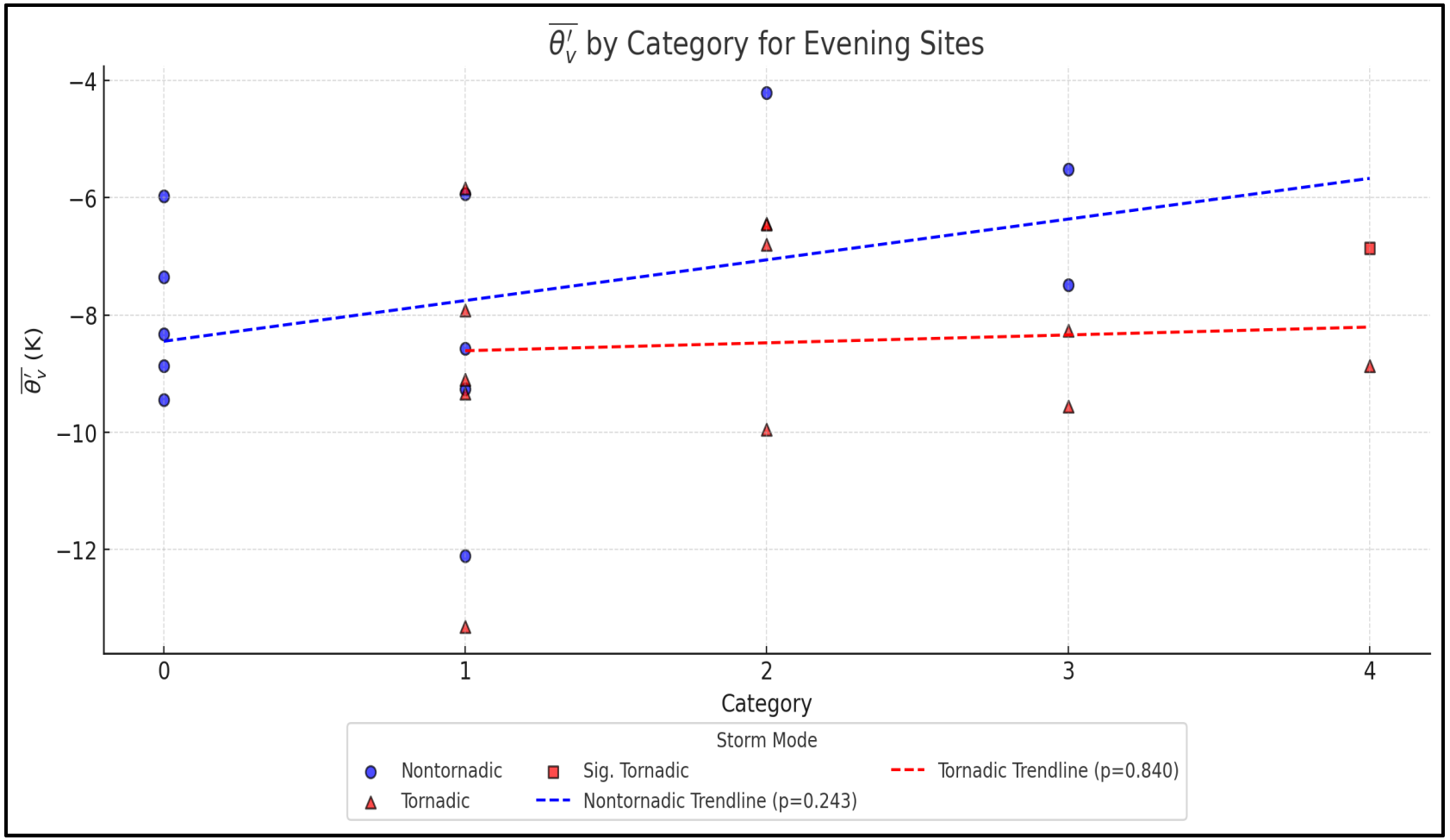
For daytime events, cold pools are more buoyant for nontornadic (Cat. 0) than weakly tornadic (Cat. 1) cases



Time of Day Analysis: Evening (1 hr before sunset – 1 hr after sunset)

Not enough in this sample yet.

