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Modulation of Annual Cycle of Tornadoes by El Niño–Southern Oscillation

John T. Allen[1], **Maria J. Molina**[1], **and Vittorio A. Gensini**[2]

[1]Department of Earth and Atmospheric Sciences, Central Michigan University, Mount Pleasant, MI, USA, [2]Department of Geographic and Atmospheric Sciences, Northern Illinois University, DeKalb, IL, USA

Key Points:
- El Niño–Southern Oscillation modulates both the timing and magnitude of the annual cycle for tornadoes
- Climate variability plays a substantial role in the characteristics of the annual cycle of tornadoes
- Seasonal cycle shifts by El Niño–Southern Oscillation are significant compared to historical tornado record trends

Supporting Information:
- Supporting Information S1

Correspondence to:
J. T. Allen,
JohnTerrAllen@gmail.com

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Abstract Long-term trends suggest shifts toward earlier tornado season peaks, and yet fail to examine the role of year-to-year climate variability. Here, El Niño–Southern Oscillation phase is demonstrated to influence annual cycle characteristics of United States tornadoes. Observations and favorable environments show substantial modification of the peak spatial distribution and the temporal onset of tornado occurrence. La Niña produces an earlier annual peak probability by 1.5–2 weeks, with a higher overall fraction of events in March and April. In contrast, El Niño leads to a week delay in the maximum probability and enhances a second peak in the fall months. Consequently, this suggests that climate change is not the sole driver of changes to seasonal onset and peak, and climate variability plays an important role in modulating the annual cycle.

Plain Language Summary What drives the onset of tornado season, and can we point to a changing climate as the cause of a trend toward an earlier season start date? In this paper, climate variability driven by equatorial Pacific sea surface temperature variations (El Niño–Southern Oscillation) is shown to modulate the characteristics of when the majority of tornadoes in any given year occur, and the timing of the season peak. La Niña is shown to shift the bulk of tornado season earlier by 1.5–2 weeks relative to years when no Pacific sea surface temperature anomaly exists, while El Niño delays the maximum daily frequency by a week. This result contrasts earlier studies that show long-term trends of a similar or smaller magnitude, which had previously suggested that climate variability does not modulate the annual cycle. The results here provide the potential for guidance as to season onset in developing seasonal tornado outlooks.

1. Introduction

Recent studies have identified shifts to the annual cycle of tornado frequency in the contiguous United States (CONUS), with an earlier start to the season (Long & Stoy, 2014; Lu et al., 2015) or increased variability in its timing (Brooks et al., 2014a). However, while the warming climate has been suggested as a potential cause, the contribution of natural climate variability to these shifts has yet to be examined. Given the susceptibility of tornado observations to trends of nonmeteorological origin and large natural variability (Verbout et al., 2006), when combined with a nonstationary El Niño/Southern Oscillation (ENSO) state, this could lead to a misleading impression of the annual cycle of tornado occurrence. Indeed, Trapp et al. (2009) noted that any manifestation of a warming climate in severe thunderstorm frequency should be decades away. Thus, it is important to consider the plausible alternate hypothesis that climate variability contributes to the observed changes of the annual cycle of severe thunderstorm frequency.

Physical modulations of favorable conditions by ENSO influence the frequency of CONUS tornado environments and observations, including the propensity for outbreaks (Allen et al., 2015; Cook et al., 2017; Cook & Schaefer, 2008; Lee et al., 2012, 2016; Lepore et al., 2017). However, in earlier studies, the role of seasonal variability and asymmetry within the signal was not considered. Herein, this is demonstrated to be an overly simplified assumption, as ENSO also modulates annual cycle evolution for tornadoes. While other signals also contribute to variance in tornado frequency (e.g., Barrett & Gensini, 2013; Elsner & Widen, 2013; Gensini & Marinaro, 2016; Lee et al., 2016; Molina et al., 2016; Tippett et al., 2015), ENSO reflects a large contribution to such teleconnections when active, and hence, its role is the focus here.

The seasonal cycle of tornadoes has been explored relatively infrequently. Long and Stoy (2014) noted an apparent shift in the peak of tornado observations over the southern and central Great Plains (1954–2009), shifting the peak 7 days earlier. However, this result may be influenced by the limited region considered (Trapp & Brooks, 2013) or the use of observations alone to understand the annual cycle. Lu et al. (2015) explored long-term annual cycle changes using both observations and favorable environments and concluded a larger shift. Wavelet analysis identified a trend of ~3.7 days per decade in the timing of the onset and peak of tornado season (1955–2013), resulting in a shift of 1.5 weeks. These approaches neglect or dismiss potential contributions of climate variability and its decadally varying frequency.

