Klepatzki, J. P. and S. M. Milrad, 2020: Multiscale environmental analysis of cool-season Florida tornado and null events. *Electronic J. Severe Storms Meteor.*, **15** (1), 1–34.

Electronic Journal of
SEVERE STORMS METEOROLOGY

Multiscale Environmental Analysis of Cool-Season Florida Tornado and Null Events

JONATHON P. KLEPATZKI AND SHAWN M. MILRAD
Embry-Riddle Aeronautical University, Daytona Beach, Florida

(Submitted 1 August 2019; in final form 24 February 2020)

ABSTRACT

This study presents a multiscale environmental analysis of 33 Florida tornado (1979–2016) and 29 null events (2003–2019). A tornado event was defined as ≥4 tornadoes within a 24-h period during December–May, which was chosen to eliminate events associated with tropical cyclones. Null events were defined as periods when the NOAA Storm Prediction Center had tornado outlook probabilities ≥5% over any part of Florida, but <4 tornadoes occurred in 24 h. Central Florida experienced the largest number of tornado events, while most null events occurred in the Florida Panhandle. Tornado events occurred slightly more frequently during El Niño and negative Arctic Oscillation, in contrast to cool-season events elsewhere in the United States. Using the North American Regional Reanalysis, a composite synoptic analysis showed that compared to null events, tornado events were associated with a coupled divergent jet streak region, a more amplified anomalous mid-tropospheric trough, a surface cyclone located farther south (Gulf of Mexico vs. Tennessee Valley), and larger equivalent potential temperature anomalies. While both event sets featured high-shear, low-CAPE environments that are typical of southeast United States tornado events, tornado events exhibited larger storm-relative helicity and 0–6-km vertical wind shear. Overall, results suggest that synoptic pattern recognition techniques and mesoscale parameter spaces can help forecasters in identifying potential Florida tornado events.

1. Introduction

a. Motivation

Florida is a densely populated state and has fast-growing urban areas such as Miami/Fort Lauderdale, Tampa Bay, and Orlando, meaning that tornado events can affect millions of people. Another important factor in Florida tornado events is time of occurrence; a large proportion of cool-season events in the southeast United States occur overnight or in the early morning when most people are sleeping (e.g., Hagemeyer and Schmocker 1991; Hagemeyer 1997; Anderson-Frey et al. 2019; Bunker et al. 2019). Furthermore, Childs et al. (2018) performed a climatology of cool-season tornado events and found a peak in Tennessee, with an increasing trend throughout the Southeast, including Florida.

Corresponding author address: Shawn M. Milrad, 1 Aerospace Blvd, Daytona Beach, FL, 32114 E-mail: milrads@erau.edu

The objective of this study is to investigate the multiscale characteristics and mechanisms associated with Florida tornado events during the cool-season outside the Atlantic tropical cyclone (TC) season (December–May), when the strongest tornadoes typically occur in the state (e.g., Hagemeyer 1997; Childs et al. 2018).

Based on a 1991–2010 climatology (NCEI 2019), Florida typically averages about eight tornadoes per month during the TC season (June–November), but many of those are weak and/or associated with TCs (Hagemeyer 1997; Agee and Hendricks 2010; Edwards 2012). In contrast, months outside the TC season (December–May) average only five tornadoes per month (NCEI 2019), but typically feature the largest events. Florida's most infamous tornado event occurred during the late-night of 22–23 February 1998; it included a strong F3 in Kissimmee that killed 42 people and injured 260 others (Kelly et al. 1998; Wasula et al. 2007).

Another infamous event occurred during the late night and early morning of 25 December 2006; it included an F2 that damaged and destroyed buildings and aircraft at Embry-Riddle Aeronautical University in Daytona Beach (Lanicci 2016).

Diurnal effects are an important factor in tornadic environments. Kelly et al. (1978) discovered a definite diurnal trend in the distribution of tornadoes. The mean peak tornado occurrence was during the late afternoon, while minimum occurrence was prior to sunrise. However, cold-season curves were not as markedly unimodal as the others, indicating a larger temporal spread in event occurrence. Kelly et al. (1978) also noted a regional maximum of weak tornadoes in west-central Florida, a conclusion that was later echoed by Hagemeyer and Schmocker (1991) and Hagemeyer (1997).

Studies have shown that high-shear, low-CAPE (HSLC) environments can produce tornado events, especially in the southeast United States (Sherburn and Parker 2014; Cohen et al. 2015, 2017; Sherburn et al. 2016; King et al. 2017; Anderson-Frey et al. 2019). Furthermore, Southeast tornado events frequently occur in the overnight and morning, posing a large threat to public safety (Sherburn and Parker 2014; Anderson-Frey et al. 2019). Studies by Kelly et al. (1978) and Hagemeyer and Schmocker (1991) also found that Florida tornadic environments were slightly more favorable in the overnight and morning than during peak daytime heating. Overall, the convective environments and event timing in the Southeast can be quite different from the Great Plains.