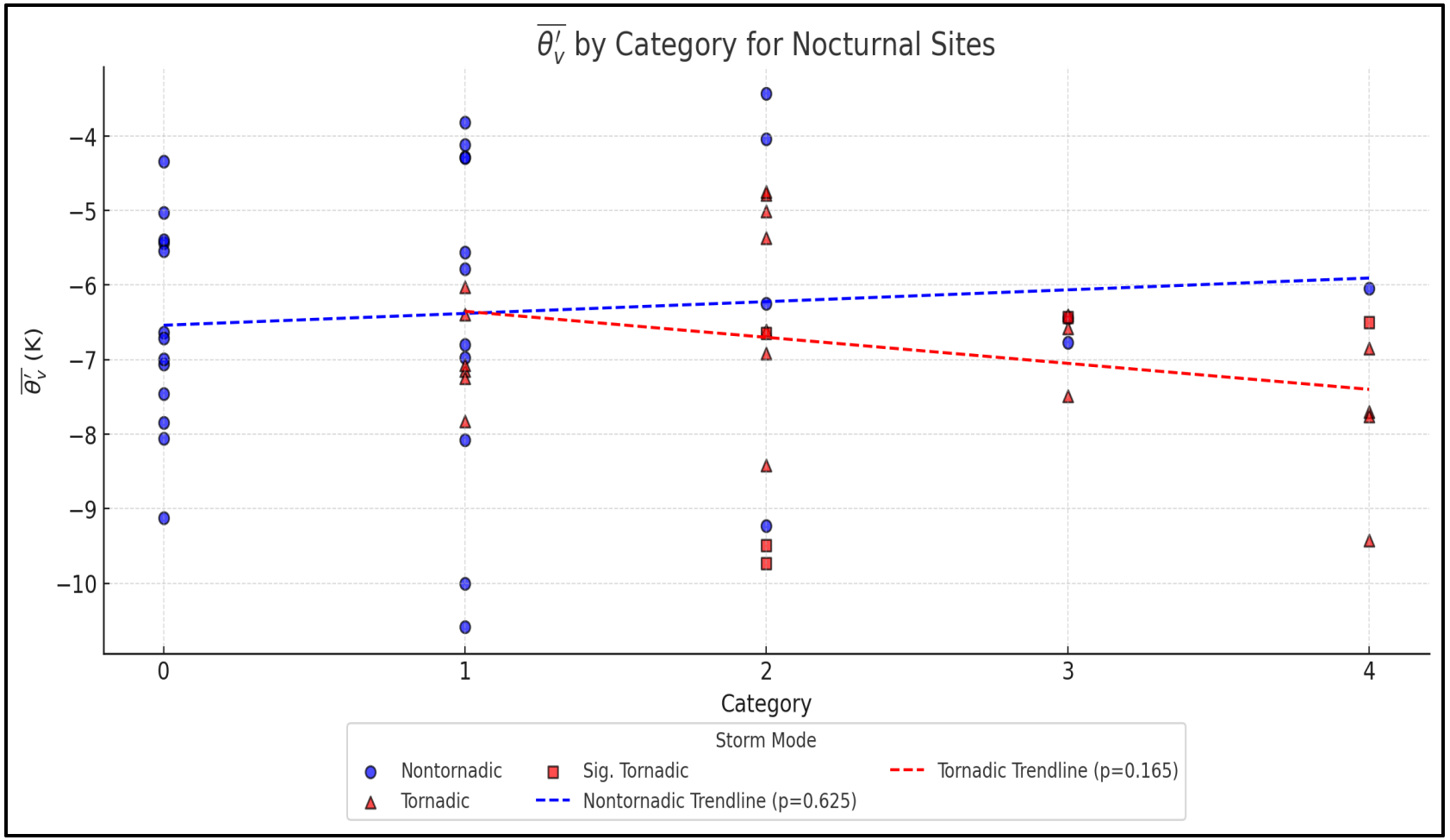
I mainly included this evening classification as a buffer to separate daytime from nocturnal events.



Time of Day Analysis: Nighttime (1 hr. after sunset – sunrise)

Lower categories: Mainly warm season events in the Plains and Midwest (nocturnal LLJ influence).

Higher categories: populated by QLCS tornado outbreaks in the Southeast.

