Manuscript title: Seasonal prediction of springtime tornado activity in the United States using a hybrid model.

ID: egusphere-2026-536

Referee # 1 comments and replies

Authors: Our replies will be in blue. We appreciate the thorough comments and suggestions from referee # 1, and we will explain any changes we make under the appropriate comments. Any referee comments or suggestions that we do not implement in the manuscript, we provide a thorough explanation to explain our reasoning and support for our study.

Summary:

This manuscript connects (synoptic-scale) weather regimes and modes of climate variability including the El Niño Southern Oscillation (ENSO), the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), and the Pacific North American pattern (PNA) to April-May U.S. tornado activity using a hybrid model and composite analysis. The role of sea surface temperatures (SSTs) as a source of predictability is also assessed. The predictions from the hybrid model, which incorporates the relationship between five weather regimes and tornado activity identified over the recent (1981-2023) historical period, have a significant correlation with observed April-May tornado outbreaks, but not with tornado days. The hybrid model is found to perform better during the positive phases of the AO, NAO, PNA, and ENSO as well as the negative phases of the NAO, AO, and ENSO. Probability anomalies of tornado activity were also found to be associated with different phases of ENSO, AO, NAO, and the PNA. For instance, tornado outbreak probability was found to be enhanced during the negative phase of the AO and La Niña, whereas tornado outbreak probability was found to be diminished during the positive phases of the NAO and the PNA. The relationship between climate modes and April-May U.S. tornado activity was further assessed by compositing the large-scale atmospheric conditions during each mode's various phases. The occurrence of weather regimes was also found to be modulated by the various considered climate modes. Finally, the SST anomalies were composited relative to weather regime and active and inactive tornado activity years, indicating that North Atlantic and North Pacific SSTs could also provide a source of predictability for April-May U.S. tornado activity.

The analysis shown in this manuscript is an interesting perspective on the seasonal prediction of late spring U.S. tornado activity, incorporating sources of predictability across synoptic and climate scales. However, there are several major comments that need to be addressed before publication. The climate modes, whose influence on April-May U.S. tornado activity are considered, need to have more in depth discussion including what the modes are and why they may be a source of predictability for U.S. tornado activity. Further, these climate modes are discussed as "low-frequency" which is not correct. This language should be updated throughout the manuscript. The section which connects the various phases of the considered climate modes to the large-scale environmental conditions and tornado activity has several inconsistencies between the referenced figures and the text and should be re-worked for clarity. Finally, the authors should carefully consider the analysis of the possible role of SSTs shown in section 3.3, and whether to incorporate some of the suggested changes indicated below or remove this section from the manuscript.

Major comments:
In the introduction, there is a substantial discussion of how modes of climate variability including the ENSO, AO, and the PNA have been found to impact U.S. tornado activity in the winter and spring. Then, in the results, the role of ENSO, AO, the PNA, and the NAO in modulating U.S. April-May tornado activity is considered. However, what these climate modes are and why they impact U.S. weather and climate (e.g., why would these climate modes possibly impact U.S. tornado activity) is never discussed in the manuscript. The authors should add a discussion which defines each relevant mode and why it might offer an additional source of predictability for U.S. tornado activity (whether it has been shown in previous literature, or whether it has a known influence on other aspects of U.S. weather and climate).

This is a valid request. These descriptions will add important information to the introduction and help support our argument for using low-frequency climate modes. We did not want to add too much to avoid making the introduction too long as many readers of this paper will likely have a basic knowledge of the climate modes presented herein. The following additions are made to the manuscript's introduction paragraph on low-frequency climate modes.

Lines 48-52 start the section on low frequency climate modes: "Low-frequency climate modes are important drivers of seasonal tornado activity and can serve as sources of their predictability. Since tornado activity depends on favorable thermodynamic and kinematic environments (Thompson et al., 2003)*, predictable shifts in jet streams or moisture transport associated with low-frequency climate variability may enhance or suppress springtime severe weather potential across the CONUS* (Cook and Schaefer, 2008)*."*

For ENSO:

Lines 52-59 now state: *"A major mode of interannual climate variability is ENSO (Chen and Van den Dool 1997), which is characterized by the anomalous warming (El Niño) and cooling (La Niña) of sea-surface temperatures (SSTs) in the central and eastern equatorial Pacific (Bjerknes 1969). ENSO modulates the strength and position of the Pacific jet stream (Bjerknes 1969) and can affect the large-scale circulations that influence the frequency, intensity, and spatial locations of CONUS severe weather. Previous studies have linked the winter ENSO phase to the variability of tornado activity (Allen et al. 2015, 2018; Cook and Schaefer 2008; Knowles and Pielke 2005; Lee et al. 2016)."*

For AO and NAO:
Lines 60-70 now state: "The Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) are prominent modes of climate variability in the extratropics (Cohen et al. 2014). Specifically, the AO refers to the leading EOF of variability in northern hemisphere sea-level pressures at mid and polar latitudes, while the NAO is characterized by the sea-level pressure difference between the Subtropical High and Subpolar Low over the North Atlantic (Thompson and Wallace 2000; Hurrell 1995; Hurrell and Deser 2010; Wyburn-Powell and Jahn 2024). NAO and AO are strongly correlated and modulate the strength and position of the midlatitude jet stream. Previous studies have linked the variability of NAO and AO to the variability of tornado activity, primarily over the central and eastern CONUS (Childs et al. 2018; Tippett et al. 2022; Elsner et al. 2016; Niloufar et al. 2021), suggesting that NAO and AO provide additional sources of predictability for springtime tornado activity."

