Southeastern U.S. Tornado Outbreak Likelihood Using Daily Climate Indices

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ABSTRACT

This study investigates relationships between climate-scale patterns and seasonal tornado outbreaks across the southeastern United States. Time series of several daily climate indices—including Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific–North American (PNA) pattern, east/west Pacific Oscillation (EPO/WPO), and both raw and detrended Gulf of Mexico SST anomalies (SSTA/SSTAD)—are collected in advance of Southeast severe convective days and grouped using self-organizing maps (SOMs). Spatiotemporal distributions of storm reports within nodes are compared to seasonal climatology, and the evolution of the regional environment for nodes associated with outbreaks is analyzed to provide physical justification for such associations. This study confirms findings from several tornado-related climate studies in the literature, while also identifying a number of new patterns associated with Southeast tornado outbreaks. Both the AO and NAO are relevant across all seasons, especially on lead time scales of 1–2 months, while SSTA/SSTADs are relevant on smaller time scales. The physical connection between these patterns and the regional storm environment is largely related to alterations of upper-level circulation and jet stream patterns, which in turn influence deep- and low-level shear, inland transport of moisture and instability, and other regional characteristics pertinent to tornado outbreaks. These results suggest that climate-scale variability can modulate and potentially be used to predict regional storm environments and their likelihood to produce tornado outbreaks across the Southeast.

1. Introduction

A multitude of thermodynamic and kinematic factors spanning multiple spatiotemporal scales influences the formation of tornadoes, such that forecasting them remains challenging. Despite this complexity, numerous studies over the preceding decades have identified storm environment characteristics that favor tornadoes and tornado outbreaks. These features range from the synoptic scale, including the positioning of upper- and midlevel troughs, jet streaks, air-mass boundaries, regional moisture and instability, and low-level jet variability (e.g., Uccellini and Johnson 1979; Kloth and Davies-Jones 1980; Maddox and Doswell 1982; Atkins et al. 1999; Thompson and Edwards 2000; Muñoz and Enfield 2011), down to more localized characteristics of the near-storm environment, such as convective available

potential energy (CAPE), storm relative helicity (SRH), lifting condensation level (LCL), and both deep (0–6 km) and low-level (0–1 km) shear (e.g., Davies and Johns 1993; Rasmussen and Blanchard 1998; Markowski et al. 1998; Edwards and Thompson 2000; Thompson et al. 2003; Rasmussen 2003; Thompson et al. 2007).

Though questions still remain regarding how synoptic and mesoscale processes affect regional storm environments, less is known about global-scale patterns that lead to conducive synoptic/regional patterns for tornadoes. A number of recent papers have probed the relationships between various large-scale circulation and pressure patterns and CONUS tornadoes. Perhaps the most thoroughly explored of these relationships is with El Niño–Southern Oscillation (ENSO), which has been known to alter the latitudinal position of the jet stream (Miller 1972; Ropelewski and Halpert 1986; Smith et al. 1998; Nunn and DeGaetano 2004), thus influencing synoptic weather patterns and the likelihood of widespread tornadic activity (Schaefer 1986; Johns and Doswell 1992). Earlier attempts to constrain this ENSO–CONUS tornado relationship yielded varying conclusions. Several such studies initially cast doubt on

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whether ENSO phase has any significant impact on the frequency (Schaefer and Tatom 1999; Marzban and Schaefer 2001) or strength (Agee and Zurn-Birkhimer 1998; Schaefer and Tatom 1999) of tornadic activity. Knowles and Pielke (2005) noted increases in the prevalence of strong tornadoes and “large number outbreaks” corresponding to La Niña conditions (i.e., the cool phase of ENSO). Cook and Schaefer (2008) asserted that winters with neutral ENSO conditions in tropical Pacific SSTs were associated with larger and more frequent tornado outbreaks, particularly in contrast with El Niño (warm phase) conditions. These and other related studies (e.g., Bove 1998; Sankovich et al. 2004) were somewhat limited, however. Limitations include large variability and the presence of nonmeteorological biases within the tornado report database and limited sample size—both in relation to tornadoes themselves, and methodological characterization of tornado/outbreak days—potentially limiting the robustness of these results.

More recent papers have sufficiently addressed these limitations and provided more agreement on this subject. Allen et al. (2015) identified robust increases in tornado and hail reports across portions of the central plains and Southeast in association with La Niña conditions, and noted a latitudinal shift in these reports in response to mean seasonal positioning of the jet stream, surface cyclogenesis, and its associated instability axes. Furthermore, this study demonstrated that the influence of ENSO on CONUS severe convection extends well into spring months, in contrast to much of the earlier literature, which suggested that any potential ENSO impacts would be isolated to winter months. Cook et al. (2017) came to similar conclusions regarding the favorability of La Niña conditions for severe convection, but instead through the lens of tornado outbreaks. The most recent additions to the literature have further contextualized this relationship by considering ENSO interactions with other parts of the climate system and in terms of its intrinsic variability. Molina et al. (2018) considered the interplay between ENSO and Gulf of Mexico (GOM) SSTs—a key source of moist instability associated with increased hail and tornado counts across portions of the United States during both the warm season (Molina et al. 2016; Jung and Kirtman 2016) and cool season (Thompson et al. 1994; Edwards and Weiss 1996). In particular, this study found that both the frequency and location of significant tornadoes (EF2+ on the enhanced Fujita scale) vary by ENSO phase and strength, and warm GOM SSTs can enhance tornado probabilities even in ENSO-neutral phases. Molina and Allen (2019) further solidified this GOM influence by performing trajectory analysis of parcels participating in tornadic storms and finding that the GOM accounts for over half of attendant moisture contributions in both spring and winter, though

the exact origin and length of these trajectories exhibit some seasonal dependence. Last, Allen et al. (2018) found that variations in ENSO intensity influence the seasonal peak and temporal onset on CONUS tornadoes.

Other studies have turned to different global patterns to explain variability in CONUS tornadic activity. Lee et al. (2013) found that warm tropical Pacific SSTs that develop during the transition between dominant ENSO phases (trans-Niño) are more conducive to spring tornado outbreaks, though the authors themselves note the weak statistical strength of this relationship. Both Thompson and Roundy (2013) and Barrett and Gensini (2013) suggested that certain phases of the Madden–Julian oscillation (MJO) modulate large-scale circulations in ways that favor or impede tornado genesis during the spring, though the phases they deem favorable vary depending on the month chosen for analysis. Tippet (2018) agreed that tornado likelihood seems to vary by MJO phase, but also noted that the exact connection is sensitive to how one defines their MJO and tornado day metrics. Muñoz and Enfield (2011) related the negative Pacific–North American (PNA) phase to a strengthening of the intra-Americas low-level jet, which subsequently enhances moisture flux into the Mississippi and Ohio River basins. Elsner et al. (2016) tangentially noted a decrease in tornadic activity across the Southeast during the positive North Atlantic Oscillation (NAO) phase. Last, some recent studies (Trapp and Hoogewind 2018; Childs et al. 2018) have suggested that Arctic conditions may influence the frequency of CONUS tornadoes via modifications of North American jet stream patterns, albeit in opposite seasons—July for the former study, winter for the latter.

