Connecting Weather Regimes to the Variability and Prediction of Warm-Season Tornado Activity in the United States

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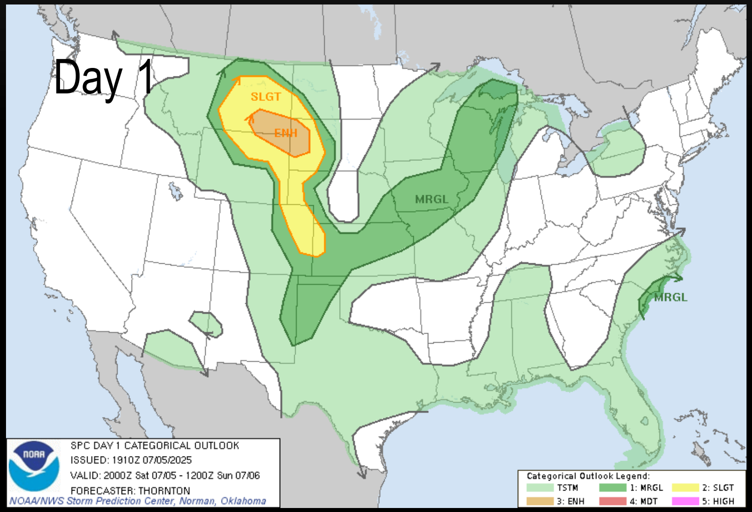
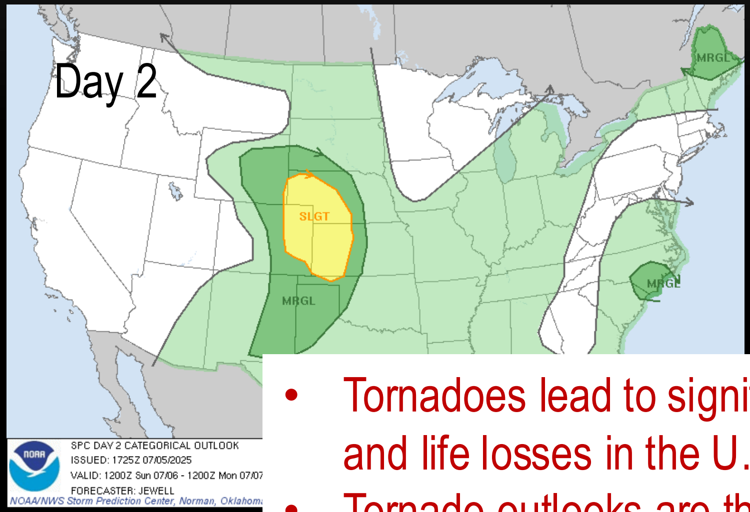
Graber, M., Z. Wang, and R. J., Trapp, 2025: Linking Weather Regimes to the Variability of Warm-Season Tornado Activity over the United States. Weather and Climate Dynamics, in press,

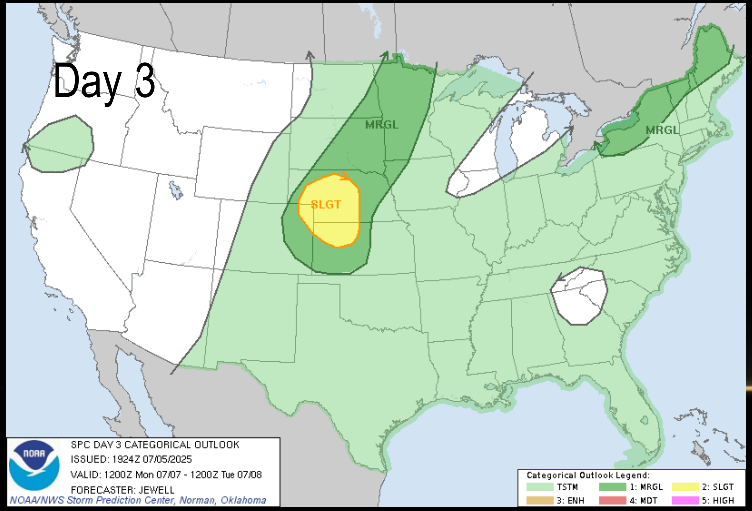
What is the predictability limit for severe weather?

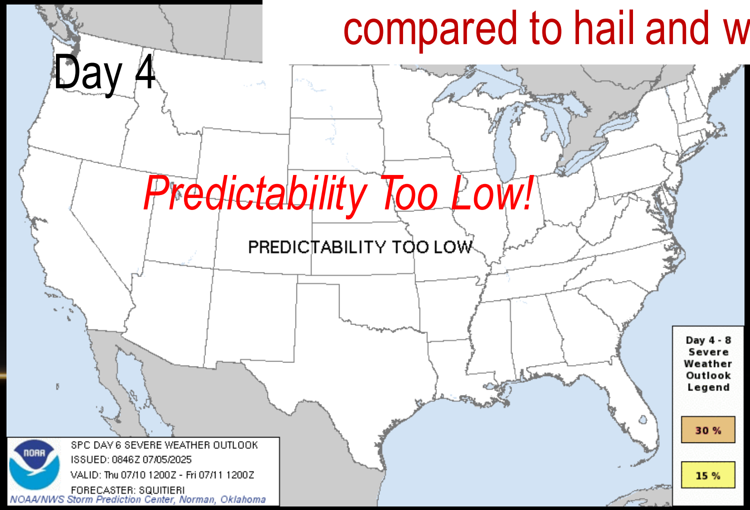
- Severe Thunderstorm Outlook by SPC, issued on July 5th, 2025