To study HSLC environments, McCaul and Weisman (2001) developed model simulations of supercells with a surface-parcel CAPE of 800 J kg^{-1} located primarily in the lower troposphere, and large vertical shear. Kirkpatrick et al. (2011) found similar results but stipulated that reducing surface parcel CAPE below 800 J kg^{-1} inhibited strong updrafts and rotation, ultimately leading to short-lived convection. More recently, however, Cohen et al. (2017) studied HSLC events in the Southeast and further reinforced the notion that the nonlinear intensification of a perturbation-pressure pattern, resulting from the interaction of an updraft and a strongly sheared wind profile, could result in supercell development in the presence of marginal buoyancy. In addition, Cohen et al. (2015, 2017) found that Southeast cool-season tornado events could be more difficult to predict because of frequent marginal instability, motivating improved planetary-boundary-layer model schemes.

Considering other climatological studies, Ashley et al. (2008) developed mean decadal values of nocturnal tornadoes since the late 1800's. They concluded that the percentage of nocturnal killer events as increasing, especially in the southeastern United States. The average number of killer tornadoes has not changed much, but deaths have greatly increased with increasing population in the Southeast (Ashley et al. 2008). More recently, Anderson-Frey et al. (2019) analyzed the environmental conditions and warning statistics for Southeast events, excluding Florida, while the Southeast studies of Cohen et al. (2015, 2017) did include a large part of Florida. To facilitate our analysis of Florida tornado events, we will compare and contrast our multiscale environmental analysis to these studies as well as the earlier Florida tornado climatologies of Hagemeyer and Schmocker (1991) and Hagemeyer (1997).

b. Previous Florida tornado research

Florida tornado events became a popular topic in literature in the 1990s, both before and after the February 1998 event. Hagemeyer and Schmocker (1991) examined atmospheric proximity soundings throughout the Florida Peninsula using layer-averaged variables (e.g., θ, θ_w, U and V) at 50-hPa intervals to 200 hPa. They found that strong cool-season Florida tornadoes occurred preferentially overnight and in the early morning, characterized by HSLC environments. In contrast, (warm-) wet-season mean soundings were different from classic tornado environments (Miller 1972) and represented the regional hybrid type described by Hagemeyer (1997).

Hagemeyer (1997) analyzed 1448 tornadoes in Florida (1950–1994) and divided tornado events into three types (extratropical cyclone, TC, and hybrid). He found that high-end tornado events (which he defined as ≥4 tornadoes in 4 h) represented only 3.4% of tornado days but caused ≈60% of tornado deaths and injuries. Hagemeyer (1997) also used proximity soundings to conclude that, similar to

Hagemeyer and Schmocker (1991), Florida events were characterized by HSLC environments.

In general, Great Plains supercellular tornado environments are characterized by large CAPE, strong 0–6-km vertical wind shear, and large storm-relative helicity (SRH) (e.g., Rasmussen and Blanchard 1998; Thompson et al. 2012; Anderson-Frey et al. 2016; 2017). However, previous Florida tornado research found key differences from the Great Plains in terms of favorable parameter spaces, particularly the prevalence of HSLC environments (Hagemeyer 1997). A growing area of research has focused on HSLC tornadic environments in the Southeast (e.g., Sherburn and Parker 2014; Cohen et al. 2015, 2017; Sherburn et al. 2016; Anderson-Frey et al. 2019), although no recent study has focused exclusively on Florida.

Florida's peninsular geography makes it unique, as water near both coasts remains relatively warm even during the cool season. In addition, cool-season extratropical cyclones often track through the Gulf of Mexico, associated with a strong subtropical and/or polar jet stream. As a result, strong vertical wind shear tends to be more common in Florida during the cool season. Hagemeyer and Schmocker (1991) concluded that 0–6-km vertical wind shear associated with cool-season tornado events was 20 m s^{-1} stronger than during warm-season events.

The goal of the current study is to better understand the multiscale environmental conditions associated with tornado events in Florida, by updating the Hagemeyer and Schmocker (1991) and Hagemeyer (1997) proximity sounding climatologies using modern reanalysis data. First, composite synoptic-scale flow patterns are investigated. Second, mesoscale convective parameter spaces are elucidated using reanalysis soundings. Overall, we investigate the lift, moisture, instability, 0–6-km vertical wind shear, and lower-tropospheric SRH ingredients for severe convection (Johns and Doswell 1992). The remainder of this paper is organized as follows: section 2 details the data and methods, section 3 details composite synoptic and teleconnection patterns, section 4 investigates mesoscale parameter spaces, and section 5 presents overall conclusions and future work.