Though these studies have provided valuable insights regarding global-scale influence on severe weather variability, the methodology adopted often limits the applicability of their results. While several of the papers mentioned above have begun to investigate cool-season tornadoes, the focus of this literature remains skewed toward warm-season storm environments and their associated tornadoes. Though the warm season coincides with a peak in tornadic activity across much of the CONUS, a secondary peak in the winter months has been documented within the southeastern United States (Fike 1993; Guyer et al. 2006). Many of these cool-season storms form in environments that deviate substantially from the prototypical high-shear, high-CAPE storm environment (Guyer and Dean 2010; Sherburn and Parker 2014; Sherburn et al. 2016). These high-shear, low-CAPE (HSLC) storms are inherently more difficult to predict (Dean and Schneider 2008, 2012; Anderson-Frey et al. 2019). Hence, studies addressing Southeast U.S. cool-season tornadoes are valuable for increasing our physical understanding of these atypical storms. Furthermore, several teleconnection patterns

and their subsequent environmental responses exhibit substantial seasonal and intraseasonal variability (e.g., Barnston and Livezey 1987; Thompson and Wallace 2000; and more recently, Gensini and Marinaro 2016; Allen et al. 2018; Molina et al. 2018). Thus, studies focused solely on warm-season months—or interpreting cool-season results through the lens of warm-season teleconnections—may fail to capture physically relevant patterns inherent to the cool season. The same can be said in terms of geographical location, in that a teleconnection phase relevant to Great Plains tornadoes may not be important for Southeast tornadoes, and vice versa, as evidenced by geographical variability in the findings of several of the studies discussed thus far. This study will attempt to address these concerns by considering teleconnections and their possible association with Southeast tornadoes across multiple seasons.

Second, several of the aforementioned studies conflate weak and significant tornadoes when analyzing storm environment in order to alleviate issues stemming from limited sample size, but proximity sounding studies have shown that the near-storm environments that spawn weak tornadoes (EF0 and EF1) bear greater semblance to nontornadic storm environments (Thompson et al. 2003). Therefore, our analyses will focus on the storm characteristics as they relate to outbreaks of significant tornadoes (EF2 and higher) as defined by the Storm Prediction Center (SPC). With these factors taken into consideration, the following research questions will be addressed:

- 1) On what time scale(s) and during which seasons do global teleconnection patterns most distinctly correspond with tornado outbreaks in the southeastern United States?
- 2) How are the storms coincident with these patterns temporally and spatially distributed, and do these distributions differ from climatological averages?
- 3) How do regional atmospheric conditions evolve during these outbreak patterns, and how are they physically linked with the teleconnections themselves?

2. Data and methods

a. Teleconnection data and indices

In light of previous research, a number of daily teleconnection indices were chosen to represent variations of large-scale environmental features (e.g., the polar front jet, Pacific SSTs). Daily indices for the Arctic Oscillation (AO), NAO, PNA, eastern Pacific Oscillation (EPO), and western Pacific Oscillation (WPO) were obtained from the Climate Prediction Center (CPC 2012; data available at <ftp://ftp.cpc.ncep.noaa.gov/cwlinks/>) and Earth System Research Laboratory (ESRL 2019; data available at

FIG. 1. (a) Prescribed Southeast domain for analysis and (b) barplot showing percentage and count of nontornadic (NT), weakly tornadic (WT), significantly tornadic (ST), and outbreak days for the entire 1982–2017 analysis period, and broken down by season.

<https://www.esrl.noaa.gov/psd/forecasts/reforecast2/teleconn/>). Daily GOM SST anomalies are taken from the NOAA OISSTv2 high-resolution analysis (Reynolds et al. 2007) and averaged over the full GOM domain established by Molina et al. (2016). These SST anomalies were then detrended using least squares regression, since clustering techniques tend to group together recent SST anomalies due to the warming trend in the dataset (Molina et al. 2016). Both the raw and detrended SST anomalies (herein referred to as SSTA and SSTAD, respectively) are analyzed for completeness. Since this SST record only extends back to September 1981, all of the chosen teleconnection patterns are only considered from 1982 to 2017 for consistency.

b. Storm report data

To categorize severe convective activity, storm report data were obtained from the SPC Severe Weather GIS (SVRGIS) database (Schaefer and Edwards 1999) comprising tornado, hail, and thunderstorm wind reports from within the prescribed southeastern U.S. domain (Fig. 1a) for the years 1982–2017. The reports were filtered following the methodology of Edwards (2010) to remove those reports potentially influenced by tropical cyclones, for which their associated near-storm environment is largely controlled by the tropical cyclone itself rather than large-scale atmospheric conditions.

Several limitations and biases pervade the observational records of storm events, including the increase in reports due to improved technology, new reporting policies, and increased population (e.g., Verbout et al. 2006; Doswell et al. 2009; Brooks et al. 2014). To mitigate these problems, a similar approach to previous teleconnection studies was adopted in which reports are consolidated into storm days. For the purposes of this study, any day (1200–1200 UTC) with 5+ wind or hail reports or at least 1+ tornado report within the study domain is categorized as a severe convective (SC) day. Other SC day thresholds were tested, but the chosen definition proved most successful in removing “false positive” days (i.e., SC days flagged due to a few isolated wind and/or hail reports) while still retaining days where large, spatially and temporally coherent groupings of severe reports occurred. In addition to this SC day definition, days with no tornadoes are considered nontornadic (NT), days with tornadoes of only F/EF0 or F/EF1 are considered weakly tornadic (WT), and days with 1–5 tornadoes of F/EF2 and above are considered significantly tornadic (ST), and days with 6 or more tornadoes of F/EF2 and above were considered outbreak days [OB; akin to the violent tornado days (VTDs) in Thompson and Roundy 2013]. Given these categorizations, with the assumption that temporal trends in reporting biases are similar for all hazard types, the biases and trends discussed above should not significantly affect our conclusions.

c. SOM clustering algorithm

Daily teleconnection indices were gathered at varying lead times of 3 days, 1 week, 2 weeks, 1 month, and 2 months prior to each SC day—chosen somewhat arbitrarily, but with the intent of covering the spectrum of potentially relevant temporal scales of teleconnection influence. These time series were then clustered using self-organizing maps (SOMs), via the SOM Matlab Toolbox (Vesanto et al. 2000). This statistical technique (Kohonen 1995) is essentially a nonlinear principal component analysis, and has been used in recent studies (e.g., Nowotarski and Jensen 2013; Anderson-Frey et al. 2017; Nowotarski and Jones 2018) to objectively classify high-dimensional meteorological data. This technique clusters input data into characteristic nodes, using a grouping function that preserves the topology of the data. The data (in this case, SC days) grouped into each node can consequently be used to identify prominent modes of teleconnection variability and examine how they lead to different storm characteristics, as opposed to averaging or correlation techniques that might obscure multiple patterns leading to tornadoes or outbreaks.