Changes to the annual cycle of tornadoes are influenced by the climatic conditions of the spring season. These conditions manifest from signals such as temperature (e.g., Brooks et al., 2014a; Wang et al., 2009), and physical interactions driven by climate variability. To illustrate this influence, ENSO phase-driven impacts on the annual cycle of tornadoes are considered. The authors disagree with assertions of Long and Stoy (2014) that suggest annual cycles are largely unrelated to the large-scale climate oscillations and hypothesize this is driven by study methodology. An evaluation of the daily annual cycle response to changes in the monthly Oceanic Niño Index (ONI) is performed using both observations and favorable environments. The annual cycle can be thought of as a deviation from the peak climatological value or an absolute shift in shape of the annual cycle. Thus, both quantities may vary as a response to ENSO state. To facilitate this analysis, instead of the deviation from climatology in terms of seasonal or monthly percentage or anomaly (e.g., Allen et al., 2015; Cook et al., 2017), the characteristics of tornado environments and observations, varying on an aggregate and spatially gridded daily basis, are investigated.

2. Data and Approach

2.1. Observations

Single track tornado observations were obtained from National Oceanic and Atmospheric Administration Storm Prediction Center storm data (Schaefer & Edwards, 1999) for 1953–2016, gridded to 80 × 80 km, and stratified into daily tornado reports and tornado days. To assess spatial seasonal cycle variability, tornado reports were smoothed both spatially and temporally using a two-dimensional 1.5σ Gaussian kernel, followed by a one-dimensional periodic 15σ (day) smoother (Allen & Tippett, 2015; Doswell et al., 2005). The smoothing process alleviates localized spatial biases and, while potentially reducing peaks, producing a less noisy data set for assessing seasonal variations driven by ENSO. To identify signals, percentiles and maximum annual probability of the Gaussian seasonal cycle are used. For composite seasonal characteristics, data were regionally aggregated to explore whether the cycle shape varies spatially. To alleviate any potential long-term trends within the record, normalization using the total annual frequency of events is applied to each day, resulting in daily fraction of annual probability.

2.2. North American Regional Reanalysis

North American Regional Reanalysis (Mesinger, 2006) three-dimensional data were used (1979–2016) on the native 32 km grid. As an environmental proxy for tornadoes, the Significant Tornado Parameter (STP; Thompson et al., 2003) was calculated from 3-hourly pseudosoundings for CONUS grid boxes. The parameter includes surface-based convective available potential energy (CAPE), surface-based lifted condensation level, 0 to 1-km storm relative helicity, and 0 to 6-km bulk vertical wind shear. For identifying the annual cycle, mean daily STP is normalized by the monthly ENSO phase, and calculated as daily fraction of the total accumulation, and cumulatively aggregated on a regional basis, before smoothing analogously to the observations for grids with mean yearly accumulation of STP≥2.5. For the cumulative frequency distribution, the normalized daily accumulated occurrence of STP≥1 3-hourly periods is used.

2.3. Oceanic Niño Index

ENSO is characterized using ONI (Climate Prediction Center, 2018), similar to earlier studies (e.g., Allen et al., 2015). ONI describes the running 3-month mean anomaly of mid-Pacific sea surface temperatures (SSTs) corresponding to the Niño 3.4 region (Barnston et al., 1997), relative to a 30-year mean to remove warming signals. ONI represents the leading empirical orthogonal function of Pacific SST variability and performs adequately in capturing variability driven by other regions or outgoing longwave radiation (L'Heureux et al., 2015). Each day for tornado observations and STP is stratified into La Niña (LN) and El Niño (EN) phases based on centered monthly ONI threshold of ±0.5.