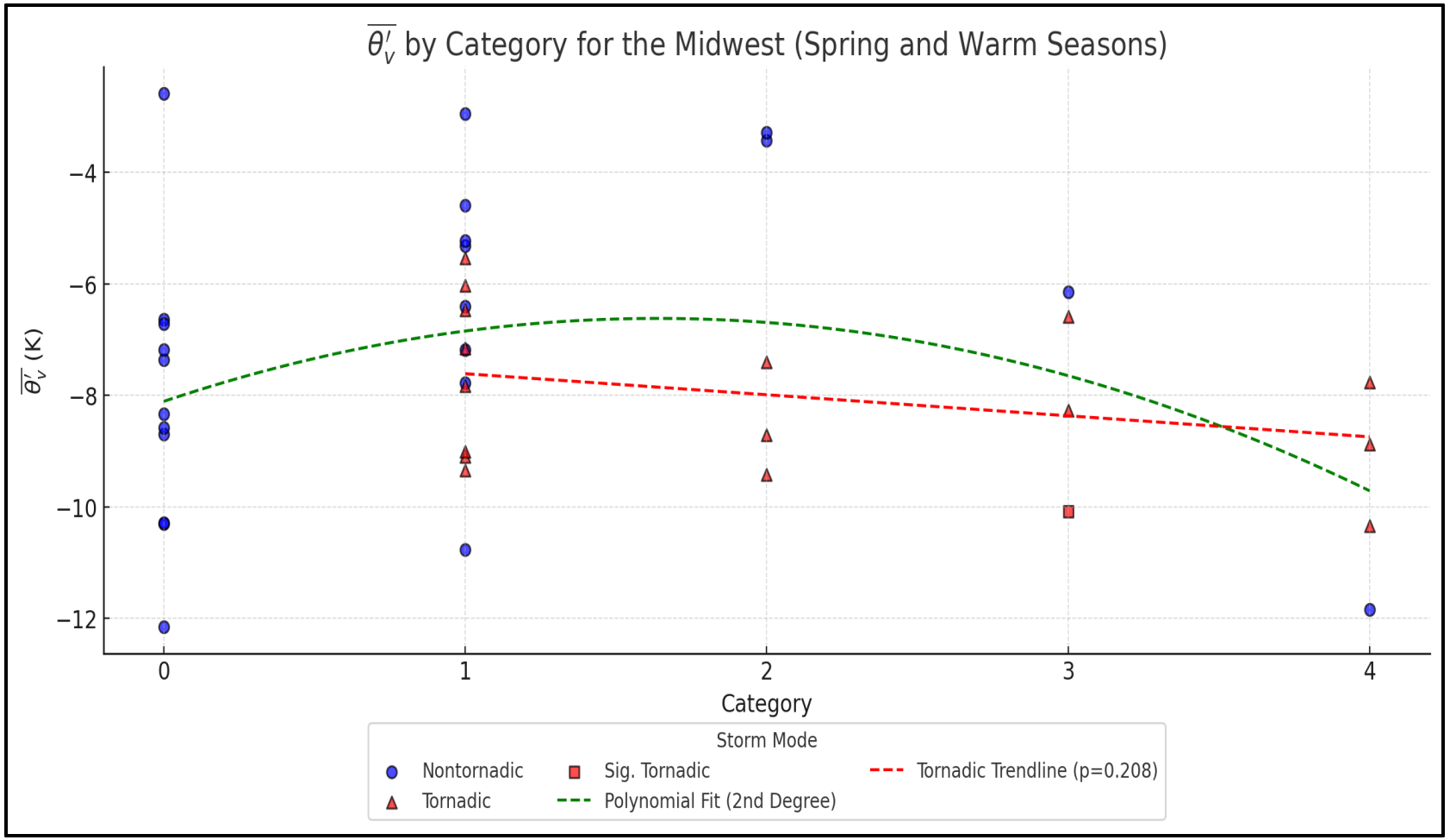


Regional Analysis: Midwest, Spring & Warm Seasons (March – September)