A 3×3 SOM was created for all seven teleconnection indices (AO, NAO, PNA, EPO, WPO, SSTA, SSTAD) at

each of the five tested lead times across four seasonal periods following the meteorological season convention—March–May (MAM), June–August (JJA), September–November (SON), and December–February (DJF)—for a total of 140 different SOM configurations. Five additional SOM dimensions were also tested in order to assess the sensitivity of the results to the SOM geometry. Though these additional SOMs will not be shown explicitly, their results are discussed later to gauge the robustness of the identified patterns. One sample SOM output (in this case, AO at a lead time of 60 days, during MAM) is shown for reference in Fig. S1 in the online supplemental material. After the SOMs were created, the percentages of NT, WT, ST, and OB days matching each node were computed. The statistical significance of each of these percentages relative to seasonal averages (from 1982 to 2017) is tested, taking into account both the percentage of matches and the size of the SOM node (i.e., the number of days grouped into a node). The z statistic is calculated following Barrett and Gensini (2013):

$$z = \frac{p_{\text{node}} - p_{\text{climo}}}{\sqrt{\frac{p_{\text{node}}(1 - p_{\text{node}})}{n_{\text{node}}}}} \quad (1)$$

where p_{node} is the storm type percentage within a given node, p_{climo} is the climatological percentage for that storm type, and n_{node} is the number of days grouped into the analyzed node. Student's t tests are performed using this z score with 95% confidence threshold to determine whether the nodal percentages significantly exceed climatology. This alone, however, is not sufficient to determine whether a nodal pattern is a unique predictor for a given storm type. Even if a given storm type percentage is statistically significant, if the node contains a small number of those storm events compared to seasonal totals, it has limited value as a predictor. Thus, a second threshold is applied to isolate only the nodes that account for an above-average ($>100\%/9$ nodes $\approx 11.11\%$) fraction of a given type of storm event. Null patterns, defined as patterns whose storm type percentages are significantly lower than climatology and contain an above-average fraction of their null event type(s), were also considered in order to assess pattern uniqueness. For NT and OB days, null events are defined as all other event types, whereas the null for WT is NT and the null of ST is both NT and WT. Subsequent analyses will focus primarily on the nodes and null nodes that pass both of the outlined criteria.

Nodal kernel density estimations (KDEs) of diurnal and seasonal storm report time and location are created for each seasonal period, as well as each of the selected nodes. This methodology mirrors recent literature (i.e., Anderson-Frey et al. 2016, 2019) that has opted for

TABLE 1. Optimized filtering bandwidths for x and y components of temporal (time of day and time of year, respectively) and spatial (longitude and latitude, respectively) KDEs.

	Temporal (x)	Temporal (y)	Spatial (x)	Spatial (y)
MAM	1.063	3.367	0.751	0.252
SON	1.698	3.882	0.903	0.364
DJF	1.884	5.181	0.800	0.341

KDEs over traditional two-dimensional binning or histogram approaches, as they provide smoother transitions between densities and avoid potential sensitivities to bin design. Each data point is replaced by a Gaussian kernel, and an optimization method is applied to seasonal climatology to determine the appropriate bandwidths (shown in Table 1) for each season, and these are subsequently applied to their associated nodes. These climatological and nodal distributions are then overlaid in order to diagnose potential spatiotemporal shifts associated with each node. Composite anomalies of regional conditions during several patterns are developed using data from National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR; Mesinger et al. 2006). The variables chosen for analysis match those selected in related literature, including 250-, 500-, and 850-mb winds (1 mb = 1 hPa); 500-mb geopotential heights; 10-m winds; deep-layer shear (10 m–500 mb); low-level shear (10 m–850 mb); 2-m temperature and dewpoint, and surface pressure; as well as CAPE, SRH, and LCL. These anomalies are computed relative to SC day seasonal climatology for each analyzed time step (i.e., 1200 UTC anomaly from 1200 UTC climatology), allowing us to identify synoptic patterns specifically related to outbreak days, while also limiting the effect of diurnal variability. Additionally, we will diagnose HSLC conditions by comparing regional CAPE and shear values to the HSLC metrics presented in Sherburn and Parker (2014), with surface-based CAPE (SBCAPE) values $\leq 500 \text{ J kg}^{-1}$ and deep-layer shear (used as proxy for 0–6-km bulk shear) values $> 18 \text{ m s}^{-1}$ corresponding to HSLC conditions.

3. Results

From 1982 to 2017 in the prescribed domain, there were 4141 SC days. Figure 1b shows the type breakdown of these days for the entire period and each season, both by percentage and number. The largest number of ST and OB days take place in MAM, as expected, but both the SON and DJF percentages of ST and OB days are higher than those of MAM. This indicates that though SC days are less likely in the fall and winter, when they do occur, they are more likely to be ST or OB days. This

extension of ST and OB days into fall and winter months beyond the peak of the Midwest/Great Plains U.S. tornado season is consistent with previous tornado climatology studies (e.g., Thompson et al. 2012; Smith et al. 2012). Last, both the number and percentage of ST and OB events in JJA are distinctly lower than those of all other seasons, for which reason we will exclude JJA results from the following discussion.

a. SOM output

Figure 2 shows the MAM outbreak SOM results. Outbreak and associated null patterns are gathered across all lead times for each teleconnection, and shown in red and blue, respectively. For all presented patterns, the line thickness corresponds to the extent to which the node's OB percentage exceeds its seasonal average (referred to as OB%), and opacity corresponds to the percentage of OB days grouped into that node (referred to as total %). The average teleconnection patterns preceding all SC days in a given season are shown for reference (in dotted purple), with ± 1 standard deviation shaded in gray. These MAM percentages are provided in Table 2 for reference. Herein, patterns will be identified by their teleconnection and lead time (i.e., AO60).