For PNA and rounding out this section of the introduction:

Lines 71-81 now state: "Another important mode is the Pacific North American (PNA) pattern, which is a leading mode of low-frequency variability over the North Pacific and North America (Phillips et al., 2014)*. Although the PNA is influenced by ENSO* (Wallace and Gutzler, 1981)*, it exhibits some independent variability* (Li et al., 2019) *and can exist in the absence of interannual SST variability (Lau 1981). PNA modulates the position and intensity of the East Asian jet stream which influences large-scale circulations relevant for severe weather over the CONUS* (Leathers et al., 1991; Li et al., 2019; Ning and Bradley, 2015)*. The negative phase of PNA has been associated with enhanced springtime tornado activity* (Munoz and Enfield, 2011)*, and previous work has linked the variability of tornado activity to SST anomalies that are connected to PNA-like patterns over the Pacific* (Chu et al., 2019)*. These relationships suggest that PNA, along with ENSO, AO, and NAO, potentially serve as sources of predictability for springtime tornado activity."*

In section 2.1: Weather regimes used in this paper are mentioned to be derived from Graber et al. (2025). If this is the case, the line in the abstract stating, “Using ERA5 reanalysis, we identify five April-May weather regimes from 1981-2023, some of which strongly modulate tornado activity,” should be removed since they are taken from another study. Then the statement from Lines 13-15 can be rephrased to something like, “Five previously identified weather regimes are incorporated into a hybrid model to predict April-May CONUS tornado activity…” If the weather regimes are identified organically in this study, but just using the same methods as in Graber et al. (2025), then section 2.1 should be rephrased to state such and the abstract can be left as is.

The WRs were derived in Graber et al. 2025 for April-July and we used those spatial structures as reference states to determine WRs on every day in the 1981-2023 April-May period. Therefore, the spatial structures are unchanged, though long-term frequencies differ slightly. This approach is important given the limitation noted in lines 112-114:

“We took this approach because K-means clustering yields slightly different WR patterns in different time periods and employing WRs during a longer time period as the reference patterns improves the robustness of the results.”

We do not remove the sentence but reword it slightly to reflect the shorter period and use of 2 months instead of 4. We replace “identify” with “analyze” and clarify that the WRs are not rederived. The time period also includes one additional year (2023).

Lines 103-106 now state: “Daily 500-hPa heights (500H) from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, version 5 (ERA5) (Hersbach et al., 2020) *were used to analyze weather regimes (WRs) during April-May, the season of peak tornado activity* (Graber et al., 2024)*, from 1981-2023.”*

Lines 108-110 now state: “Rather than re-deriving WRs for this period, we used the WRs derived by Graber et al. (2025) using the K-means clustering method for 1960-2022 April-July as the reference WR patterns.”

The abstract has also been revised, replacing identify’ with ‘analyze’ and combining it with the hybrid model description.

There are several statements in the section running from Line 221 to Line 256 where the discussion is inconsistent with what is shown in the figures. Please re-work this discussion.
- Lines 228-229: "TD" should be replaced with "TO"

This line was changed to 'TO' to be consistent with figure 5. The original sentence referencing figure S2 in the supplemental information which shows TD probability anomalies on a gridpoint-by-gridpoint basis which shows slightly different results than the regional results in figure 5. Figure S2 showed spotty anomalously positive TD probabilities around the Southeast and SGP that is not apparent in figure 5.

- Lines 230-232: Why would enhanced VWS in the presence of negative MUCAPE anomalies be supportive of suppressed TD activity and enhanced TO activity when AO -? Figure 5a also indicates that AO - is associated with largely positive anomalies of TD probability (except over the MW). Also, here we are looking at April-May composite anomalies of 500 hPa height, MUCAPE and VWS anomalies, so couldn't you also argue that enhanced VWS is only occurring on days where MUCAPE is already high? This sentence needs to be re-worked.

This is a good question and thank you to the reviewer for pointing it out. TD activity is suppressed relative to TO activity in terms of the probabilities, but this is the case for all of the climate modes, which goes with our argument in lines 248-250 that climate modes modulate TOs more efficiently. To rework this sentence, we will focus solely on why TO anomalies are enhanced during -AO. It is important to remember that tornado outbreaks are relatively rare, so the anomalously high VWS anomalies would be beneficial on days where MUCAPE is already high.

Lines 252-256 got reworded: "Although reduced MUCAPE tends to suppress TD probability, the increased VWS supports positive TO probability anomalies when it occurs on days where MUCAPE is high (Diffenbaugh et al., 2013; Sherburn et al., 2016)*. These positive TO probability anomalies during -AO are only statistically significant over the Midwest, consistent with the region of anomalously positive VWS anomalies."*

- Lines 233-234: This sentence should be rephrased to, "The TD and TO probability anomalies during the NAO phases are sometimes in agreement with those during AO phases," or something similar. There are many places where there is not consistency (e.g., for TDs - CONUS (NAO/AO +), NGP (NAO/AO -), SE (AO/NAO +); TOs - MW (AO/NAO +), NGP (NAO/AO -), SGP (NAO/AO +)). Also: why would the probability anomalies during NAO phases be consistent with that of AO phases? Why might they not?

Thank you to the reviewer for pointing this out as we made it unclear. In all instance where either mode features a <u>significant</u> TD or TO probability anomaly, the anomaly has the same sign for both phases (e.g., for TDs – CONUS (+AO/NAO), NGP (+AO/NAO), SGP (+AO/NAO); TOs – CONUS (-AO/NAO), MW (-AO/NAO), NGP (+AO/NAO)). This can be explained by the strong correlations between NAO and AO. This is made clear now in lines 257-259:
"The TD and TO probability anomalies during the NAO phases are generally consistent in sign with those during AO phases when one phase is statistically significant, but quantitative differences exist."

- Lines 236-243: This section needs to be re-worked. At the beginning it is stated that during NAO + there are negative anomalies of MUCAPE, leading to reduced TD probabilities. However, Figure S2e indicates positive anomalies of MUCAPE, if anything. Additionally, the sentence from lines 240-243 states that 500 hPa height anomalies during the NAO + lead to enhanced MUCAPE and positive TO probability anomalies. This last sentence may be referring to the NAO -? Either way, these two statements are in contradiction with one another and are also not correct.