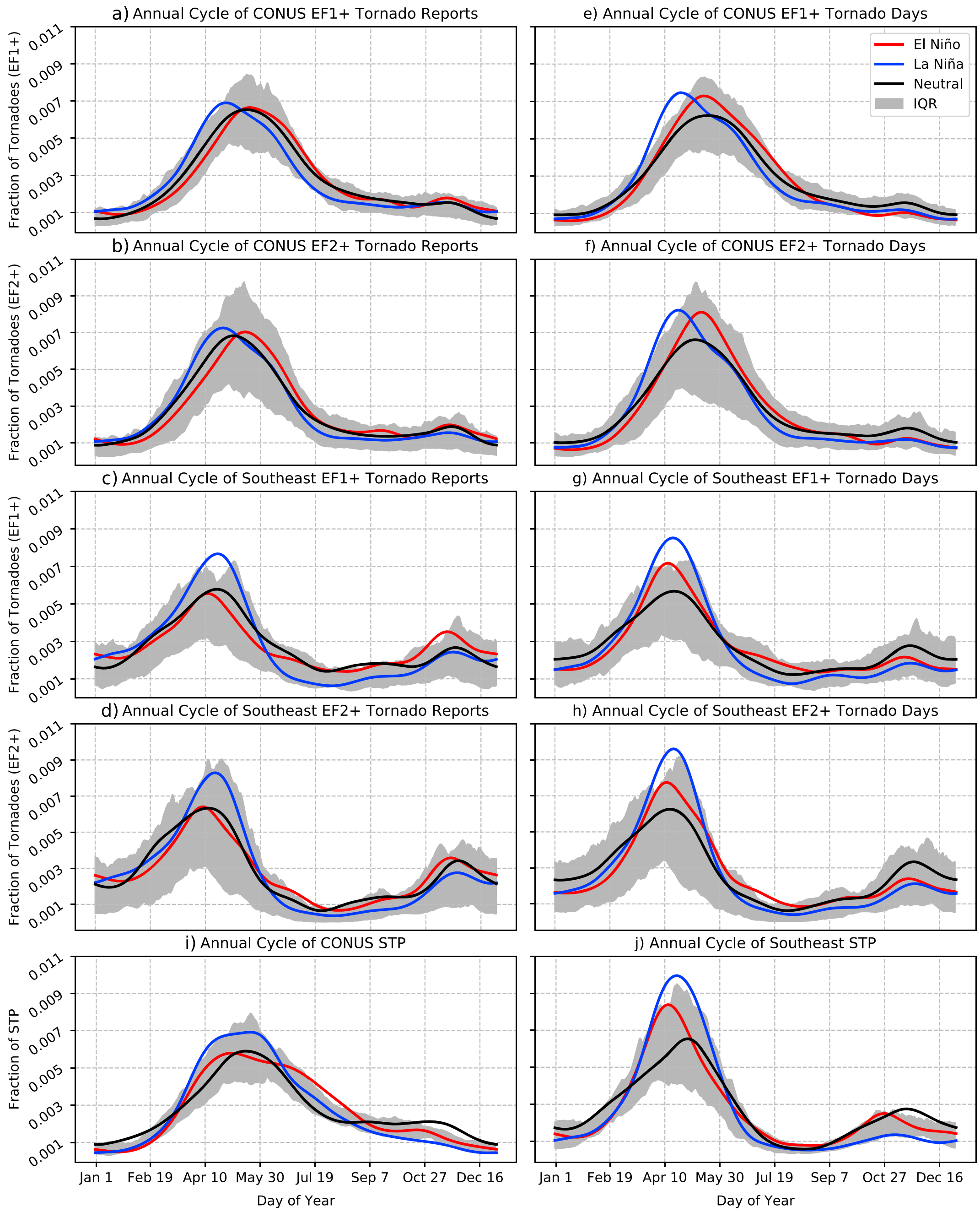

Figure 1. Daily probability of seasonal cycles of tornado reports (a, b, c, d), tornado days (e, f, g, h) and daily fraction of accumulated STP (i, j), composited for days meeting monthly ONI thresholds. The gray region reflects IQR of all years. IQR = interquartile range; STP = Significant Tornado Parameter; CONUS = contiguous United States.

3. Results

3.1. Asymmetry in Annual Cycle as a Response to ENSO

The annual cycle of tornado reports and days shows a strong sensitivity to the ENSO phase (Figures 1a and 1e). The peak frequency and cumulative 10th percentile of EF1+ tornadoes occur considerably earlier in LN composite years compared to neutral years, by 18 and 10 days earlier, respectively (Table 1). LN annual probability is higher earlier in the season and declines rapidly compared to neutral through June, suggesting an abbreviated tornado season, reaching the 75th percentile 13 days earlier while reaching the 90th percentile 3 days later. Peak frequencies during EN are lower and closer to neutral years, peaking on 17 May, lagging neutral

Table 1
Timing of Seasonal Distribution Characteristics

Phase	10th	25th	50th	Peak	75th	90th
			EF1 + Reports			
Neutral	17/03	22/04	31/05	17/05	25/07	12/10
El Niño	**+2**	+4	+5	+3	+3	+11
La Niña	**−10**	**−11**	**−12**	**−18**	**−13**	+3
			EF2 + Reports			
Neutral	8/03	12/04	21/05	06/05	19/07	24/10
El Niño	+7	+9	+7	**+10**	+8	+7
La Niña	**−3**	**−5**	−8	**−10**	**−17**	−8
			EF1 + Days			
Neutral	13/03	20/04	01/06	19/05	26/07	15/10
El Niño	**+10**	+4	−2	*−3*	*−12*	**−30**
La Niña	+2	*−7*	**−14**	**−24**	**−20**	**−21**
			EF2 + Days			
Neutral	09/03	14/04	23/05	08/05	22/07	25/10
El Niño	*+11*	+7	+0	**+5**	−12	**−29**
La Niña	+3	−5	**−13**	**−16**	**−27**	**−31**
			STP			
Neutral	10/03	21/04	04/06	16/05	16/08	28/10
El Niño	**+14**	+3	+4	**−12**	**− 15**	**−21**
La Niña	**+11**	−2	**−10**	**+5**	**−35**	**−46**

Note. Percentiles of cumulative daily fraction and maximum annual probability in neutral years and deviation in days during the respective ENSO phases. Statistically significance (bold, italicized) in each phase based on a 10,000-member bootstrap of differences at the two-tailed 95th and 90th percentiles, respectively. ENSO = El Niño–Southern Oscillation; STP = Significant Tornado Parameter.

seasons by 3 days, and resulting in a 3-week difference compared to LN. Little variation occurs for EF1+ tornadoes throughout the fall season with a slight increase during fall EN (Figure 1).