During MAM months, eight significant OB patterns (red lines in Fig. 2) were identified across six teleconnections. For the AO (Fig. 2a), there is a 60-day pattern of sustained large, positive indices. For the NAO (Fig. 2b), there are two patterns—one at a lead time of 30 days showing a transition from weak positive to sustained negative values. The second NAO pattern is consistent with this, showing sustained negative indices seven days out from the SC day. Both the NAO7 and NAO30 patterns differ from the identified null patterns, which show positive NAO values up through the SC day. The PNA teleconnection (Fig. 2c) shows one pattern consisting of prolonged, moderately negative indices for 60 days. The EPO (Fig. 2d) displays an oscillatory OB pattern, shifting between positive and near-zero values over a span of 14 days. However, similar patterns (albeit with lower magnitude values) were identified as null nodes, so the uniqueness of EPO14 is debatable. For the WPO (Fig. 2e), there is one OB pattern showing weakly negative values for a period of 7 days. This is contrasted by two null patterns, which contain positive values during that time frame. No OB patterns exist for SSTA (Fig. 2f), but there are several null patterns displaying prolonged negative anomalies. Last for SSTAD (Fig. 2g), there are two OB patterns—one oscillating between negative and positive values across a 60-day period, and a second showing slightly negative anomalies increasing toward zero 7 days prior to the SC day. The null nodes for SSTAD show generally decreasing trends, though the

MAM OB

FIG. 2. Outbreak node patterns (in red) and null patterns (in blue) associated with the MAM period, with line thickness corresponding to deviation from climatology and line opacity corresponding to percentage of OB days grouped into each node; the average SC day pattern is shown in dotted purple, with associated error bounds in light gray.

magnitudes of these anomalies vary. As with the EPO, the overlap between the SSTAD OB patterns and these null patterns challenge the usefulness of said OB patterns.

SON nodal output (Fig. 3) shows five OB patterns across four teleconnections, with associated OB percentages provided in Table 3. The NAO displays two OB patterns (Fig. 3b)—one lasting 60 days consisting of slightly to

moderately negative values, increasing to slightly positive values up through the SC day, and a second with this same pattern but spanning only 30 days. The 60-day NAO null node mirrors these OB patterns, but the others show some overlap. For the WPO (Fig. 3e), there is one OB pattern lasting 60 days, showing initially neutral values increasing gradually from roughly 60 to 20 days out,

TABLE 2. Nodal percentage of OB days and percentage of total MAM OB days for each of the identified MAM OB nodes.

MAM (OB% = 2.93%)	Percent OB (nodal; %)	Percent of total OB days (%)
AO60	8.05	17.07
NAO14	6.78	19.51
NAO30	6.02	24.39
PNA60	7.03	21.95
EPO14	6.75	26.83
WPO7	5.91	29.27
SSTA14	5.67	26.83
SSTA60	6.18	26.83

before decreasing for the remainder of the period. The WPO null nodes generally contrast this OB pattern except during the two weeks prior to the SC day, where there is substantial overlap. Both SSTA and SSTAD SOM outputs (Figs. 3f and 3g, respectively) contain an OB pattern consisting of strongly negative anomalies three days prior to the SC day. The null nodes for both indices contain mostly neutral to positive anomalies at varying time scales, except for one node that bears a resemblance to the OB pattern.

There are six OB nodes spanning five teleconnections during the DJF period, as shown in Fig. 4, with associated OB percentages provided in Table 4. For the AO (Fig. 4a), there exists an OB pattern at a lead time of 30 days, containing strongly positive values that steadily decline to neutral values. A second, 14-day OB pattern shows somewhat consistent results, oscillating between neutral and weak positive indices up through the SC day. The AO null nodes show indices decreasing from neutral values to strongly negative values. The NAO (Fig. 4b) displays one OB pattern of sustained positive values during the 30 days preceding the SC day. Though the null nodes show varying magnitudes, they all consistently display lower values than the OB pattern. For the PNA pattern (Fig. 4c), the single OB pattern shows positive indices decreasing to neutral values over 14 days. There is some overlap between PNA null patterns and this OB pattern, though none of the null nodes show the same shape and magnitude of said pattern. SSTA output (Fig. 4f) shows one OB pattern with mostly neutral anomalies for a period of 30 days, while SSTAD (Fig. 4g) has a 14-day OB pattern showing an increase from weakly negative to weakly positive anomalies. The null nodes for both SSTA and SSTAD mostly exhibit sustained negative anomalies on their respective time scales.

b. Temporal report distributions

Next, we examine how the storm reports associated with the significant OB nodes are temporally distributed. Figure 5 shows the climatological and nodal distributions of these

reports, as well as the OB and total percentages for each pattern. MAM climatology (light/dark gray shading in all panels of Fig. 5 with associated OB% of 2.93%) shows storm reports throughout the entire season, with the highest densities spanning April and May. The diurnal range of these report densities spans from 1800 to 0300 UTC (from 1900 to 0200 UTC at the 90th percentile). The majority of the MAM OB nodes resemble climatology, particularly at the 90th percentile, but all seven nodes exhibit some diurnal broadening at various points in the MAM period. NAO7 (Fig. 5b) shows the most prominent broadening, with a pronounced extension of reports toward 0900 UTC in late May. In terms of seasonal skew, NAO7 is the only pattern showing a discernible shift in report densities toward later in the MAM period, while AO60 (Fig. 5a) shows a shift toward earlier dates.

The SON climatology (Fig. 6; with associated OB% of 3.13%) shows report densities largely confined to mid-October and November. The diurnal range for the October grouping spans from 1800 to 0600 UTC (from 1900 to 0000 UTC at the 90th percentile), and then broadens from 1500 UTC to the following 1100 UTC (from 1800 to 0500 UTC at the 90th percentile) during November. NAO30 and NAO60 (Figs. 6a and 6b, respectively) lack the mid-October grouping and instead show some high report densities in early September and October. That said, all of the SON OB nodes display a primary grouping in the latter half of November, coincident with prominent diurnal broadening. This broadening extends across nearly the entire SC day for several of the nodes, which may suggest the prevalence of nocturnal storms that persist into the following day.

Last, the DJF climatology (Fig. 7, with associated OB % of 4.57%) has a pyramid-like structure with a small grouping of reports in late December showing a tight diurnal range, which broadens with time into late February. By late February, report densities span nearly the entire SC day, though the highest densities remain between 1800 and 0600 UTC. The DJF OB nodes exhibit the most nodal variance of the analyzed seasons. AO30, PNA14, and SSTAD14 (Figs. 7b, 7d, and 7f, respectively) all resemble climatology, though the latter two show an extension toward later hours. AO14 and SSTA30 (Figs. 7a and 7e, respectively) show some skew toward the latter half of January along with diurnal broadening (most prominently in AO14). NAO30 (Fig. 7c) shows a unique pattern, with two secondary groupings in late December and early January showing broad diurnal ranges, and a primary grouping in late February that spans the entire SC day.

c. Spatial report distributions

Next, we consider the spatial characteristics of the identified OB nodes. Figure 8 shows the MAM spatial

SON OB

FIG. 3. As in Fig. 2, but for the SON period.

distribution of both climatology and the OB nodes (with the same color scheme as Figs. 5–7). MAM climatology shows report densities stretching across most of the northern extent of the study domain, with the highest densities located across Arkansas, northern Louisiana, and Mississippi, along with a small grouping across eastern Tennessee and northern Georgia. The MAM OB nodes are essentially identical to climatology at the 70th percentile, perhaps due to increased sample size. The higher report density contours exhibit more variability, with NAO7

and WPO7 (Figs. 8b and 8f, respectively) favoring the east and west portions of the domain, respectively, but still largely resemble climatological locations.