Some minor changes were made. The anomalous 500H high over the west-central CONUS would favor northerly flow over the central CONUS and ridging over the western CONUS. The northerly flow would hinder moisture and heat transport since it is coming from Canada over the central CONUS. Ridging over the western CONUS would hinder ascent over the central CONUS. We removed the statement on anomalously low CAPE because if anything, there are no CAPE anomalies, or they are faintly positive. The statement on anomalously low VWS is also correct over the southern portion of the SGP. The anomalous high over the western Atlantic and the anomalous 500H low over the Southeast help to enhance southerly flow over the Southeast region specifically. This is why there are anomalously high CAPE and TD probability anomalies over the Southeast which is also supported by positive TO probability anomalies in that region shown in figure 5d.

Lines 260-267 now state (underlined sections are new): "+NAO years feature an anomalous 500H high over the west-central CONUS, which hinders moisture and heat transport from the Gulf of Mexico. These circulation changes result in anomalously low TD probabilities over the SGP and NGP (Fig. S3e). Additionally, anomalously low VWS over the SGP further limits tornado potential during +NAO years. However, +NAO years <u>also</u> feature an anomalous 500H high over the western Atlantic <u>and anomalous 500H low over the Southeast</u>, which enhances southerly flow and moisture transport into the Southeast (Zhao et al., 2025)*, supporting positive MUCAPE anomalies (Fig. S3e) and corresponding positive TO probability anomalies in that region (Fig. 5d)."*

Section 3.3: Possible role of SST anomalies could use some additional consideration.
- ENSO (via the Nino3.4 index), one of the modes of climate variability that is considered in section 3.2, is defined using central and east Pacific sea surface temperature anomalies, and as such, is inherently considering the role of SST anomalies in influencing the atmosphere. Thus, this section is not necessarily independent of section 3.2.

We agree. We have revised the sentence as follows, "In addition to low-frequency climate modes, slowly-evolving SST can also be an important source of predictability, sometime through their coupling with these modes. The role of SSTs is further examined in Fig. 7.".

- How would the results be different if the months of April and May were considered?

This is a good question. Originally we did consider composites of April and May together, which are shown below (Fig. 1). The issue we ran into was that SST anomalies weaken later in the boreal spring season, and the April + May composites did not yield as many significant signals, which is consistent with Chu et al. (2019).

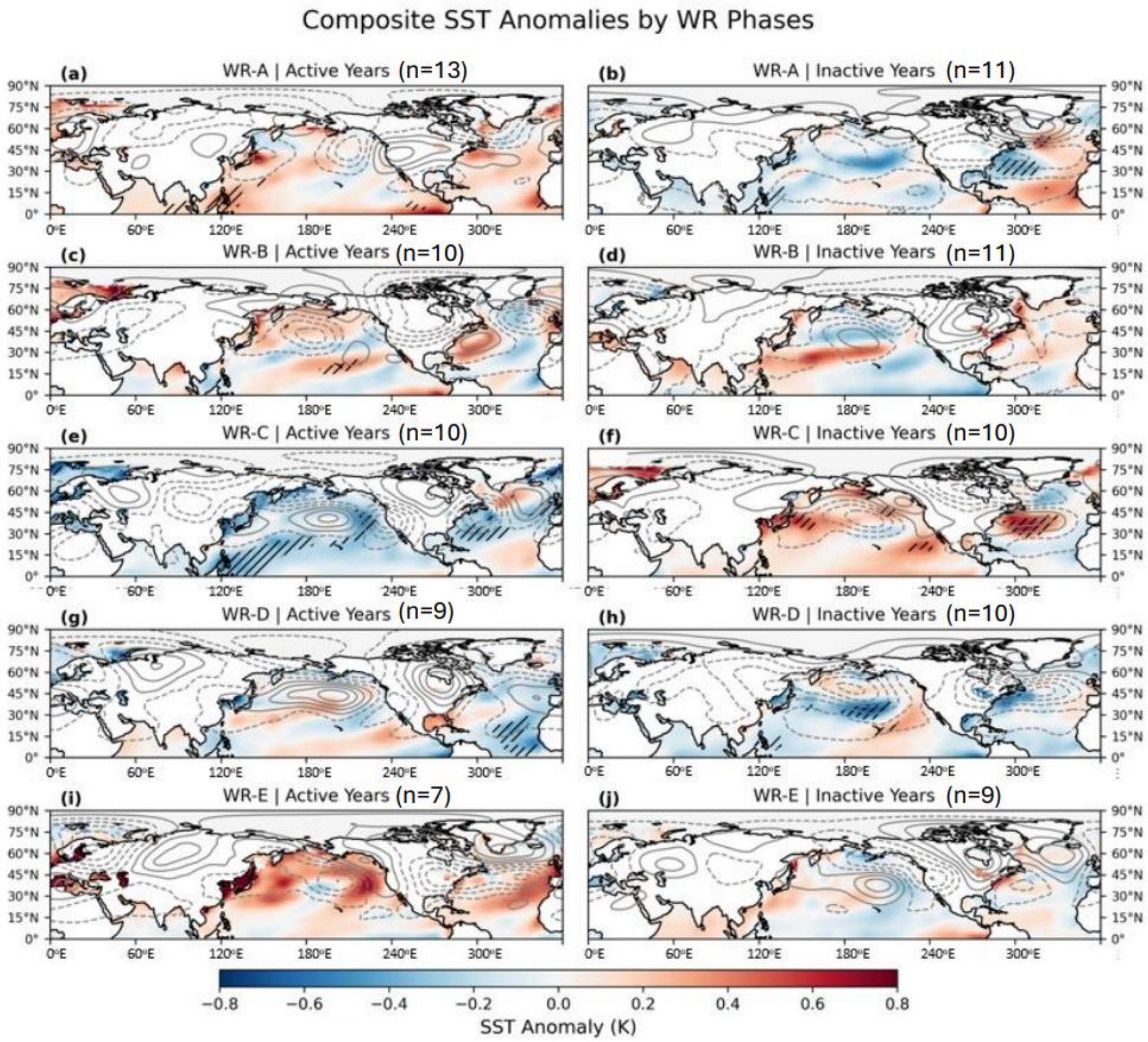
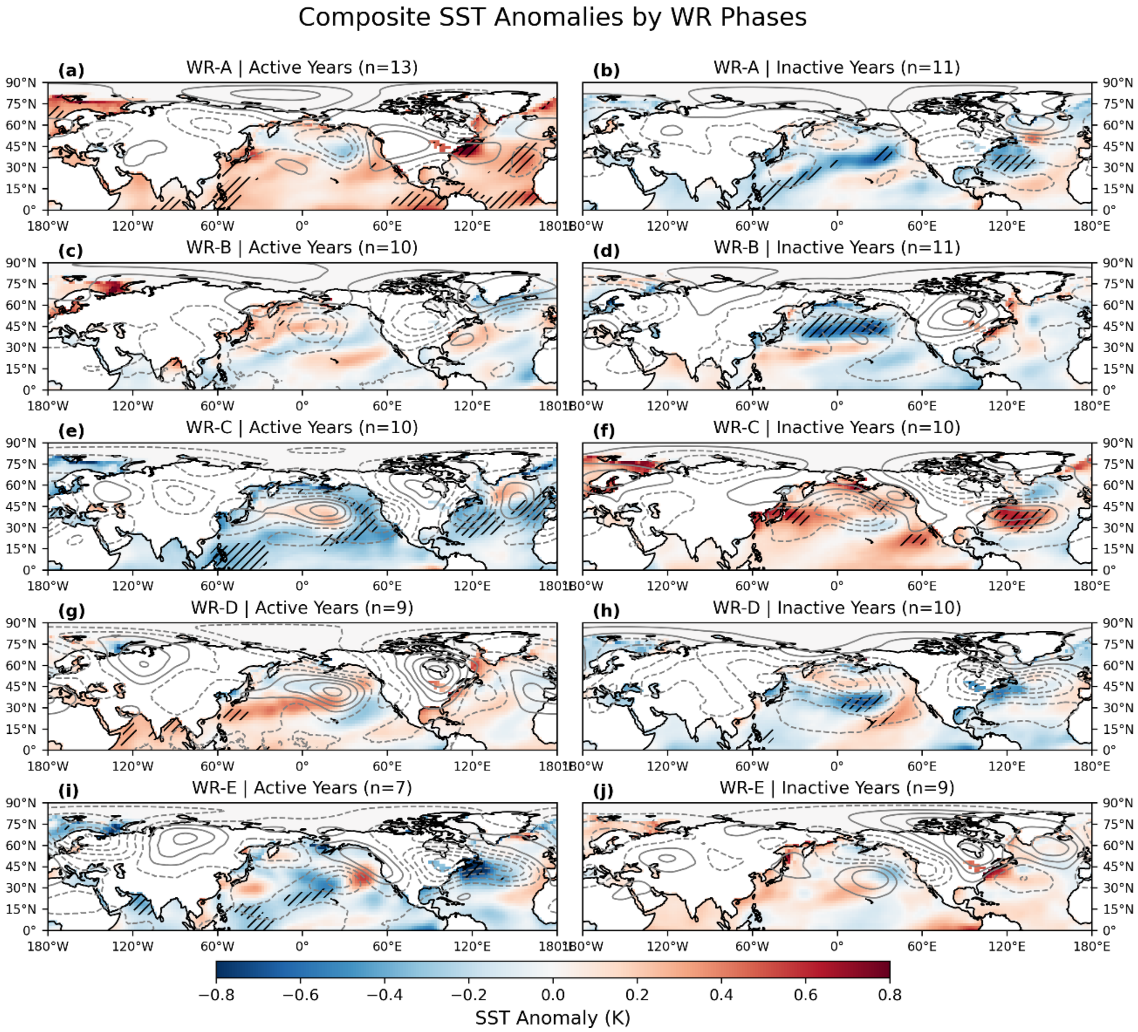