For strong tornadoes (EF2+), the peak seasonal frequency of neutral years is earlier than for EF1+ tornadoes on 6 May (Figures 1b and 1f). The corresponding shift due to LN results in the peak leading the neutral expectation by 10 days and EN by 20 days. In contrast to the signal for EF1+ tornadoes, LN tends to lead to a suppressed fall peak in EF2+ tornadoes. For EF1+ and EF2+ tornado days, the peak is also earlier during LN, with deviations exceeding 2 to 3 weeks by the peak and continuing throughout the year. Applying STP analogously (Figure 1i), EN seasons tend to start later, before accelerating into the summer and fall months. LN has a later signal in the earliest part of the season, a similarly timed peak to neutral conditions, but reaches the 50th, 75th, and 90th percentiles considerably earlier. However, STP may not be an ideal parameter in high shear low CAPE scenarios of the winter and spring (Sherburn & Parker, 2014) and likely underestimates the earlier season, explaining part of this inconsistency. STP also does not have a one-to-one relationship with tornado observations, as it ignores lift or initiation (Thompson et al., 2003), and multiple tornadoes may occur in close proximity.

The cycle over southeast United States has a bimodal shape that is sensitive to ENSO phase (Figures 1c, 1d, 1g, and 1h). There is a large increase in maximum annual probability (60%–70%) but a lesser influence on timing. Higher probabilities for southeast tornadoes occur during LN years, with fractions greater than neutral March–May, and lower probabilities through year end.

EN seasons begin more slowly, with smaller deviations compared to neutral years through the seasonal peak. The second fall peak shows increases in EF1+ tornadoes fraction during EN with earlier timing but is not as consistently found for EF2+, which may reflect limitations of sample size of this higher threshold, or more weak tornadoes occurring during the fall season. Tornado days show a larger increase in the maximum annual probability over the southeast compared to reports (Figures 1g and 1h).