- Tornadoes lead to significant economic and life losses in the U.S.
- Tornado outlooks are the least skillful compared to hail and wind outlooks





https://www.spc.noaa.gov/products/outlook/day3otlk.html

Beyond the synoptic time scale…

- Most operational models do not have sufficient resolution to resolve tornadoes (or even severe convective storms) explicitly.
- Subseasonal tornado predictions make use of tornado proxies or environmental parameters important for tornado formation (e.g., Brooks et al., 1994; Brooks et al., 2003; Grams et al., 2012; Weisman & Klemp, 1982), such as CAPE and vertical wind shear.
- Low-frequency climate modes, including the ENSO (Allen et al. 2015; Cook & Schaefer 2008) and MJO (Thompson & Roundy 2013; Tippett 2018), modulate tornado activity on the subseasonal time scale. Statistical models have been developed based on these climate modes to predict severe storm activity on the subseasonal time scale (Baggett et al., 2018; Gensini et al., 2019).
- Efforts to predict tornado activity beyond the subseasonal time scale are rather limited:
  - It is partly due to the perceived low predictability.
  - The calculation of CAPE requires sub-daily data in high vertical resolution and is sensitive to model parameterization.
- Objective: use the concept of weather regimes (WRs) to better understand and predict tornado activity.

Weather Regimes

- Weather regimes (WR) are large-scale recurrent atmospheric patterns (Rex, 1950; Michelangeli et al., 1995).
- They can be regarded as the multi-equilibrium states of the nonlinear climate system (Charney & Devore, 1979).
- Climate variability can be considered as the variability of regime characteristics in response to boundary or external forcing, especially in terms of WR frequency and persistence (Corti and Palmer 1999; Molteni et al. 2006).
- **Two questions**
  - *How is tornado activity over the United States related to WRs? -- observational analysis*
  - *Can we exploit the predictable information of WRs in the seasonal prediction of tornado activity? – a hybrid model*

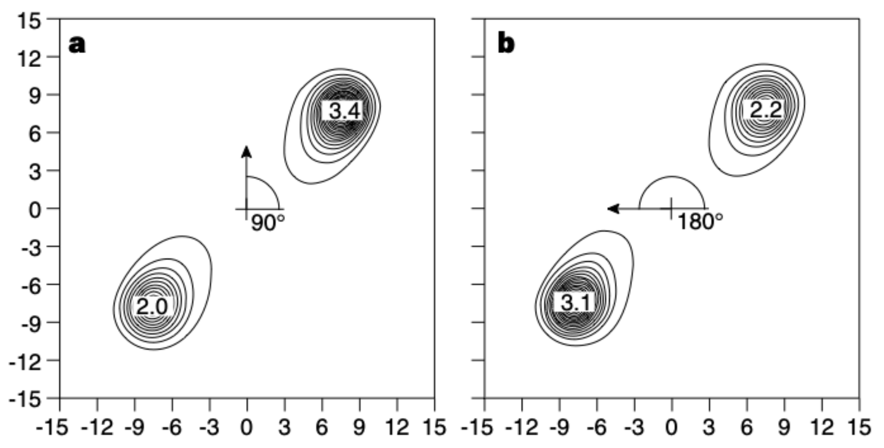


Figure 1 Response of a nonlinear chaotic model to imposed forcing. Illustrated is the state vector PDF (invariant measure) of a forced Lorenz[3] attractor, with governing equations $\dot{X} = -10X + 10Y + 2.5\cos\theta$, $\dot{Y} = -XZ + 28X - Y + 2.5\sin\theta$, $\dot{Z} = XY - (8/3)Z$, in X, Y phase space. The arrow shown is the forcing vector $(2.5\cos\theta, 2.5\sin\theta)$ in this two-dimensional phase space. A short running time-average has been applied to the state vector to emphasise the regime character of the Lorenz attractor. **a**, $\theta = 90°$; **b**, $\theta = 180°$. The numbers shown correspond to maxima of the PDF at the regime centroids. The quantities plotted on the horizontal and vertical axes are values of X and Y respectively. See ref. 3 for details.