2. Data and methodology

Tornado reports were retrieved from the NOAA Storm Prediction Center (SPC) archive for 1979–2016, to coincide with the availability of the NOAA National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR, Mesinger et al. 2006). Tornado events were defined as ≥4 tornadoes occurring in 24 h within Florida during December–May. This was somewhat different from Hagemeyer's (1997) definition (≥4 tornadoes in 4 h) but was done to provide us a large-enough case repository to perform composites. Overall, we found 33 events for 1979–2016, for which event duration was defined as the time from the first Florida tornado report to the last (Table A1).

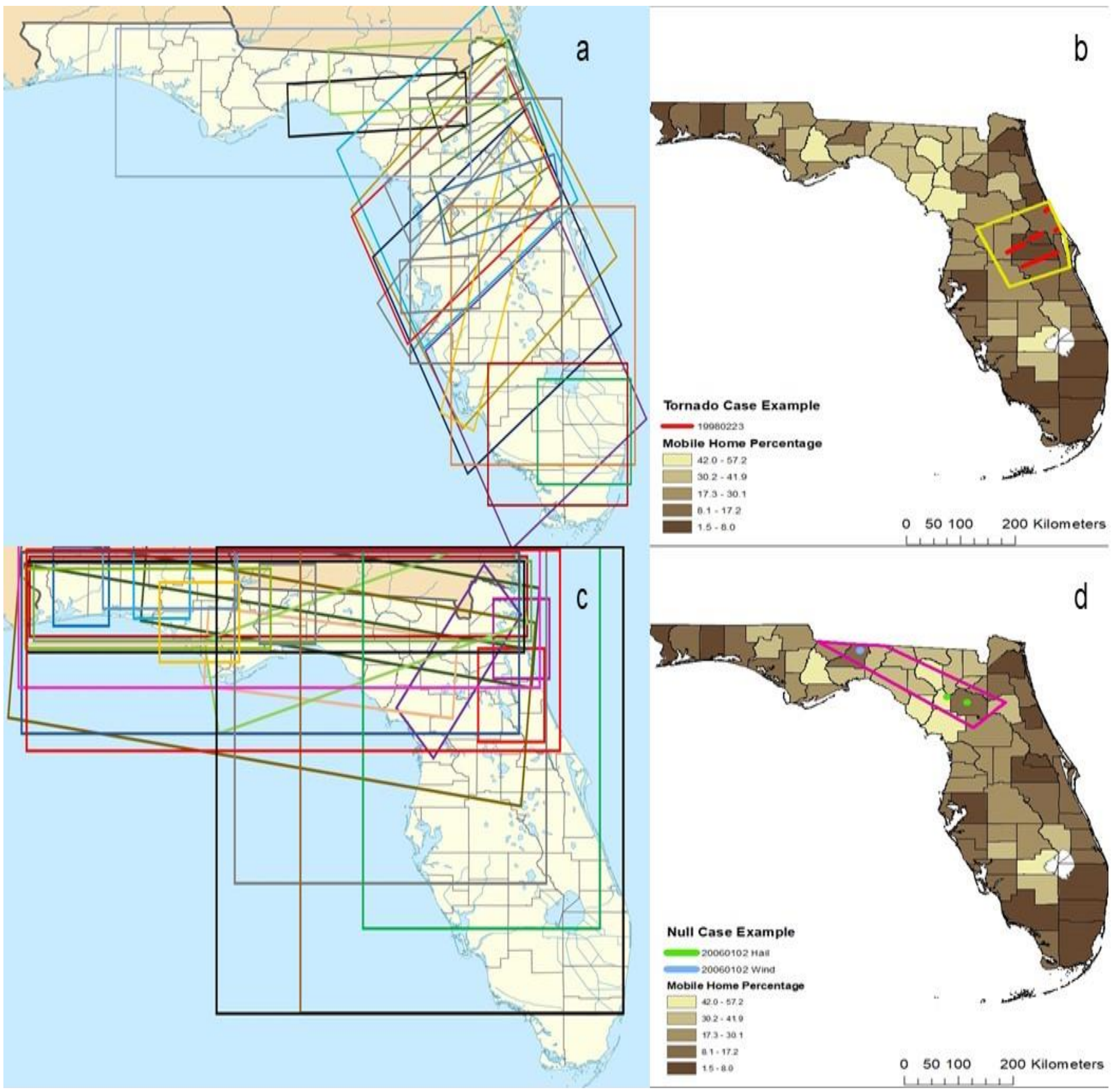
Null events were defined as December–May cases in which the 0600 UTC SPC day-1 tornado outlook featured probabilities ≥5% over any part of Florida, but <4 tornadoes in 24 h were observed. Because the online SPC convective outlook archive only dates back to 2003, our case selection was limited to 2003–2019. We found 29 null events, for which event duration was defined as the time from the first Florida hail/wind report to the last (Table A2).