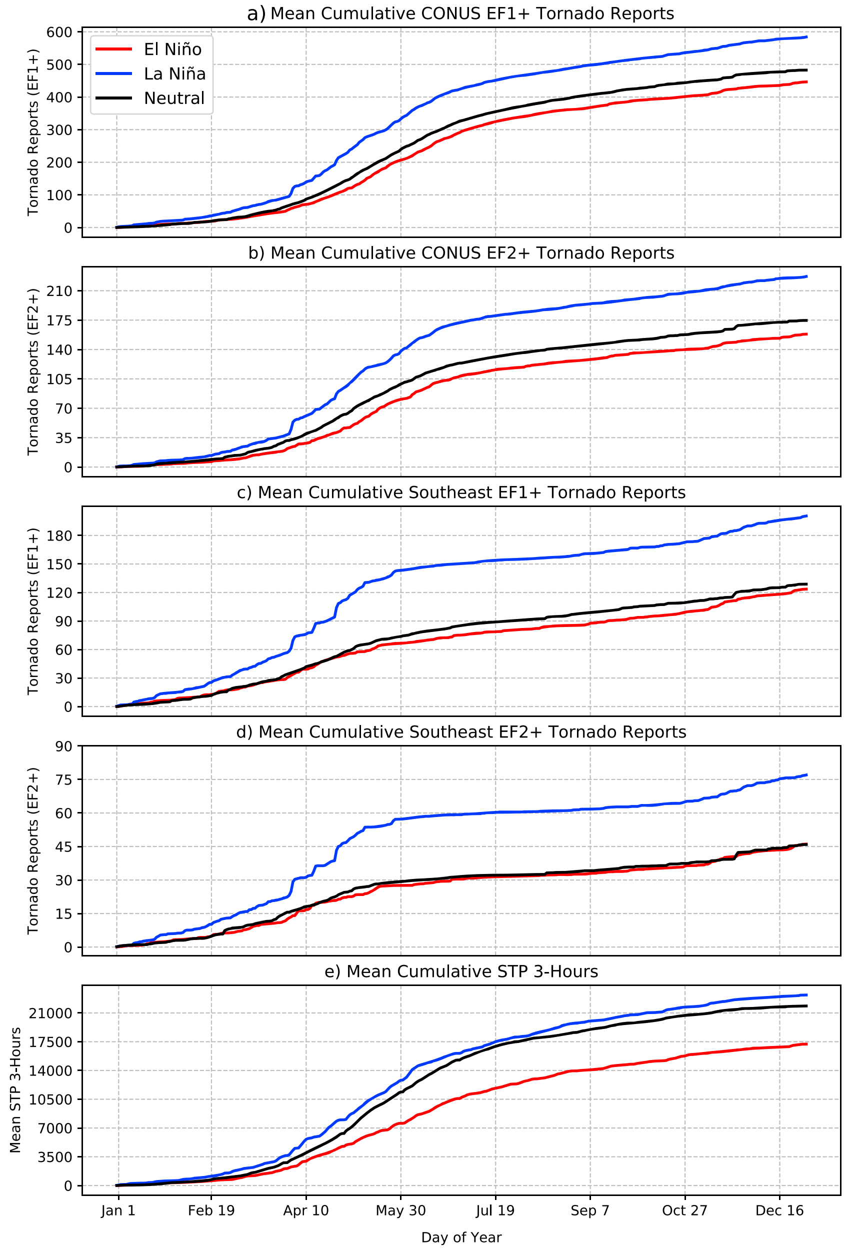

Figure 2. Mean annual cumulative distributions of EF1+, EF2+ tornado reports, and 3-hourly $STP_{\geq}1$ periods on a daily basis stratified by ENSO phase. STP = Significant Tornado Parameter; CONUS = contiguous United States.

Considered as cumulative frequency (Figure 2), LN years are characterized by higher than neutral tornado days, predominantly prior to June. The number of tornadoes accumulates more quickly, particularly over the southeast than during EN and neutral conditions. In contrast, EN has a generally lower frequency, though EF2+ reports over the southeast during EN tend to accumulate at a similar rate to neutral years. STP 3-hourly period accumulations show that LN is marginally faster than neutral years, while EN years accumulate these periods more slowly for spring and summer.

3.2. Variability in Tornadoes and Tornado Days Driven by ENSO Magnitude

Ranking of monthly tornado frequency relative to climatology by ONI strength shows a strong ENSO influence, particularly between December and February (Figure 3). Strong EN events are characterized by enhanced EF1+ and EF2+ frequency in December and February, contrasting lower January frequency (Figures 3 and S1 in the supporting information). Interpreting these lower frequencies in December and January

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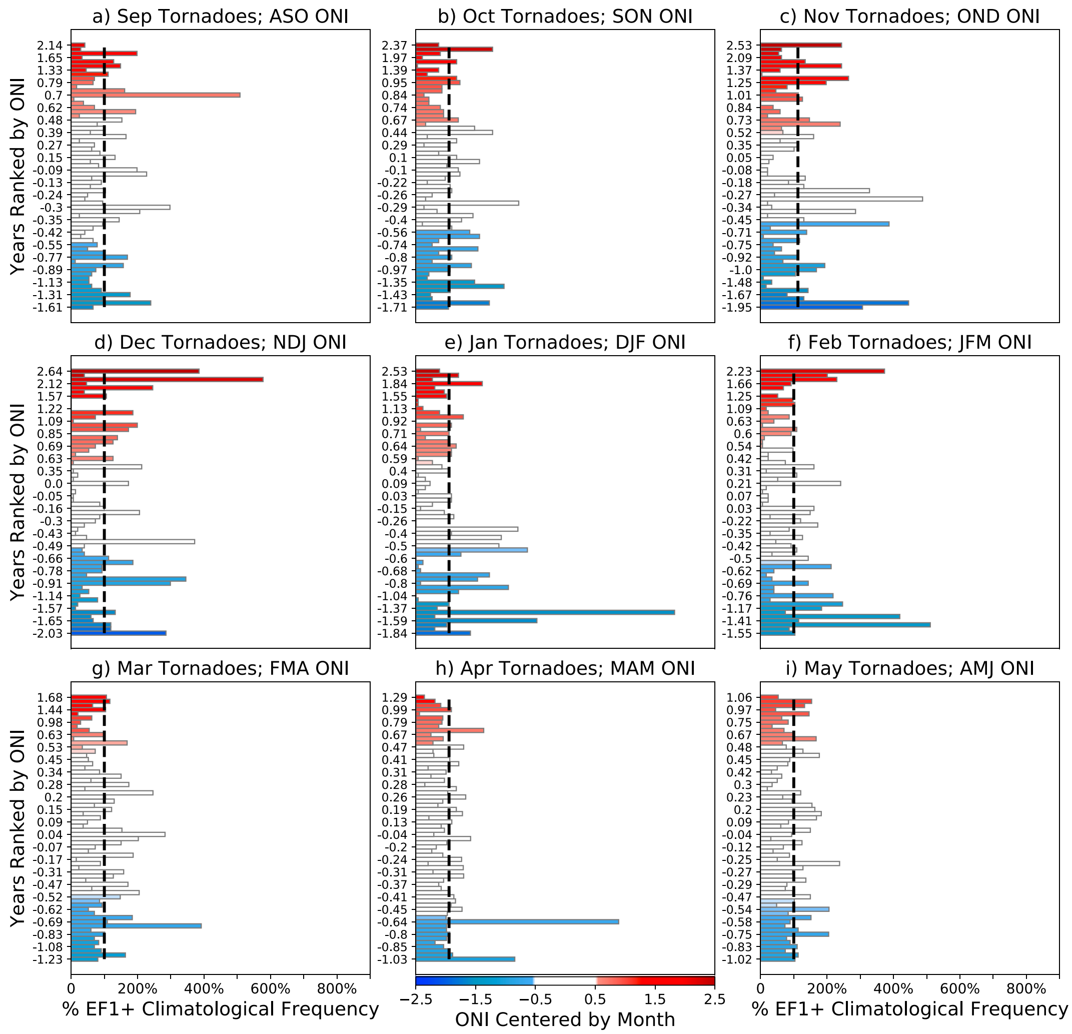