From Corti and Palmer 1999

Data and Methodology

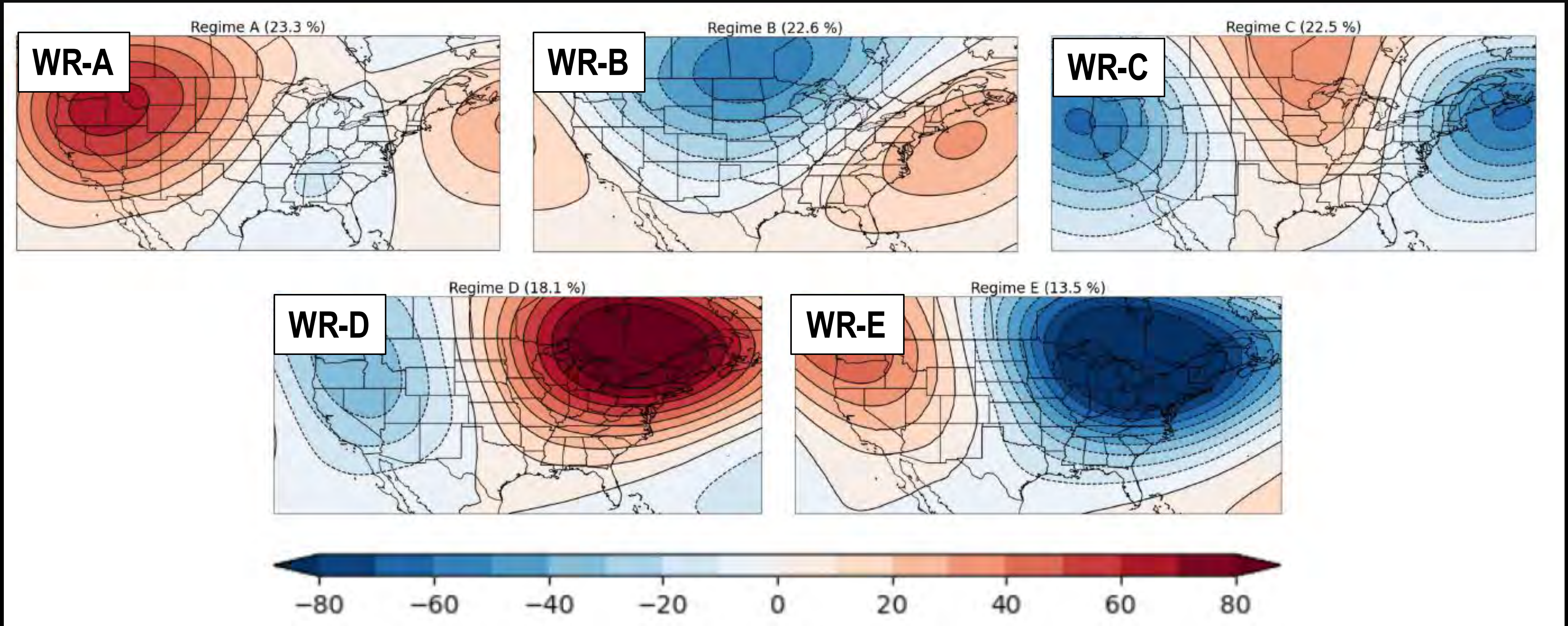
- ERA-5 reanalysis data:
  - most unstable CAPE (MUCAPE), 500 hPa H, convective precipitation (CP), 0-6 km bulk wind shear (S06)
- Weather Regimes
  - K-means clustering analysis applied to the H500 daily anomalies
- Tornado reports: the NOAA Storm Prediction Center (SPC) Severe Weather Database
- Tornado probability anomalies (Pa) for a WR:

$$P_a = \frac{P_i - P_c}{P_c} \times 100\%$$

Pc is the climatological mean probability during 1960-2022, and Pi represents the probability for WR-I

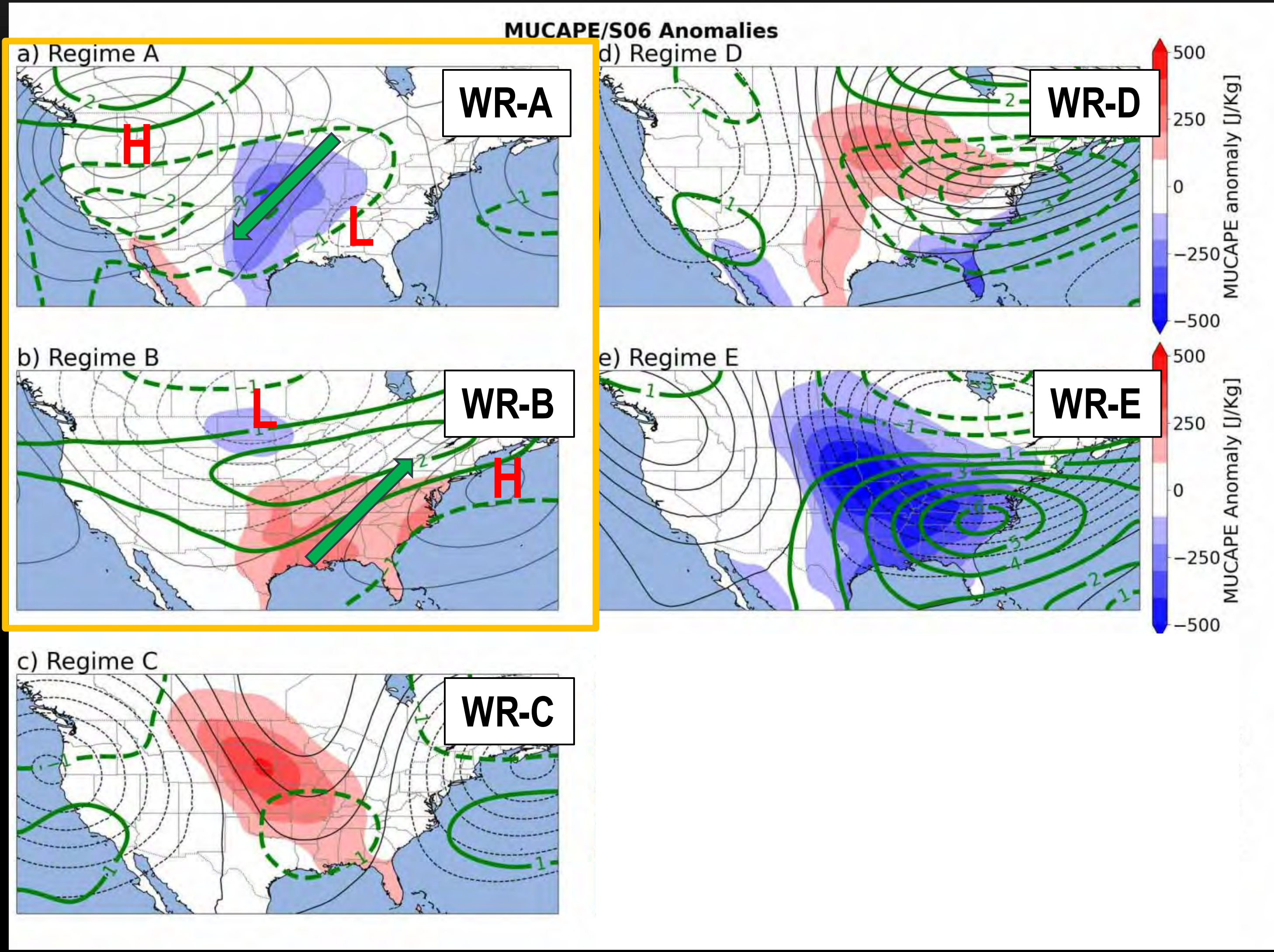
- We will focus on the **warm** season: April to July