Figure 1: April-May SST anomalies for active and inactive WR years, and hatching indicates significant SST anomalies ($p \leq 0.05$) using a one-sample, two-sided t-test. 500H anomalies are shown in gray contours.

- Composite analysis considers 60 years of data, which is then composited into 10 groups (~6 samples per composite). Please add the number of samples that goes into each composite in Figure 7 (e.g., n=XX). Additionally, the reason why some of the SST fields are noisy could be due to sample size issues.

In the revised Fig. 7 (also see the figure below), sample sizes are indicated in each panel title. It is possible for a year to be used more than once, which is why the samples add up to a number that is greater than 64. For example, 1973 and 1974 are both inactive WR-A years and active WR-B years so both are included in both composites. Overall, the sample sizes are reasonable except that they are a little small for WR-E.


Composite SST Anomalies by WR Phases

(a) WR-A | Active Years (n=13)

(b) WR-A | Inactive Years (n=11)

(c) WR-B | Active Years (n=10)

(d) WR-B | Inactive Years (n=11)

(e) WR-C | Active Years (n=10)

(f) WR-C | Inactive Years (n=10)

(g) WR-D | Active Years (n=9)

(h) WR-D | Inactive Years (n=10)

(i) WR-E | Active Years (n=7)

(j) WR-E | Inactive Years (n=9)

Figure 2: April SST anomalies for active and inactive WR years, and hatching indicates significant SST anomalies ($p \leq 0.05$) using a one-sample, two-sided t-test. 500H anomalies are shown in gray contours. Sample sizes are included in each panel title.

- I wonder if it might be fruitful to composite SST anomalies relative to only active and inactive tornado years, and then 500 hPa heights could also be composited in this way. Resemblance or not to weather regime anomaly patterns could connect SST fields to weather regimes and potentially modes of climate variability. This would also increase sample size and should show a less noisy SST field.

This is an interesting point and is one that is worth pursuing considering results that we will show herein. Below we will show 3 new figures to try and address what this would look like.