Figure 3. Monthly (September–May) percent of climatology stratified by ordinal ranked ENSO years for all EF1+ tornadoes, as compared to mean frequency (dashed line). ENSO = El Niño–Southern Oscillation; ONI = Oceanic Niño Index.

of some years, this reduction is likely driven by extreme southward displacement of the subtropical jet stream (Allen et al., 2015; Cook et al., 2017). During spring, EF1+ and EF2+ tornadoes are generally near or below average, likely related to the increased likelihood of cold continental air being advected southward over the southeast behind the enhanced Gulf Coast cyclone track (Allen et al., 2015).

LN also shows a magnitude-dependent influence on the annual cycle, with enhanced activity from November through March (Figure 3). Active early winters occur in a range of LN magnitudes, but large signals occur in January and February, with modulation of frequency into spring, contrasting reduced EN frequencies. Similar signals are found for EF2+ frequency (Figure S1), with the highest frequencies on record for January through April during LN.

Over the southeast, high frequencies for EF1+ occur for both ENSO phases (Figures S2 and S3). LN's influence is primarily from January through March for both EF1+ and EF2+ tornadoes, though there is some suggestion of above normal frequencies as early as November. In contrast, EN's contribution to anomalously positive frequency comes from as early as October through February, though individual outbreaks in these relatively low frequency months present challenges in assuring robust signals. Given the spring reflects the climatological peak of southeast tornadoes, the anomalously low frequencies over the southeast between March and May drive much of the CONUS signal.