SON spatial climatology, shown in Fig. 9 bears semblance to MAM climatology, but its 70th percentile extends southeastward toward the Louisiana Gulf Coast. WPO60 (Fig. 9c) matches this climatology all but perfectly, and NAO30 (Fig. 9a) differs only in that its 90th percentile extends into the eastern portion of the domain. The remaining three nodes (Figs. 9b, 9d, and 9e, respectively) are

TABLE 3. As in Table 2, but for SON OB nodes.

SON (OB% = 3.13%)	Percent OB (nodal; %)	Percent of total OB days (%)
NAO30	9.09	35.29
NAO60	13.21	41.18
WPO60	8.86	41.18
SSTA3	18.18	21.95
SSTAD3	11.9	29.41

not dissimilar from climatology, but all display an extension of their highest report densities toward the Louisiana coast.

Figure 10 shows the DJF spatial climatology, which is positioned farther southward of the other seasonal climatologies, with its highest densities centered on

Mississippi and extending slightly east and west into its neighboring states. All DJF OB nodes except AO30 show their 90th percentile contours extending northward relative to climatology across Arkansas, and also into western Tennessee for NAO30 and SSTA30 (Figs. 10c and 10e, respectively). In terms of east–west placement, AO14 (Fig. 10a) has the westernmost skew of the OB nodes, while AO30 (Fig. 10b) is the only node displaying report densities as far east as Georgia and down into the Florida Panhandle.

d. Discussion

In the final section of this paper, we examine the environmental conditions associated with the OB

FIG. 4. As in Fig. 2, but for the DJF period.

TABLE 4. As in Table 2, but for DJF OB nodes.

DJF (OB% = 4.57%)	Percent OB (nodal; %)	Percent of total OB days (%)
AO14	12.7	36.36
AO30	13.21	31.82
NAO30	14.58	31.82
PNA14	11.11	31.82
SSTA30	13.64	27.27
SSTAD14	11.29	31.82

teleconnection patterns identified in order to provide a general physical justification for each pattern. These analyses will focus on the most unique and robust patterns. To make this determination, we will compare the OB patterns with current literature, as well as consider the consistency of these patterns across all tested SOM dimensions.

Beginning with the MAM OB patterns, the NAO results fit within the context of [Elsner et al. \(2016\)](#) with OB patterns showing sustained negative NAO indices directly preceding the SC day, and null OB patterns showing opposite patterns. These same OB and null patterns were present, in some form, in every one of the SOM geometries tested, further solidifying their significance. The Elsner study hypothesized that a positive NAO and its associated North Atlantic subtropical high would decrease Southeast tornado likelihood, so conversely a negative NAO could increase tornado likelihood due to a weaker subtropical high and lower pressure across the Southeast. However, since this has not been shown explicitly, we will further examine the NAO30 pattern and its positive to negative NAO transition, thus bridging the gap between the Elsner study and our own. PNA60 agrees with the conclusions of [Muñoz and Enfield \(2011\)](#), and its prolonged negative PNA values—typically associated with La Niña events—also lends support to [Allen et al. \(2015\)](#) and [Cook et al. \(2017\)](#). Though addressing different teleconnection patterns, these studies relate their findings to a shift in the jet stream and cyclone track, which through various physical processes favor deep convection and increase tornado likelihood across the central and southeastern United States. Given the thoroughness of these previous analyses, we will not explicitly examine PNA60 in our study. EPO14, SSTAD7, and SSTAD60 all show substantial overlap with their associated null nodes, which could suggest that they are not uniquely associated with outbreaks. Furthermore, these patterns do not appear in the majority of the other SOM geometries. Despite analyzing different seasons, the lack of a clear SSTAD signal aligns well with [Molina et al. \(2018\)](#) in that GOM SST anomalies can provide thermodynamic support, but additional tropical–extratropical interaction might

be necessary for corresponding convection to form. WPO7 is consistent with its null cases, but several of the other tested SOM dimensions either omit or conflict with this pattern. This leaves AO60, which appears in nearly all tested SOM dimensions and therefore will be chosen for further investigation.

The selection of SON OB nodes is much less clear cut, as all of the identified patterns show varying levels of overlap with their associated null patterns. The transition to slightly positive or near-neutral shown in both NAO patterns would not seem distinctly favorable for tornadic activity in the context of both the Elsner study and our MAM results. That said, similar NAO patterns appear as predictors of both ST (Fig. S2) and OB days in every tested SOM dimension. We will further analyze NAO60 given its higher OB percentages. Patterns similar to WPO60 appear in several of the other examined SOM geometries, but these patterns show even more overlap with null cases. The strongly negative values in both SSTA3 and SSTAD3 disagree with previous literature—namely, [Edwards and Weiss \(1996\)](#) and [Thompson et al. \(1994\)](#)—and seem counterintuitive given our current understanding of Gulf of Mexico influence of CONUS severe convective activity. These cold anomalies are thought to limit the inland transport of low-level moisture and instability across the Southeast, thus inhibiting thunderstorm activity. Despite this contradiction, patterns resembling SSTA3 and SSTAD3 show up in every tested SOM configuration, so the regional conditions associated with these patterns warrant additional investigation. Though SSTA3 also contains a high OB percentage, we will further analyze SSTAD3, since this quantity has been utilized in several recent GOM SST severe studies (e.g., [Molina et al. 2016](#); [Jung and Kirtman 2016](#); [Molina et al. 2018](#)).

Of the DJF OB nodes, the most inconclusive are PNA14 and SSTA30. The former shows some overlap with its null nodes, while the latter is neither consistent with nor opposed to the existing literature, and neither pattern appears in the majority of the tested SOM geometries. Perhaps the net neutral values in SSTA30 indicate that its associated storms bear weak relation to GOM SSTs. SSTAD14, however, is consistent with [Edwards and Weiss \(1996\)](#) in that a positive trend in GOM SSTs is related to an increase in Southeast severe convection, though we are dealing with SST anomalies and outbreaks. Similar patterns show up in both SSTA and SSTAD OB plots in several of the other analyzed SOM configurations. AO14 and AO30 echo the findings of [Childs et al. \(2018\)](#) that the AO is relevant to cold-season tornadoes, though the Childs et al. study cites the positive AO phase as being supportive of tornadic activity. This phase supports warm, moist Southeast conditions due to an enhanced polar jet that confines

FIG. 5. Kernel density of storm reports associated with MAM OB nodes by time of day and time of year, with outer and inner shading/contours representing the 75th and 90th percentiles, respectively; black shading corresponds to the MAM climatology, and red contouring corresponds to nodal distributions.

continental polar air to northern latitudes. Though this signal can be seen in the DJF ST patterns (Fig. S3), the OB patterns instead show a decrease from positive values. In terms of SOM dimension, half of the tested SOM maps show the AO14 pattern, while the other half show the AO30 pattern. We will examine the AO30 node further given its initially large, positive AO values in order to provide additional comparison with the Childs study. Last, NAO30 directly contrasts the findings

of the aforementioned Elsner study, which along with agreement between NAO30 and its null patterns, leads us to further analyze this pattern.