Figure 3 shows composite SST and 500-hPa height anomalies for active and inactive tornado outbreak years, defined by normalizing April-May outbreak counts in every April-May from 1960-2023 and selecting years with normalized values $\geq \pm 1.0$. *This yielded 9 active years and 7 inactive years. The resulting patterns differ markedly between the two groups.*

Inactive years exhibit statistically significant SST anomalies, including positive anomalies over the eastern equatorial Pacific and central tropical Atlantic, and negative anomalies over the western Atlantic and north-central Pacific. Corresponding 500H anomalies depict a +PNA pattern, with an anomalous high over the western CONUS and anomalous lows over the northeast Pacific and southeast CONUS, features characteristic of WR-A and WR-E, both of which are unfavorable for tornado activity.

In contrast, active TO years show weaker and less coherent signals. Statistically significant SST anomalies are largely absent, aside from localized negative anomalies off the California coast. 500H *anomalies are similarly muted, with only a weak anomalous low over the central CONUS. Overall, the limited SST and 500H anomalies during active years weakly mirror the patterns associated with WR-B and WR-D, helping explain why active TO years exhibit lower predictability than inactive years.*

When reducing the sample to the 5 most active years (figure 4): 1973, 2003, 2008, 2011, 2019, some SST anomalies strengthen, particularly positive anomalies over the equatorial Atlantic and along the Atlantic coastline. The 500H anomalous low over the central CONUS is stronger here, loosely resembling WR-B which is favorable for tornado activity.

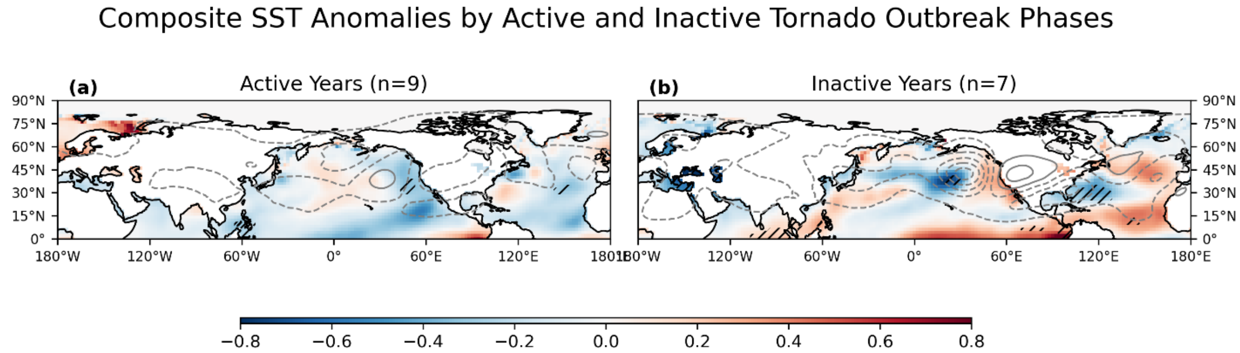


Figure 3: April composite SST anomalies for active and inactive tornado outbreak years, and hatching indicates significant SST anomalies ($p \leq 0.05$) using a one-sample, two-sided t-test. 500H anomalies are shown in gray contours. Sample sizes are included in each panel title.

The above figure has been added to the supplemental information as figure S6, and a paragraph has been added in the SST section addressing it after the discussions of each WR. It also ties in nicely to the higher model skill in Inactive TO years:

Lines 393-399 now state: "We also examined the composite SST and 500H anomalies for active and inactive TO years (Fig. S6). Interestingly, significant SST anomalies are found over equatorial eastern Pacific, North Pacific, and subtropical western North Atlantic during inactive TO years, while significant SST anomalies are nearly absent during active TO years. The lack of significant SST anomalies in the active tornado years are consistent with the relatively limited SST signals during the active WR-B and WR-D years and during the inactive WR-A and WR-E years, and it helps to explain the higher predictability of inactive tornado years discussed in the previous section."

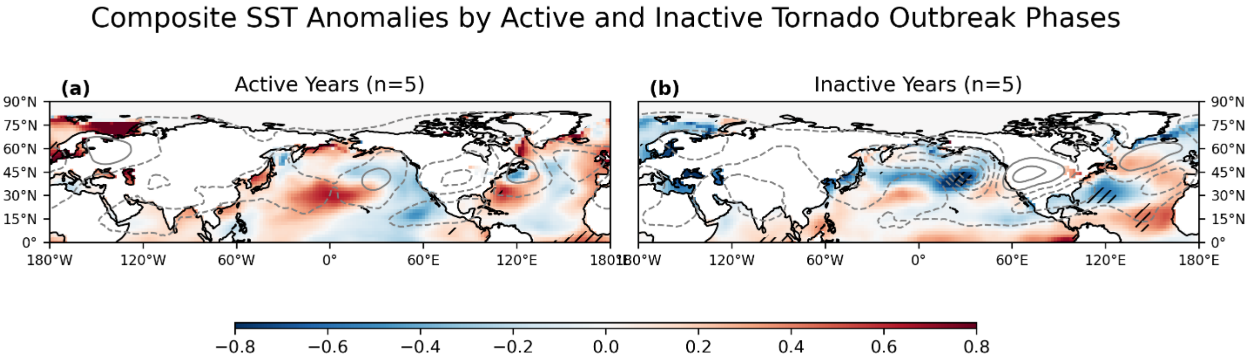


Figure 4: April composite SST anomalies for the 5 most active and inactive tornado outbreak years, and hatching indicates significant SST anomalies ($p \leq 0.05$) using a one-sample, two-sided t-test. 500H anomalies are shown in gray contours. Sample sizes are included in each panel title.

Individual years reveal substantial variance in large-scale circulations (figure 5). NAO phases vary across the 5 active years: 1973, 2008, and 2019 exhibit -NAO patterns; 2011 shows a +NAO pattern consistent with its Southeast-focused tornado activity; and 2003 is neutral. PNA phases also differ, with 1973 showing +PNA, 2003 and 2011 showing -PNA, and 2008 and 2019 near neutral. This variance indicates multiple circulation pathways can lead to active TO years, in contrast to a more uniform pattern observed during inactive years.

Overall, inactive TO years display more coherent and statistically significant SST and 500H anomalies, contributing to their higher predictability. Active TO years, by contrast, arise from a wider range of large-scale circulations, showing the need for further work to understand the mechanisms that produce active TO seasons.