Five Weather Regimes (April-July)



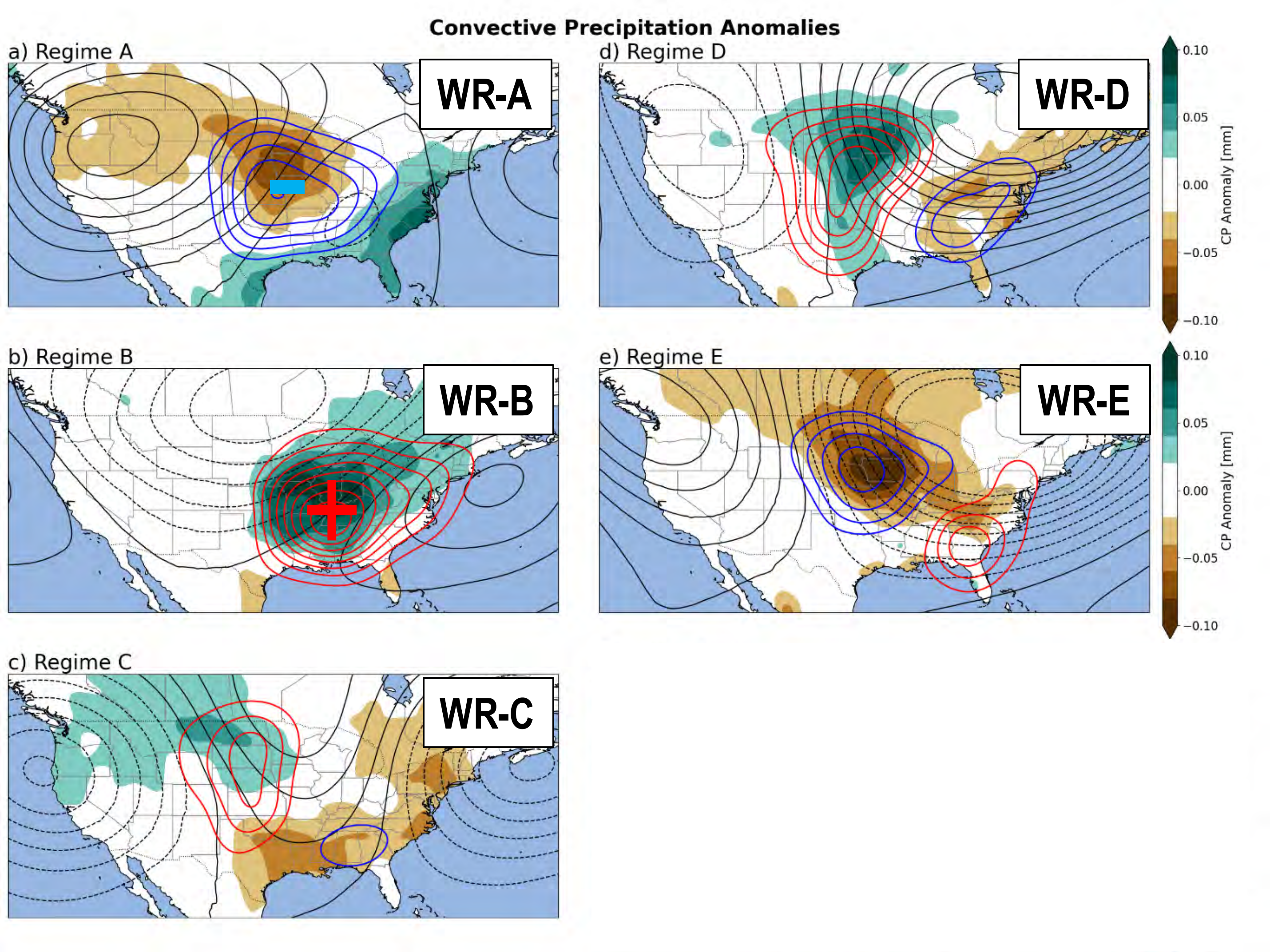
K = 5 is determined by using the elbow method and the Davies-Bouldin index.