More generally with these OB patterns, we see that AO and NAO are most consistently related to OB days across the analyzed seasons, with SSTA and SSTAD also showing up frequently. Interestingly, both of the Pacific patterns (EPO and WPO) show very limited utility in distinguishing OB days, despite ample literature relating

FIG. 6. As in Fig. 5, but for the SON period.

other Pacific-related patterns (viz., ENSO) to CONUS tornado frequency. The closest such relationship we are able to discern comes from the PNA pattern, which is indirectly correlated with El Niño phases. This is not to draw into question Pacific influences on CONUS tornadoes, though it might suggest that EPO and WPO are less useful predictors compared to ENSO. Last, in regard to temporal scales, we see that AO and NAO are more often related to Southeast OB days at longer time scales of 30 or 60 days, while the influence of SSTA/SSTAD is most pronounced on a shorter time scale of 3 days. These differences are likely explained by both the varying temporal scales of these teleconnections and the proximity of their primary driver (i.e., the Arctic and North Atlantic, as opposed to the Gulf of Mexico) to the study domain.

e. Environmental characteristics

1) MAM

Since the identified OB patterns are either unvarying or bimodal (e.g., values transitioning from positive to

negative), we examine the 0000 UTC anomalies (from 0000 UTC averages) only during relevant periods. For sustained patterns like MAM AO60, this average is computed over the entire period in question, while for bimodal patterns such as MAM NAO30 we examine the conditions during the two dominant phases to highlight potential differences. The 0000 UTC step was chosen as it is the closest available time to the mean event times shown in presented temporal density plots (cf. Figs. 5–7). All time steps were analyzed to diagnose possible diurnal variation, but this variation was found to be negligible. It bears reiterating that the presented anomalies are relative to severe convective climatology in a given season. We know a priori that severe convection exists on these days, so our intent is to key on the factors that specifically favor widespread tornado development.

Starting with the MAM OB patterns, the sustained positive values shown in AO60 are consistent with an intensified polar vortex and zonal polar front jet across northern latitudes. This pattern inhibits the intrusion of continental polar air into southern latitudes, allowing for

FIG. 7. As in Fig. 5, but for the DJF period.

above-average geopotential heights across the southern CONUS. This is evidenced by 250-mb patterns in Fig. 11a, showing negative speed anomalies and easterly mean vector anomalies across Mexico and the GOM, and positive anomalies and westerly vector anomalies across central and northern CONUS (very similar to Fig. 3b in Allen et al. 2015). Moreover, the southeastern region is located in the right entrance region of the mean 250-mb jet streak, conducive to synoptic-scale ascent and destabilization. These patterns are corroborated by 500-mb (Fig. 11b) and surface patterns (Fig. 11c) showing positive geopotential height and surface pressure anomalies across the Southeast. This pattern extends down through the depth of the atmosphere, with mostly southerly anomaly winds and positive speed anomalies at the 850-mb and 10-m levels throughout much of the period (not shown). In addition to these spatial anomalies, it is also worth considering the temporal trends in variables pertinent to the regional storm environment. As such, Figs. 12 and 13 show domain-averaged quantities at 0000 UTC for the duration of each OB pattern, as well as SC climatological time series for

reference. Figure 12 shows 2-m temperature and dewpoint, as well as approximate LCL height, while Fig. 13 contains deep-layer shear, SBCAPE, and 0–3-km SRH during each analyzed OB pattern, along with climatological values and aforementioned HSLC criteria consistent with Sherburn and Parker (2014). Since these values are averaged across the study domain, and thus could conflate both convective and nonconvective environments, they are not meant to convey the exact environmental state in which storms are developing. Rather, these values serve to represent general trends during the analyzed periods.

These pressure and circulation patterns would support increased low-level moist instability across the Southeast during this period. Though both temperature and dewpoint values remain largely below climatology (Figs. 12a and 12b, respectively), their respective trends support gradually increasing CAPE (Fig. 13b). Furthermore, these thermodynamic trends immediately prior to the SC day favor low LCLs—a key distinguishing factor between nontornadic and tornadic supercells (e.g., Rasmussen and

FIG. 8. Spatial kernel density of storm reports associated with MAM OB nodes, with outer and inner contours representing the 75th and 90th percentiles, respectively; black contouring corresponds to the MAM climatology, and red contouring corresponds to nodal distributions.

Blanchard 1998; Thompson et al. 2003) that has been shown to impact the positioning and strengthening of near-surface circulation in supercell environments (Brown and Nowotarski 2019). This positive trend in CAPE places SC day values beyond the bounds of HSLC CAPE criteria. Concurrently, deep-layer shear values decrease in magnitude (Fig. 13a) but remain mostly above climatology (and the HSLC shear threshold), as do regional SRH values (Fig. 13c). Though the CAPE values remain close to

climatological values, the sustained increases are likely significant given that numerous studies examining HSLC environments (e.g., Sherburn and Parker 2014) have noted that HSLC events are typically associated with ample shear (as supported by Fig. 13a), and thus CAPE is the key limiting factor.

For NAO30, a shift from positive (from $t - 30$ to $t - 21$ days from SC day) to negative values (from $t - 10$ to $t - 0$ days from SC day) would indicate a transition from

FIG. 9. As in Fig. 8, but for the SON period.

above-average to below-average geopotential heights across the eastern United States (North Carolina Climate Office 2011), possibly causing a southward intrusion of Arctic air and displacement of the jet stream closer to the study domain. The latter is shown in Figs. 14a and 14b, displaying negative speed anomalies and easterly mean vector anomalies across the Southeast, transitioning to positive speed anomalies and westerly anomaly winds. The 500-mb height anomalies shown in Figs. 14c and 14d reflect this synoptic shift, with positive height anomalies and anticyclonic circulation transitioning to negative anomalies and cyclonic circulation with time, which in turn supports phasing of positive to negative surface pressure anomalies over the eastern United States (Figs. 14e,f). As with AO60, thermodynamic trends for this pattern support decreasing LCLs (Fig. 12c) and increased CAPE (Fig. 13b), as well as increased shear (Fig. 13a). Both CAPE and shear fall outside their respective HSLC criteria, suggesting a more

traditional storm environment with increased CAPE and shear.