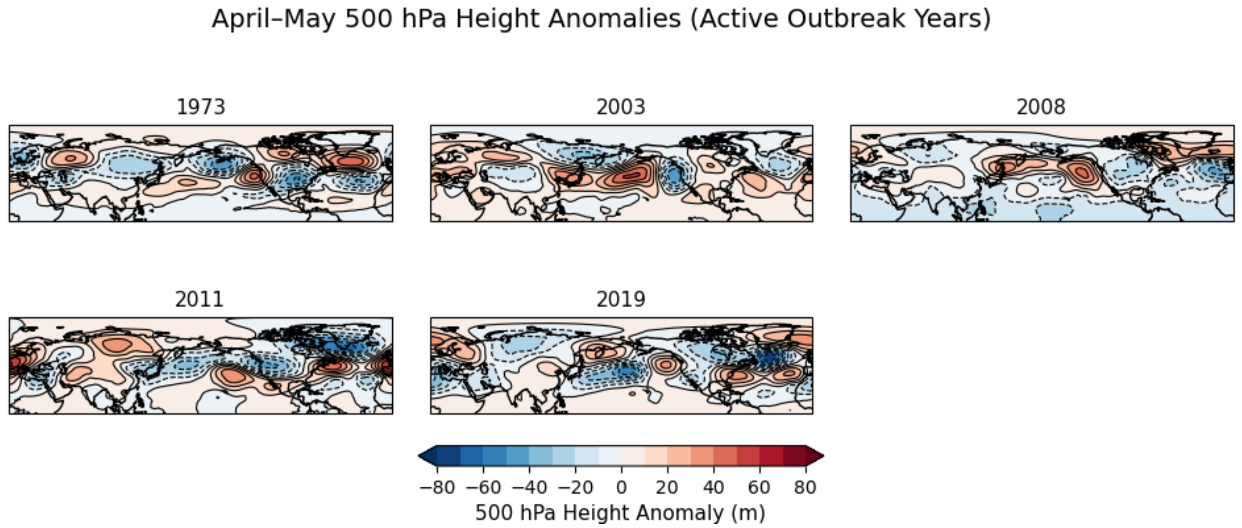


Figure 5: Composite hemispheric 500H anomaly patterns for the 5 most active tornado outbreak springs.

Minor comments:

Throughout the manuscript, the authors refer to ENSO, AO, the NAO, and the PNA as “low-frequency climate modes.” In climate science, low-frequency climate modes are known to be those that operate on decadal to multidecadal timescales (e.g., the Pacific Decadal Oscillation, Atlantic Multidecadal Variability). ENSO is known to be an interannual mode of climate variability (Bjerknes, 1969), while AO, NAO, and the PNA are intraseasonal climate modes (Hurrell, 1995; Thompson & Wallace, 1998; Wallace & Gutzler, 1981). Please change the wording in the general description of these climate modes from “low-frequency climate modes” to something like “modes of climate variability.”

We appreciate this comment regarding terminology. In this study, we refer_“low frequency” variability to variability on the seasonal and longer time scales, in contrast to variability on the synoptic and subseasonal time scales. We average the climate mode across the season April-May to best identify that year’s phase. In essence, this measures the low-frequency variability of each climate mode. To clarify this, we revised the text in section 2.4, “The impacts of some climate modes, ENSO (via Nino3.4), PNA, NAO, and AO, on tornado activity and WR counts were investigated to provide a physical basis for TD and TO predictability. We focus on their low-frequency variability on the seasonal and longer time scales and derived their April-May seasonal indices using the data from the NOAA Climate Prediction Center (2024a,b).”

In section 2.1, the authors mention removing the seasonal cycle from April-May 500 hPa heights, but they do not mention detrending. Given the recent warming trend, the authors should detrend the 500 hPa heights before any other analysis (as they mentioned doing in Graber et al. (2025). Additionally, the authors should elaborate more on the method used to identify the considered weather regimes. Are just the same weather regimes that are identified in Graber et al. (2025) used for this analysis, or is the same method used to identify the weather regimes considered here?

We chose not to detrend 500H from the ERA5 to be consistent with the ECMWF forecast data, since the latter is not detrended. We used the same weather regimes that are identified in Graber et al. (2025) as the reference regimes. We have revised the text in section 2.1, "Unlike Graber et al. (2025), we did not remove the long-term linear trend in 500H of ERA5 to be consistent with the ECMWF seasonal forecast data. Rather than re-deriving WRs for this period, we used the WRs derived by Graber et al. (2025) using the K-means clustering method for 1960-2022 April-July as the reference WR patterns. WRs were assigned by finding the reference WR pattern with the smallest Euclidean distance from the daily 500H anomalies."

Use of detrended anomalies produced similar results with worse model skill for TDs and the ECMWF forecast data had a poor time predicting the seasonal frequency of WR-C.

In the introduction paragraph from Lines 66-80 which discusses that weather regimes fill the gap between tornado activity and modes of climate variability, can you please discuss a bit more how weather regimes fill this gap. For example, if tornado activity is largely a mesoscale phenomena, and climate modes have global impacts (and longer time scales), where do weather regimes fit into the continuum (e.g., synoptic scale)?
The purpose of the WRs is to provide synoptic-scale information since the climate modes we analyze tend to evolve on timescales that are longer than individual weather systems. So, while there may be years that are favorable or unfavorable for tornado activity based on the seasonal phases of ENSO, NAO, AO, and PNA, the seasonal phases do not pick up the higher-frequency variability that drives the day-to-day weather which is where WRs come in. The WRs then interact with environmental variables like CAPE and vertical wind shear, which make some WRs favorable for tornado activity and others unfavorable. This was the main goal of Graber et al., (2025) *which found potential links between warm-season tornado activity and WRs by plotting composite anomalies of CAPE and VWS.*

While ENSO, NAO, AO, and PNA may act as reliable sources of predictability for tornado activity on seasonal timescales, the WRs allow us to have a framework that can predict tornado activity. This is demonstrated in figure 6 of the manuscript where we plot the fraction of WR days, which shows low-frequency climate modes can modulate seasonal WR frequency. However, other WRs can still occur in years where they are not favored. This is addressed in a new sentence in lines 82-84 to bridge the introduction from low-frequency climate modes to WRs:

"Since climate modes evolve on the seasonal and longer timescales, they may serve as sources of predictability for seasonal tornado activity. However, they do not fully capture the synoptic-scale variability of atmospheric circulation. Weather regimes (WRs) can effectively bridge the gap."