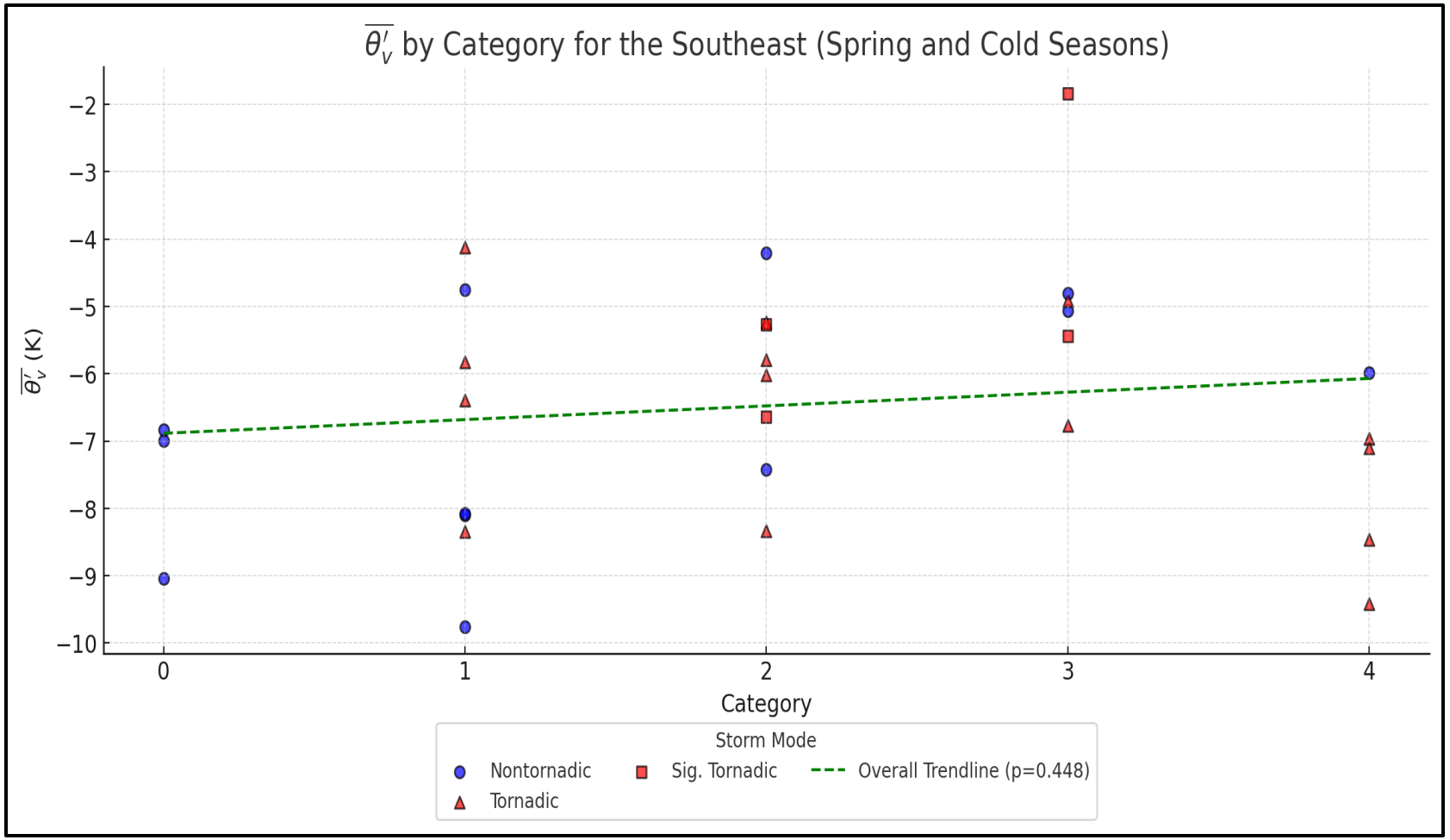
Cold pools trend more buoyant from nontornadic to weakly tornadic cases.

Cold pools trend less buoyant from weakly tornadic to strongly tornadic cases.