MUCAPE (shading) and S06 (green) Anomalies



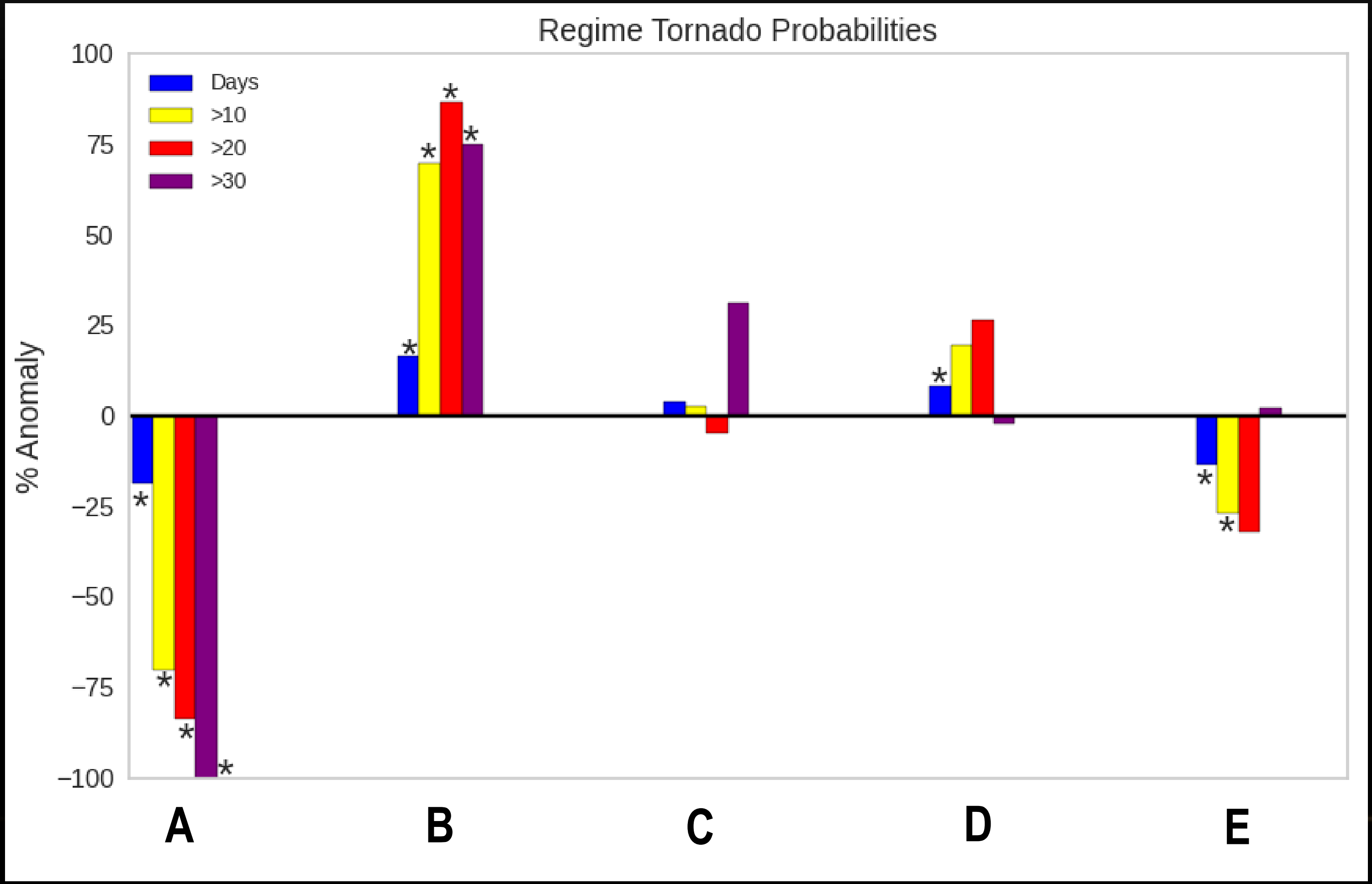
- WR-A favors anomalously low MUCAPE and reduced S06.
- WR-B favors anomalously high MUCAPE and enhanced S06.