In lines 216-220, several regions of the U.S. are described. Please show the delineation of these regions in a supplementary figure. This is particularly important given the later discussion which looks at anomalies of TD and TO probabilities over the CONUS and regionally.
This was added to the supplementary information as figure S2 and is shown below (Fig. 6). Figure numbers were updated accordingly.

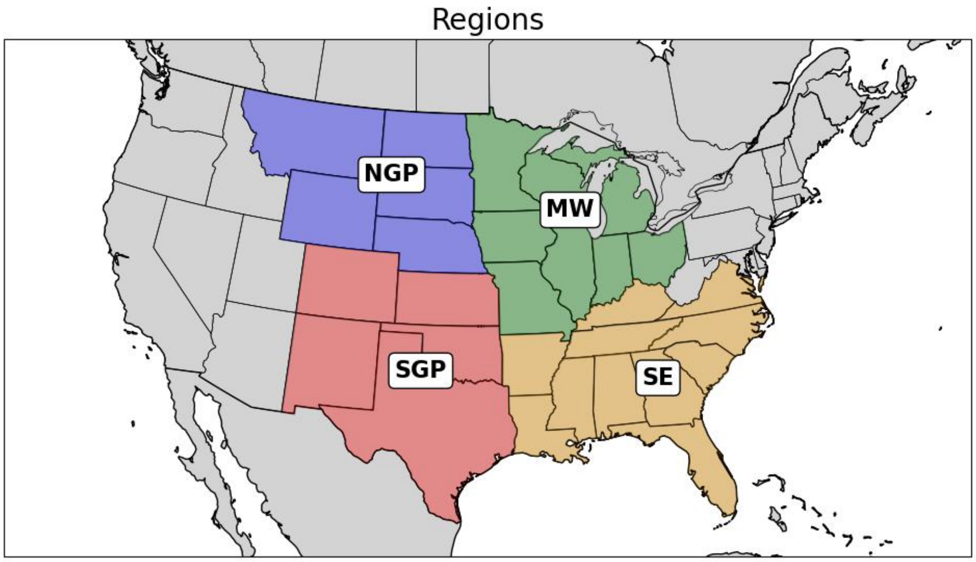


Figure 6: Regions used in this study based on (Moore, 2018): Southern Great Plains (red), Northern Great Plains (blue), Midwest (green), Southeast (yellow).

Line-by-line comments:

- Line 29: Tornado outbreaks (TOs) should be defined here.

Done, and in addition, Schneider et al. 2004 found in their study that roughly 80% of tornado-related fatalities are associated with tornado outbreaks. We did this calculation for 1981-2023 and got 76%, so we put 76% in this line, and still cited Schneider et al. 2004 since it is consistent.

Lines 28-30 now state: "Of these tornado-related fatalities, roughly 76% are associated with tornado outbreaks (TOs; hereinafter, days with > 10 EF/F-1 tornadoes; Graber et al. 2025), consistent with Schneider et al. (2004)."

- Line 41: Madden Julian Oscillation should be written out in words.

Done

- Line 43: El Niño Southern Oscillation should be written out in words.

Done

- Line 87: ERA5 should be written out as the "European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, version 5 (ERA5)." Then, in line 96, ECMWF can just be written out.

Done

- Lines 96-104: Please elaborate on how far out ECMWF seasonal forecasts go out (i.e., up to seven months in the future)

The ECMWF seasonal forecasts are on 12-hour temporal resolution and go out 7 months.

Lines 117-118 explain this now in greater detail: "The 25-ensemble forecasts are initialized once per month, are available on a $1^o \times 1^o$ grid, are on 12-hour temporal resolution, and go out 7 months"

- Lines 108-110: Are tornado outbreaks and tornado days defined in this way by any other literature other than Graber et al. (2024) and Graber et al. (2025)? Are there other definitions of tornado outbreaks and tornado days that have been previously used? If so, why was this particular definition selected?

The definition of tornado days (any day with ≥ 1 EF/F-1+ tornado) is a common definition that has been used by multiple other studies to alleviate reporting biases (Brooks et al., 2014; Elsner et al., 2014; Moore, 2017). Tornado outbreaks have no official definition (Cwik et al., 2021). Multiple observation-based definitions over the years have been used in various studies including: > 30 EF/F-1+ tornadoes (Brooks et al. 2014), ≥ 6 EF-2/F-2+ tornadoes (Thompson and Roundy, 2013), > 20 EF/F-1+ tornadoes

(Trapp, 2014), among others. In Graber et al., (2024), we defined a tornado outbreak as any day with >10 EF/F-1+ tornadoes which shows the same increasing trend as >20 and >30 EF/F-1+ tornadoes but increased the sample size. This was done to allow ourselves to have a larger sample size while still analyzing days with high societal impact (Strader et al., 2024). To maintain consistency across all our studies, we have kept our definition of a tornado outbreak at >10 EF/F-1+ tornadoes.

- Line 120: No need to cite Graber et al. (2025) again as it was cited at the beginning of the paragraph.
Taken out

- Lines 141-142: “ENSO3.4” → “Nino3.4”

Done

- Lines 147-148: “... where the climatological mean TD probability (P_c) is defined as the total number of TDs divided by the total number of days; P_r is TD probability for the given phase of the climate mode…” → “... where the climatological mean TD **(TO)** probability (P_c) is defined as the total number of TDs **(TOs)** divided by the total number of days; P_r is TD **(TO)** probability for the given phase of the climate mode…”

Done

- Lines 153-154: “WR-A features anomalous highs over both the western and eastern U.S. coasts.” → “WR-A features anomalous highs centered over the Pacific Northwest and off of the U.S. east coast.”