Kruskal-Wallis p-value: **0.195** *(not statistically significant)*

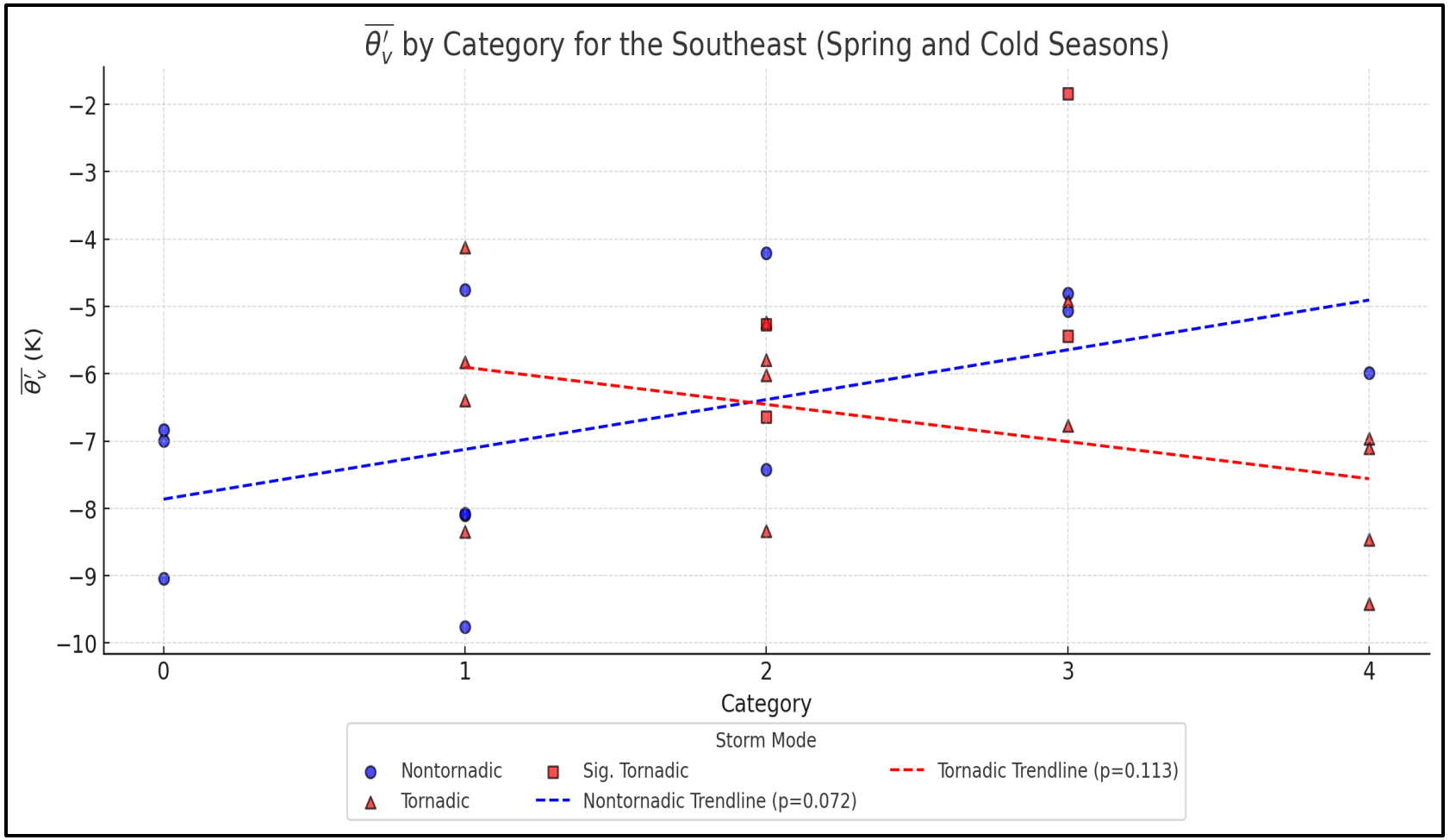


Regional Analysis: Southeast, Cold & Spring Seasons (October – May)



Regional Analysis: Southeast, Cold & Spring Seasons (October – May)

Given this distribution, a linear regression doesn't seem appropriate.