Convective Precip (shading) and Tornado Day Probability Anomalies (color contour)



- Convective precipitation (CP) shows an overall good agreement with CAPE.
- WR-A: reduced CAPE, CP, S06 → reduced tornado day probability over the central CONUS
- WR-B: enhanced CAPE, CP, S06 → enhanced tornado day probability over the Midwest and Southeast US

Probability Anomalies of CONUS Tornado Activity



$$P_a = \frac{P_i - P_c}{P_c} \times 100\%$$

Pc: the climatological mean probability
Pi: the probability for WR-i

Can we use the information of the large-scale circulation to predict tornado activity?

-- An Empirical model for tornado activity

Persistent WRs (>= 5 days)

Non-persistent WRs

$$TI(t) = \sum_{i=1}^{5} f(i,t)_p \times P_{i,p} + \sum_{i=1}^{5} f(i,t)_{np} \times P_{i,np}$$

TI(t): a tornado index

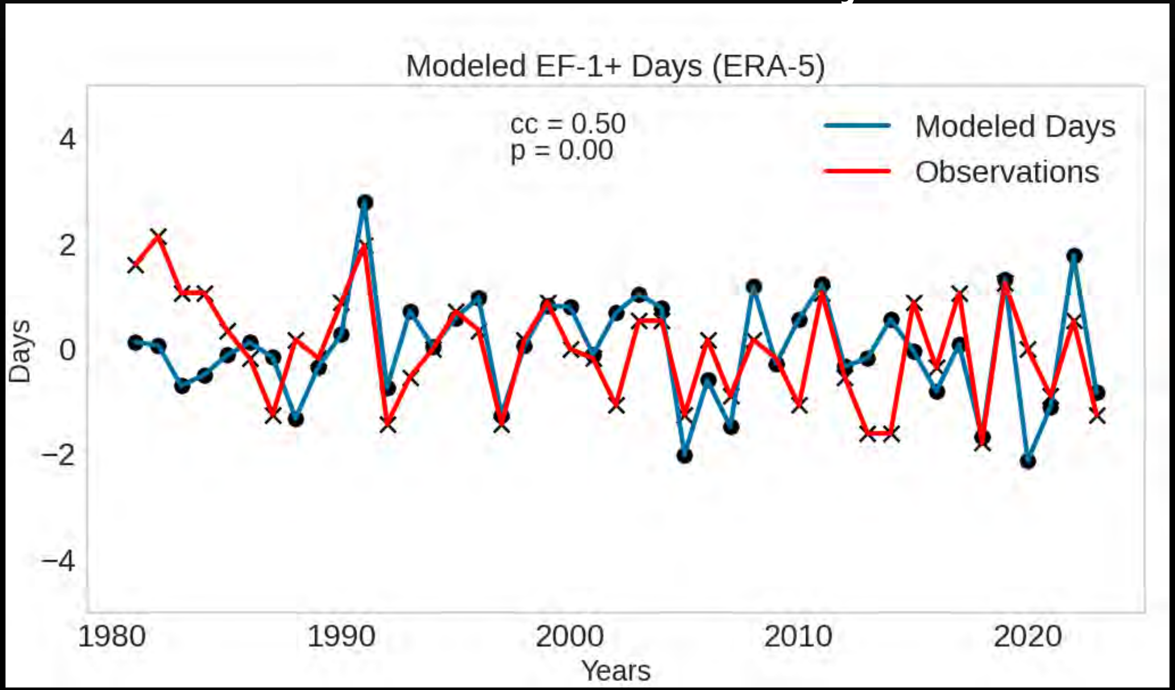
f (i): WR-i frequency

Pi: tornado probabilities for WR-i

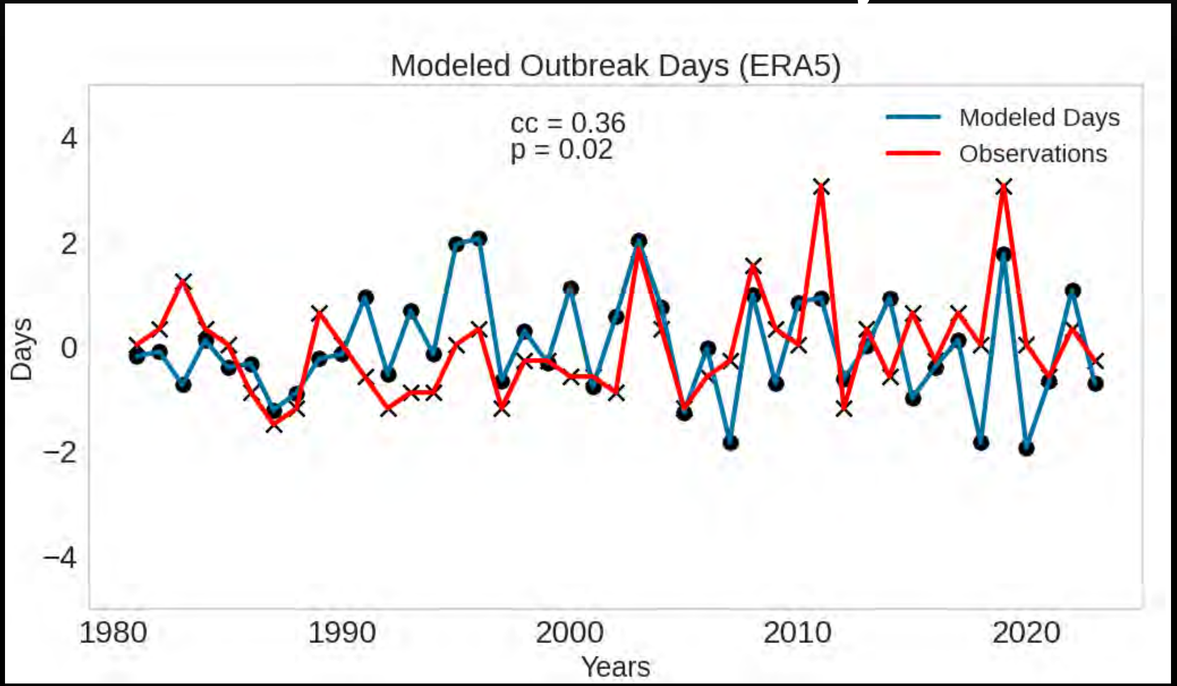
Assumption: a stationary relationship exists between WRs and tornado activity (i.e., Pi does not change with time)