2) SON

Regarding SON OB patterns, NAO60 displays a shift from negative (from $t - 60$ to $t - 21$ days from SC day) to weakly positive values (from $t - 20$ to $t - 0$ days from SC day), signaling a transition from below-average to near or slightly above-average geopotential heights across the eastern United States. This pattern would be consistent with a slight northward lifting of Arctic air giving way to warmer conditions in its wake, which could also act to shift the jet stream northward. This generally holds true in these analyses, with initially positive speed anomalies and westerly anomaly winds at 250 mb, giving way to neutral anomalies and weak anticyclonic circulation (Figs. S4a,b). At 500 mb (Figs. S4c,d), negative height anomalies persist over most of the CONUS 60–21 days out from the SC

FIG. 10. As in Fig. 8, but for the DJF period.

day, but become neutral thereafter. Upper-level synoptic pattern changes drastically during this pattern, with the predominantly westerly flow across the southern United States turning southwesterly with time. These upper-level patterns and associated anomalies are magnified several times over for SSTA30 (Figs. 15a,b), with a jet streak extending from Texas up through the Northeast, along with an intense 500-mb Colorado low. Interestingly, this elongated jet streak is nearly identical to the jet-level pattern shown in Fig. 6a from Sherburn and Parker (2014) as being associated with Southeast HSLC events. The 500-mb pattern offered in their Fig. 6b also is similar to our Fig. 15b, though the axis of their 500-mb trough is shifted farther eastward.

Given these similarities, we would expect the SON patterns to exhibit HSLC conditions leading up to their SC days. Starting with NAO60, Fig. 13d shows generally increasing shear values, though these values remain well

below the HSLC shear threshold through the SC day. Thermodynamically, NAO60 shows steadily decreasing temperatures (Fig. 12d), dewpoints (Fig. 12e) and CAPE values (Fig. 13e) for most of its duration, though these variables increase slightly immediately prior to the SC day. These CAPE values are both below SC climatology and within the bounds of the HSLC CAPE criteria, with average SC day values of 500 J kg^{-1} . For SSTA30, domain-averaged shear values are noticeably higher, exceeding the HSLC shear threshold by the SC day (Fig. 13d). SSTA30 resembles NAO60 in that its thermodynamic variables increase immediately before the SC day, but the magnitudes of these variables are uniformly lower, with only 300 J kg^{-1} of SC day CAPE. From these observations, we see that HSLC conditions appear to be invigorated in our SSTA30 synoptic regime. The differences between NAO60 and SSTA30 in terms of deep-layer shear are relatively straightforward;

MAM AO60

FIG. 11. Composite anomalies associated with the MAM AO60 pattern consisting of (a) 250-mb speed anomalies (m s^{-1}) and wind anomaly vectors (with node average speed contours 40, 45, and 50 m s^{-1} shown in black), (b) 500-mb geopotential height anomalies (m) and wind anomaly vectors (with node average height contours of 5400, 5500, 5600, 5700, and 5800 m), (c) surface pressure anomalies (mb), and (d) 2-m temperature (K).

the upper-level flow of the latter (Figs. 14a,b) is noticeably stronger is association with prominent troughing over the central United States. The more perplexing question, however, remains—what is limiting CAPE in this synoptic regime?

Examining the low-level characteristics of both NAO60 (Figs. S4f,h) and SSTAD3 (Figs. 15c,d), we see that both exhibit mostly easterly anomaly winds and positive 10-m wind anomalies across the GOM in association with high pressure across the Carolinas. This forcing contributes to pronounced negative anomalies in both SSTA3 and SSTAD3 via mechanical mixing and overturning (such as in Fig. S5). As to whether this influences Southeast CAPE values, near-surface air transported over these waters would be drier (and possibly cooler) relative to a typical northern Gulf parcel, especially given that easterly parcel trajectories are likely originating from the nearby surface ridge. CAPE deficits increase in magnitude for the patterns exhibiting stronger surface ridging, supporting this argument.

Given the slower response time of overturning and subsequent inland transport, this mechanism would be most relevant under sustained flow regimes in which air parcels continuously originate from areas of enhanced mechanical mixing. However, a closer examination of low-level streamlines in both OB nodes suggest a

transition to southerly surface transport immediately preceding the SC day, likely in response to approaching troughs and associated frontal boundaries. This shift away from areas of cold, overturned waters would support an influx of heat and moisture into the Southeast, as evidenced by increasing temperatures and dewpoints, and rapidly decreasing LCLs (Figs. 12d–f). All else held constant, these low-level thermodynamic adjustments would result in large increases in surface-based CAPE, but the observed CAPE increases (Fig. 13e) still leave values well below SC climatology. Thus, there must be some secondary limiting factor aloft partially counteracting these surface influences. It is possible that the aforementioned surface ridging is associated with subsidence and mid-upper-level warming, which would act to reduce regional CAPE values. Closer examination of the mid-upper troposphere (850–500 mb) temperature profiles (Fig. S6) immediately prior the SC day reveals a warming trend throughout the depth of this layer, consistent with subsidence. To this end, the magnitude of this upper-level heating increases along with the strength of the coincident anticyclonic circulation. In spite of these upper-level trends, enhanced low-level shear (not shown) and SRH (Fig. 13f) in response to invigorated low-level flow, combined with lower LCLs related to shifting low-level

FIG. 12. Time series of domain average 2-m temperature (K), 2-m dewpoint (K), and approximate LCL (km) during the analyzed OB patterns as well as SC climatology (in solid black).

trajectories (Fig. 12f) provide sufficient impetus for widespread severe convection, even with relatively reduced instability.

3) DJF

Last, with DJF patterns, AO30 shows a steady decline from strongly positive to near-zero values, which should correspond to a gradual weakening of an initially strong, zonal polar front jet, allowing for a slight southward intrusion of Arctic air and a southward jet stream displacement. This progression is shown in the associated 250- and 500-mb fields with a jet streak expanding southwestward (albeit with variable speed anomalies), placing the domain broadly in its left entrance region (Figs. S7a,b), along with a transition from positive to neutral 500-mb geopotential height

anomalies (Figs. S7c,d). These patterns support positive surface pressure anomalies that decrease in magnitude with time (Figs. S7e,f). CAPE and shear trends are generally consistent with SC climatology (Figs. 13g,h), but climatology itself corresponds to HSLC conditions. Finally, NAO30 displays sustained positive NAO values, which correspond with prolonged above-average geopotential heights over the eastern United States, as demonstrated by anomalous anticyclonic circulation aloft and associated positive surface pressure anomalies (Fig. S8). These patterns suppress shear across the Southeast, with values plummeting below average by the SC day (Fig. 13g), but result in above-average CAPE values (Fig. 13h). The net effect of the synoptic regimes for both DJF OB patterns are decreased LCLs (Fig. 12i) and increased SRH

FIG. 13. Time series of domain average deep-layer (10 m–500 mb) shear (m s^{-1}), SBCAPE (J kg^{-1}), and 0–3-km SRH ($\text{m}^2 \text{s}^{-2}$) during the analyzed OB patterns as well as SC climatology (in solid black), with the HSLC criteria from Sherburn and Parker (2014) shown by dotted black lines.