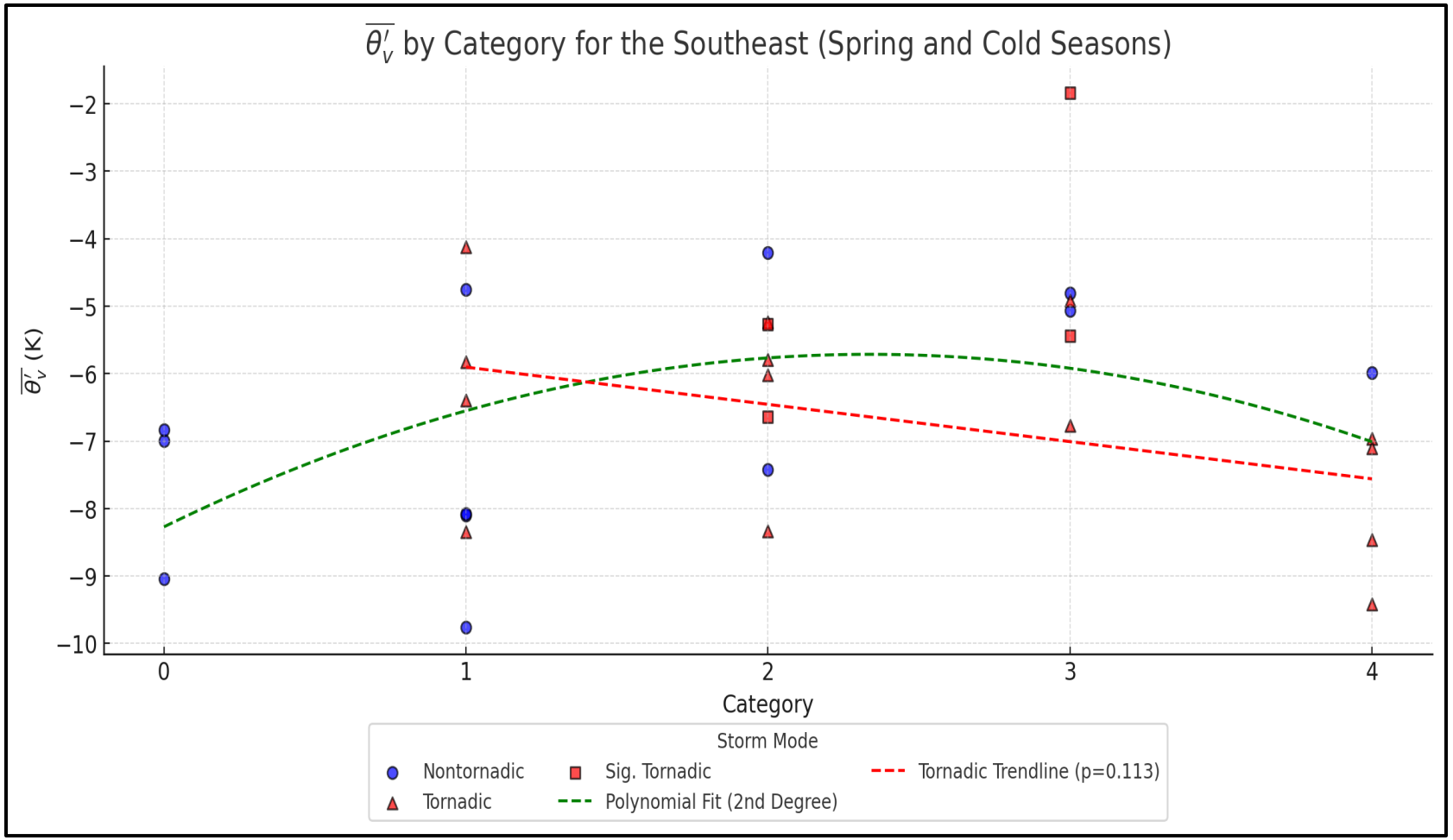


Regional Analysis: Southeast, Cold & Spring Seasons (October – May)

First a trend up, followed by a trend down in cold pool buoyancy as we progress toward the biggest QLCS tornado outbreaks.

How important is vertical wind shear?

Kruskal-Wallis p-value: **0.048** *(statistically significant)*



Conclusions

Hypothesis 1: More buoyant cold pools lead to increased tornado production in QLCSs.

- When comparing nontornadic to weakly tornadic QLCSs, more buoyant cold pools appear more favorable for tornado production.
- Especially for late spring and warm season QLCSs in the Midwest
- Also observed in cold and spring season QLCSs in the Southeast
  - ➢ Non-parametric statistical test revealed significance for these events.

Hypothesis 2: Cold pool buoyancy is a less effective indicator of tornado production in QLCSs in environments with stronger vertical wind shear.

(In progress)

Thank you!

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And a very special thanks to:

IEM

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