Tornado Activity: Empirical model estimation vs. obs
(April-July 1980-2023)

EF-1+ Tornado Days



Tornado Outbreak Days

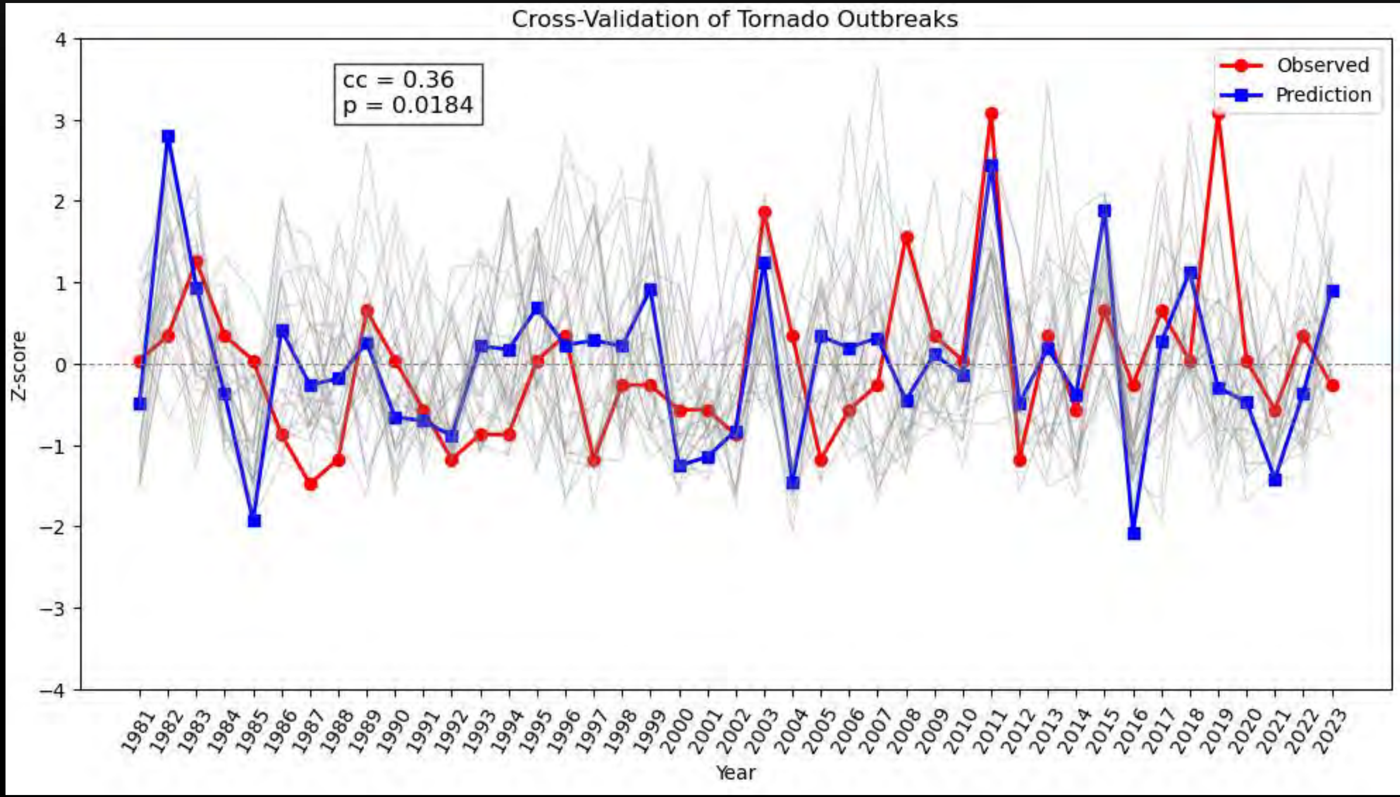


$$TI(t) = \sum_{i=1}^{5} \boldsymbol{f(i,t)_p} \times P_{i,p} + \sum_{i=1}^{5} \boldsymbol{f(i,t)_{np}} \times P_{i,np}$$