(Fig. 13i), both of which favor the development of tornadoes.

4. Summary and conclusions

This study relates numerous climate indices to Southeast tornado outbreak likelihood across multiple seasons using a self-organizing map technique. Several of the identified outbreak patterns explicitly agree with or fit into the context of previous literature, particularly in spring months (MAM), while other patterns either differ from the literature or are altogether new. The physical implications of these patterns for tornado outbreak likelihood vary slightly by teleconnection but are largely consistent with one another and with

previous studies. Though the direct influence of these patterns is often dynamic—particularly the positioning and strength of the jet stream and modulation of cyclone tracks—their ramifications are twofold. Dynamically, these modulations provide synoptic ascent and a source of shear, while alteration of lower-tropospheric flow patterns causes an influx of Gulf moist instability. For MAM teleconnections, the net result of these factors is a high-shear, high-CAPE Southeast setup reminiscent of a traditional Great Plains outbreak environment. For DJF teleconnections, similar increases in CAPE and shear exist, but HSLC conditions emerge as a result of the season. SON teleconnections are unique, however, in that their associated synoptic patterns actually

MAM NAO30

FIG. 14. Composite anomalies associated with MAM NAO30 pattern consisting of (a),(b) 250-mb speed anomalies (m s^{-1}) and wind anomaly vectors (with node average speed contours of 40 and 45 m s^{-1} shown in black), (c),(d) 500-mb geopotential height anomalies (m) and wind anomaly vectors (with node average height contours of 5400, 5500, 5600, 5700, and 5800 m), and (e),(f) surface pressure anomalies (mb).

contribute to HSLC conditions through a combination of processes both aloft and at the surface.

As with any study relating atmospheric characteristics across multiple spatiotemporal scales, there are some factors that must be considered. First, there are inherent limitations when focusing exclusively on tornado outbreaks, particularly smaller sample size and sensitivity of spatiotemporal distributions to individual reports. In our study, the former concern is largely addressed by our statistical significance testing. The latter might be partially offset by the fact that the frequency of severe reports on outbreak days exceeds that of nonoutbreak SC days, but this

could also mean that outbreak reports dominate such distributions.

One other matter is the temporal consistency of the identified OB patterns. In other words, if we see an OB pattern at a longer time scale, should not this same pattern also show up on shorter time scales? Sometimes this is accurate, as with SON NAO30 and NAO60 (cf. Fig. 3b), but this is not always the case. This could be a matter of statistical significance, as SOMs with smaller temporal scales could be overclassifying teleconnection patterns—such as trying to differentiate between varying magnitudes of positive AO values in MAM, when the most important characteristic is simply the

FIG. 15. Composite anomalies associated with SON SSTAD3 pattern consisting of (a) 250-mb speed anomalies (m s^{-1}) and wind anomaly vectors (with node average speed contours 40, 45, and 50 m s^{-1} shown in black), (b) 500-mb geopotential height anomalies (m) and wind anomaly vectors (with node average height contours of 5400, 5500, 5600, 5700, and 5800 m), (c) 10-m speed anomalies (m s^{-1}) and wind anomaly vectors, and (d) surface pressure anomalies (mb).

existence of sustained positive values. This excessive sorting could compromise the statistical significance of these shorter patterns, even if their underlying physical meaning is valuable. Alternatively, the existence of longer OB patterns that do not manifest themselves on smaller time scales could underscore the importance of prolonged synoptic patterns for outbreak potential. For instance, extended periods of enhanced heat or moisture flux into a region (as with MAM AO60) or increased shear in response to jet placement (as with MAM NAO30) could prime the region, thus increasing the likelihood of widespread severe convective activity (and by extension, tornado outbreaks). This notion of synoptic priming has been offered up in different contexts, including fire weather (Papadopoulos et al. 2014), MJO convection (Katsumata et al. 2009) and convection initiation in the southern Great Plains (Frye and Mote 2010), so it is possible that a similar concept could apply to Southeast severe convection as well. Also temporally, the methodology employed allows for temporal covariance, in which consecutive SC days occurring within the same synoptic regime cause teleconnection patterns to count multiple times within the SOM analyses. Though not entirely unphysical, this could lend undue statistical significance to certain synoptic regimes, particularly for OB cases in which sample size is already limited.

Another key factor is the potential influence of seasonal and intraseasonal variability. Given the analyzed lead times, particularly 30 and 60 days, several of the presented OB patterns span much of their respective seasons or extend into a separate season altogether. As such, there are associated trends in thermodynamic variables (e.g., temperature, dewpoint, CAPE, LCL) and some dynamic variables (e.g., deep-layer shear, given jet stream seasonality) that could contribute to the regional conditions presented. This is especially true for the time series shown in Figs. 12 and 13 where, for instance, the gradual decrease in CAPE coinciding with SON NAO60 (blue line in Fig. 13e) may be partially related to a progression toward winter months. Keeping with this example, however, the magnitude of these CAPE values relative to SC climatology for that particular season does tell us something unique about the conditions associated with that particular teleconnection pattern. Taking into account both the trend and magnitude of the analyzed variables is crucial to leverage these seasonal influences.

Further research is necessary to fully characterize the identified patterns and their contribution to Southeast tornado outbreak frequency. This includes investigating the environmental characteristics of the patterns not examined in the final section of discussion—specifically,

those consistent with previous literature for comparison with their findings, as well as patterns deemed nonunique due to overlap with null nodes in order to understand why their connection to outbreak potential is less distinct. Different classification or machine learning methodologies might also provide additional insight, as would extending the presented methodology to different regions, time periods, and climate indices. Furthermore, our SOM methodology could be modified to identify patterns of multidimensional data (as in Anderson-Frey et al. 2017) conducive to tornado outbreaks, with the teleconnection patterns corresponding to these patterns being determined subsequently. Other novel techniques, such as the spectral methods implemented in Childs et al. (2018), may prove skillful in separating out components of climate-scale, seasonal, and intraseasonal variability that superimpose themselves on the examined synoptic fields and potentially complicate these sorts of analyses.

In any case, the results presented here add to a growing body of literature on teleconnections between global-scale patterns and regional severe weather likelihood. In addition to the intrinsic value of better understanding the links between the largest and smallest scales, this work may also prove useful in forecasting applications, such that awareness of regional responses to global-scale patterns by local forecasters may improve the identification and forecast lead time of potential severe weather outbreaks.

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