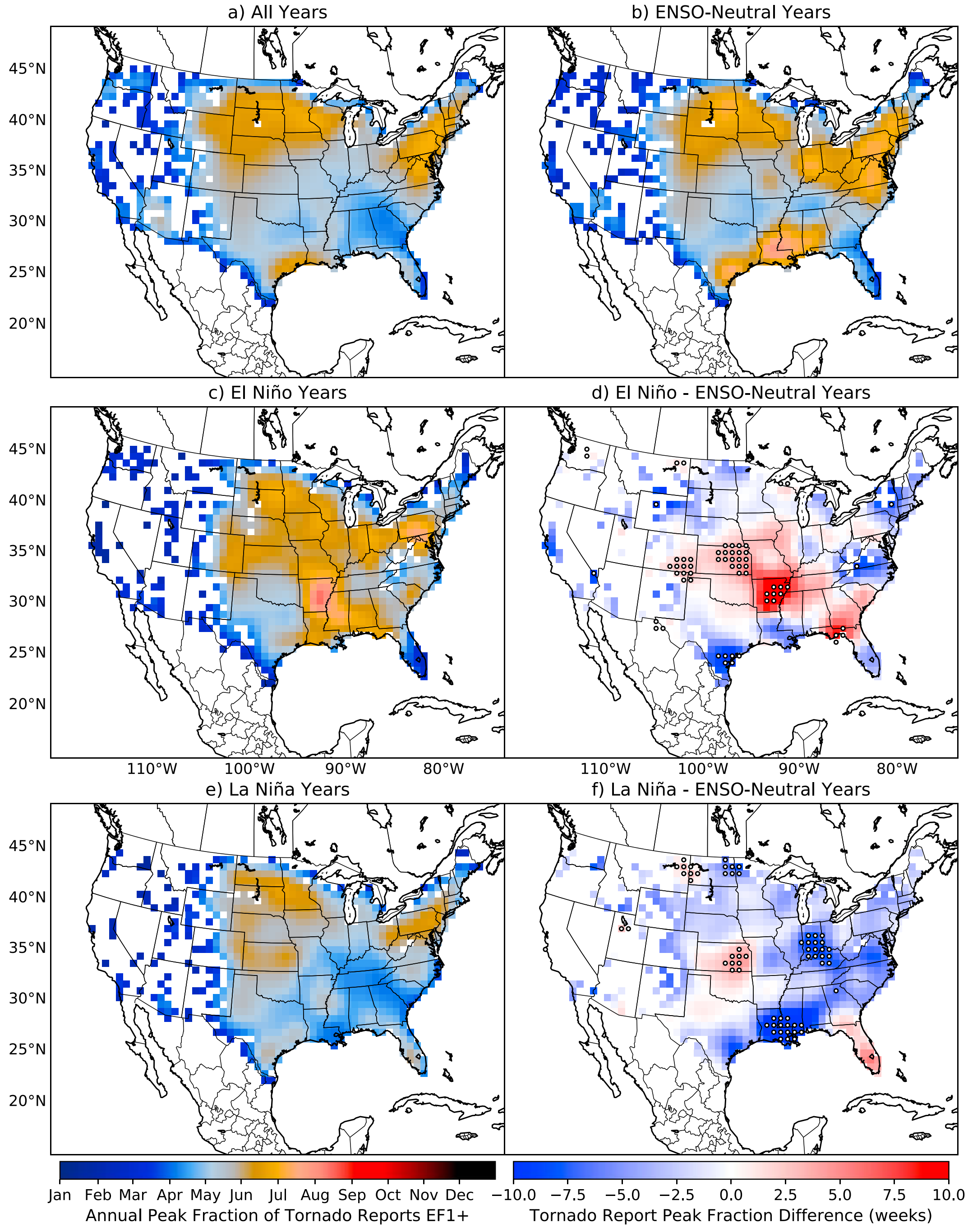

Figure 4. Seasonal EF1+ tornado peak date by monthly ENSO phase and differences from neutral. Stippling reflects where cycle peak date is a significant grid point difference using a 10,000-member bootstrap of differences exceeding the two-tailed 95th percentile. ENSO = El Niño–Southern Oscillation.

Tornado days differ from tornado frequency, with anomalously high tornado day frequency in both LN and EN from November through March (Figures S4 and 5). This is accompanied by generally higher frequency with increasing EN intensity and a more mixed response for LN. EF2+ tornado days are generally more common during LN years, particularly for December through March, while EN drives higher EF2+ day numbers from November through January (not shown). The higher frequency of tornadoes during LN springs is generally coincident with fewer tornado days, suggesting increased clustering toward tornado outbreaks.