WR frequency derived from the ERA5 reanalysis

Hybrid Prediction of Tornado Outbreak Days

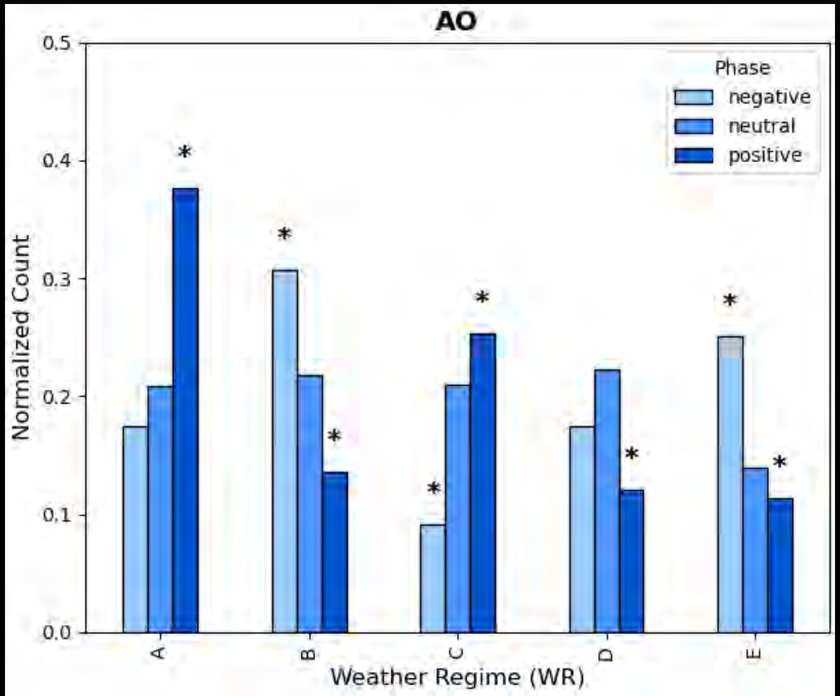
(leave-one-year-our cross validation; April-May 1980-2023)



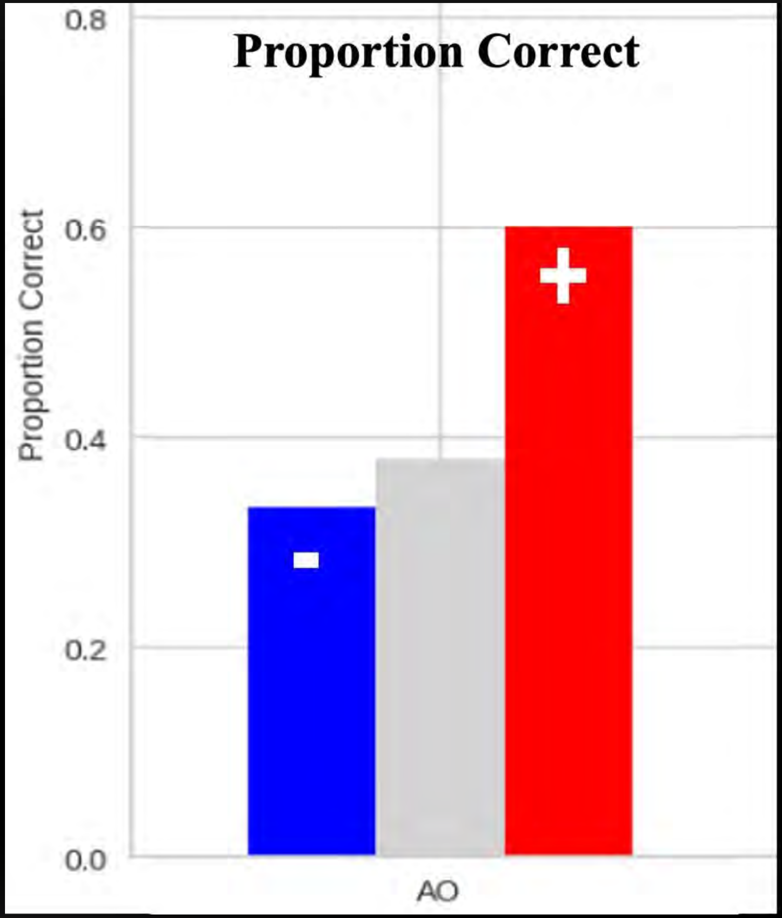
Hybrid Prediction using leaving-two-years-out validation: WR frequencies are derived from the ECMWF IFS (re)forecasts initialized on April 1

$$TI(t) = \sum_{i=1}^{5} \boldsymbol{f(i,t)_p} \times P_{i,p} + \sum_{i=1}^{5} \boldsymbol{f(i,t)_{np}} \times P_{i,np}$$

Where does predictability come from?



The changes in tornado activity can be partly explained by the modulation of WR characteristics by climate modes (such as AO).



Higher skill of tornado outbreak prediction in the AO+ phase.

Summary

- WRs strongly modulate tornado activity, which can be explained by their modulation of environmental parameters, such as CAPE and S06.
- The empirical model based on WR frequency and persistence shows promising performance in the seasonal prediction of tornado days and outbreaks.
- Ongoing work explores the application of the framework on the interannual to decadal time scales.

Thank you