Done

- Line 155: “Southeast” → “southeast”

We capitalize “Southeast” throughout the manuscript. After removing “CONUS” in the following comment, we feel it best to keep “Southeast” capitalized here.

- Line 156: Remove “CONUS”

Done

- Lines 161-162: “The impacts of the WRs on tornado activity in the CONUS…” → “The impacts of the WRs on CONUS tornado activity…”

Done

- Lines 163-165: Please briefly describe why certain weather regimes are more or less favorable for tornado activity.

This was a discussion point in our previous paper, Graber et al., 2025 (https://doi.org/10.5194/wcd-6-807-2025). In short, certain weather regimes are favorable for tornado activity depending on their interactions with environmental parameters such as most unstable convective available potential energy (MUCAPE), 0-6km vertical wind shear (VWS), and convective precipitation (CP). In Graber et al. (2025), WR-A was found to have anomalously low MUCAPE, VWS, and CP over the central CONUS. In contrast, WR-B was found to have anomalously high MUCAPE, VWS, and CP over the central CONUS. Respectively, these are associated with anomalously low and high tornado day probability anomalies in these regions. Similar relationships were made for WR-C, WR-D, and WR-E, though WR-A and WR-B were the clearest, and this makes sense given the TD and TO probability anomalies presented in Fig. 1 of the manuscript.

- Line 183: “(Fig. 3a-b)” → “(Fig. 3)”

Done

- Lines 305: Why do you restrict analysis in the earlier part of the study to 1981-2023, if 1960-2023 are going to be considered for section 3.3.?

The ECMWF seasonal forecasts only go back to 1981, hence why the earlier analysis is restricted to 1981-2023. 1960-1980 was included in section 3.3 to expand the sample size. To indicate the possible role of sea-surface temperatures, we elected to go back to 1960.

- Lines 305-307: Do you mean to say that, “For each WR, active and inactive years are identified as the years when the spring time **tornado** count of the WR exceeds +/-1 standard deviation,”?

No, though as written it could be clearer. Active WR-i years, as an example, are defined as years where the April-May WR-count exceeds +1.0 standard deviation. So, these are the years that feature the highest amount of WR-i days. Given what we know about the different WRs and their link to tornado activity, we would expect active WR-A years to have below-average tornado activity. In contrast, we would expect *active WR-B years to have above-average tornado activity. Inactive WR-i years are the exact opposite. These are years that feature the fewest WR-i days.*

Lines 345-347 now state: "For each WR, active and inactive regime years are defined as the years when the springtime WR count exceeds ± 1 standard deviation from the mean."

- Figure 1: The legends for Figure 1f and Figure 1h are incorrect. What do the light green bars in 1f represent? What do the pink bars in 1h represent? Are these bars the thin lines in the legend?

Thank you for pointing that out. The thin bars were a mistake, and this has now been amended in the updated manuscript. The light green bars in Figure 1f represent the TD probability anomalies for persistent WRs (WR duration for ≥ 5 consecutive days). The pink bars in figure 1h represent the same for TO probability anomalies. The new figure 1 is shown below with an updated figure caption where the colors of the bars have been specified (Fig. 7):

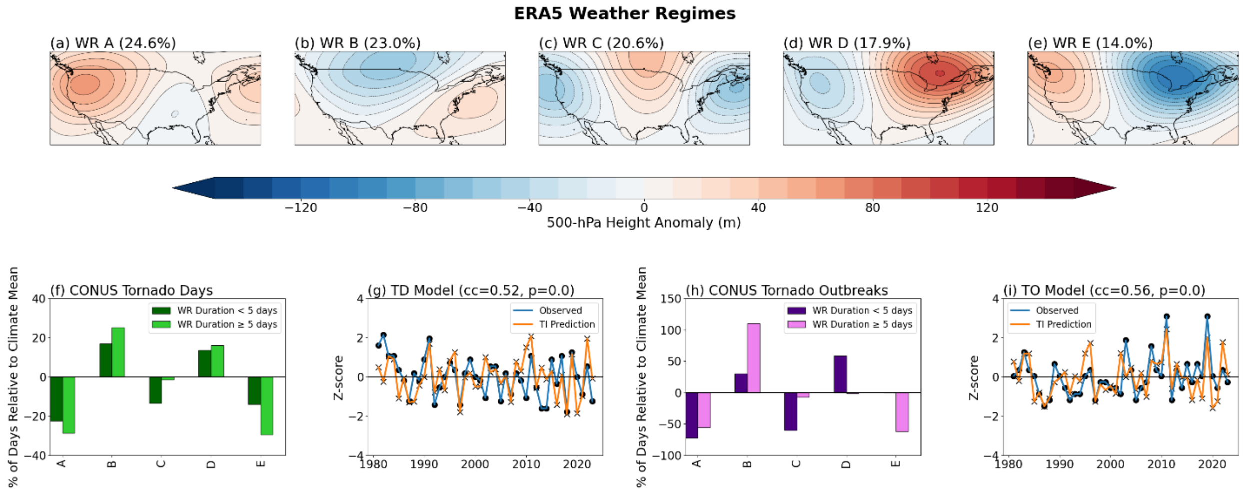


Figure 7: *500H anomaly patterns of WRs A-E with long-term frequency indicated in panel title (a-e). ERA5 tornado day (f) and tornado outbreak (h) CONUS probability anomalies for persistent (≥ 5 days; light green, pink) and nonpersistent (< 5 days; dark green, indigo) WRs. Time series of standardized tornado days (g) and tornado outbreak days (i) from the observation (blue) and estimation of the empirical modeling (red). Spearman rank correlation and p-value are indicated in panels g and i.*

- Figure 5g and 5h: "positive" and "negative" might be changed to "El Niño" and "La Niña" for clarity.

This has been done as requested.

- Figure 7: "500H anomalies are shown in black contours." → "500H anomalies are shown in gray contours."

Done

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