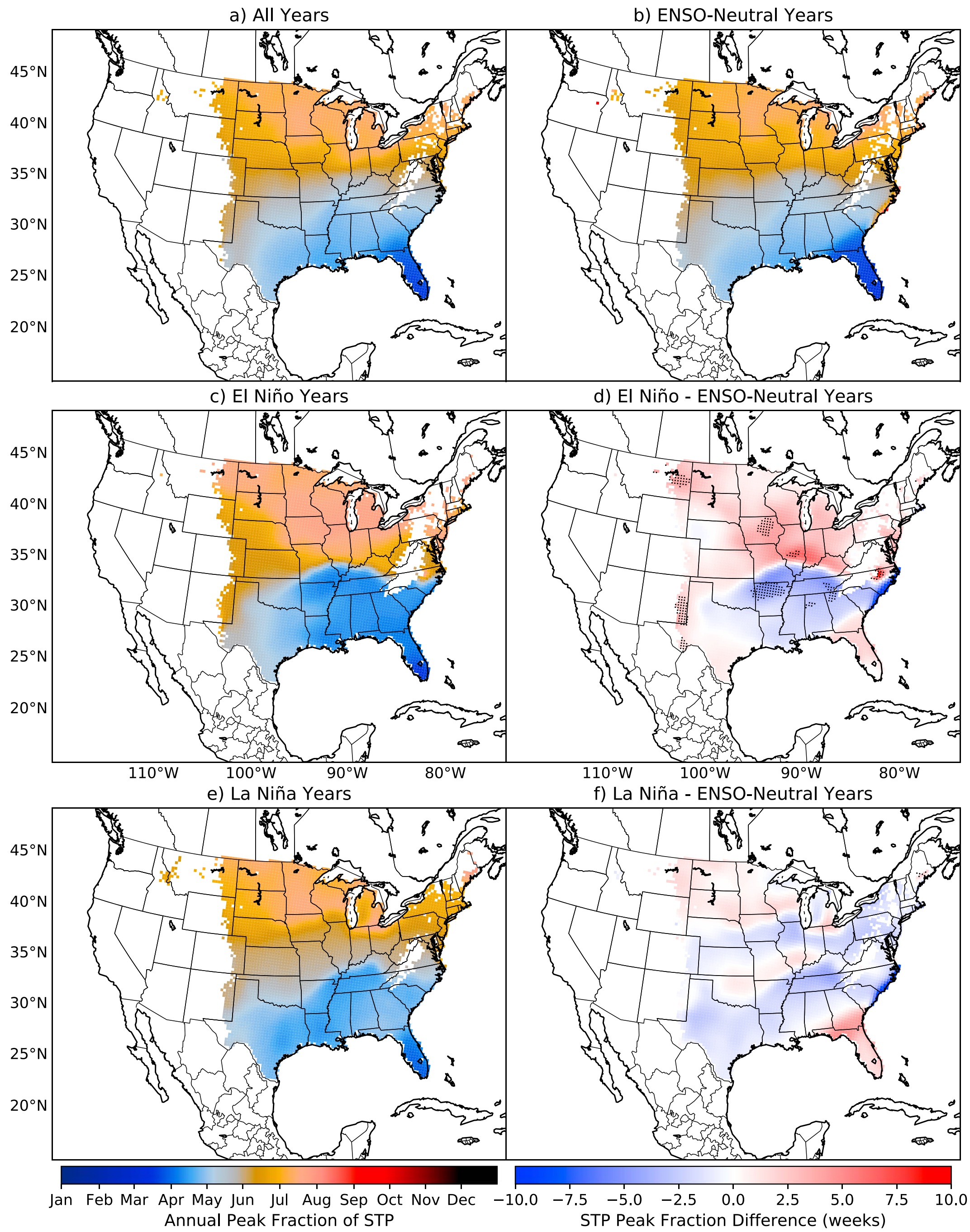

Figure 5. As in Figure 4 except peak date of mean STP fractional accumulation. STP = Significant Tornado Parameter.

3.3. Spatial Variability Induced in Peak of Annual Cycle

Considering spatial characteristics, the highest annual probability occurs over the southeast and Florida during April–May, shifting northwestward toward a June–July peak for the Northern Plains and Midwest (Figure 4). Despite smoothing, large spatial variability in annual tornado occurrence contributes to somewhat noisy composite signals. During ENSO-neutral years, this pattern is offset later over the Midwest, Northeast, and Gulf Coast toward July–August. In contrast, EN seasonal peak shifts later than neutral by 2–5 weeks, particularly over the southeast, Central Plains, and Midwest, while peaking earlier along the Gulf Coast. This is consistent with increased likelihood of cooler air over the continent during EN and southward displacement of the cyclonic track, and its shift northward with the weakening of the subtropical jet stream (Allen et al., 2015).

Increased activity accompanies EN over the High Plains and northeast during the summer months when the limitations of cold air and moisture are offset by seasonably favorable tornado conditions. During LN, the pattern reverses, with an earlier peak tornado season by 2.5 weeks, and up to a month or more in localized areas. The southeast bimodality may also mask potential results in seasonal shifts. Half-year splits reinforce that these results are realistic for the spring season (Figures S6 and S7), with weaker influence in the fall season for EN, contrasted by a robust later signal for LN years, and with peak differences of 2–5 weeks later.

Comparable analysis of STP yields a later seasonal peak consistent with parameter biases, and yet shifts in peak are broadly consistent with observations (Figure 5). Differences between STP and observations generally reflect the limitations of STP including CAPE during the cool season, and deep-layer shear terms during summer, or the presence of other variables that are not included in this analysis. Later seasons over the Midwest and Plains during EN contrast a slightly earlier peak over the southeastern states, suggesting that the lack of variation in peak cycle timing is driven by overlapping positive and negative signals. In LN, earlier seasons are relatively widespread, excluding a later signal over both Florida and the northern Plains.

4. Discussion

These results suggest that attribution of earlier shifts in seasonal peak or annual cycle shape of tornadoes to a changing climate may be premature. Variability in seasonal cycle induced by ENSO shows a marked influence of as large as 2–8 weeks, with the spring season shifted earlier over much of the eastern CONUS during LN. This contrasts winter peaks over the Gulf Coast and Florida during EN and a later spring season. These results are further supported by the analysis of STP, though STP has a number of limitations particularly over the southeast during the early season, and its calibration for stronger tornadoes.

The magnitude of the seasonal shift is at least in part a function of ENSO intensity, though a large sample size would be necessary to accurately characterize this relationship. This suggests a complicating signal for analysis of trends or annual cycle shifts. Shifts driven by ENSO appear to be equal or larger than earlier analyses (Long & Stoy, 2014; Lu et al., 2015), suggesting that the significance of any cycle shift may be indistinguishable from variability. It is also unclear that the extent to which the regional focus of earlier results (Long & Stoy, 2014) may reflect shifts driven by regionality of tornado occurrence (Childs et al., 2018; Trapp & Brooks, 2013), or that tornado season peak over this region occurs when the modulations of the jet stream associated with the weakening Pacific SST anomalies are diminishing. However, this analysis provides little explanation for the increasing variability trend noted by Brooks et al. (2014b), and thus, this hypothesis cannot be excluded.

Guidance on spatial variations and annual cycle timing also has the capacity to inform forecasts (Allen et al., 2015; Lepore et al., 2017). Limitations to the approach here include the use of canonical ENSO characteristics in neglect of other potential climate drivers. Further exploration is needed to investigate alternative indices that may capture EN variability or other contributions. Given the influence of ENSO, it is also reasonable to suspect other climate signals contribute to shifts in tornado frequency annual cycles, as outside of moderate to strong events, a large portion of variability remains unexplained.

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