Using SPC storm reports, we mapped the spatial extent of all tornado and null events and produced composite charts for each (Figs. 1a,c). Each box in Figs. 1(a,c) represents the maximum spatial extent of a tornado and null event, based on tornado and hail/wind reports, respectively. We required that the boxes had to be rectangular. Therefore, for some events that encompassed a large portion of Florida, boxes extend over adjacent waters, particularly the Gulf of Mexico. This does not indicate that waterspouts occurred, but suggests events that encompassed a larger percentage of Florida. Tornado (23 February 1998) and null (2 January 2006) event examples (Figs. 1b and 1d, respectively) illustrate how we drew the spatial-extent boxes.

For tornado events, Fig. 1a shows that events occurred throughout the entire state, except for the Keys and western Panhandle, with some clustering evident in Central Florida. Table A1 shows that most of the 33 tornado events occurred at night or during the morning, which is common in the Southeast (Anderson-Frey et al. 2019; Bunker et al. 2019). The only event that spanned multiple calendar days (UTC) was the

22–23 February 1998 event (Wasula et al. 2007), which produced 10 tornadoes, tied for the third-most among our events (Table A1). The numerically largest tornado event in our study was the 23 April 1997 event (22 tornadoes), followed by 2 February 1983 (14 tornadoes).

Figure 1c shows that the 29 null events occurred throughout Florida north of the Keys and southern Everglades, but with a clustering farther north than the tornado events (Fig. 1a). In fact, all but four null events encompassed at least part of the Florida Panhandle, while the majority of the 33 tornado events did not. One noteworthy issue with the geographic distribution of tornado events is that Florida Panhandle counties have a larger percentage of mobile homes (Figs. 1b,d), a casualty risk factor that has been widely noted in Southeast tornado studies (e.g., Anderson-Frey et al. 2019). Because a larger percentage of our null events occurred in the Panhandle, this may indicate that the most susceptible populations are



<u>Figure 1</u>: Location and spatial extent of Florida cool-season a) 33 tornado events (1979–2016) and c) 29 null events (2003–2019). Each box represents the spatial extent of a tornado and null event, based on tornado and hail/wind rep southwest) in the tornado events than in the null events. orts, respectively. Panels (b) and (d) show examples of a tornado (23 February 1998) and null (2 January 2006) event, respectively, with tornado tracks (red lines) and hail/wind (green/blue dots) reports respectively plotted. In (b) and (d), the mobile-home percentage in each Florida county is shaded. *Click image to enlarge*.

at risk for more frequent false alarms. Table A2 shows that only two of 29 null events occurred at night, which was a key difference from our tornado events. However, many null events occurred during the morning just after sunrise, not during peak daytime heating (Table A2). The highest tornado-outlook probability for any null event was 30%, with a relatively large number of events having 10 and 15% probabilities (Table A2).

Following our tornado-event identification and analysis, we analyzed synoptic and mesoscale environmental parameters using the NARR (Mesinger et al. 2006), which has a 32-km horizontal grid spacing, 3-h temporal resolution, and is available from 1979–present. Several studies (Gensini and Ashley 2011; Gensini et al. 2014; King and Kennedy 2019) investigated the ability of the NARR to analyze severe convective environments. Gensini and Ashley (2011) found that NARR severe convective environments generally corresponded to storm reports, although Gensini et al. (2014) emphasized caution with thermodynamic parameters. To that end, Gensini et al. (2014) found that parcel-ascent choice was important, because the NARR had regional biases and sometimes overestimated thermodynamic indices. King and Kennedy (2019) analyzed a wide range of datasets and found that the NARR featured some of the smallest biases. One of their important recommendations was to focus on fixed-layer parameters (e.g., 0–3-km SRH) instead of parameters dependent on effective storm inflow bases.

For our synoptic-scale tornado composites (section 3b), we defined 00 h as the closest 3-h NARR time to the first tornado report. The null composites used 00 h as the closest 3-h NARR time to the first hail or wind report. Plots were developed for every 3 h from –24 to 00 h, although not all composite times are discussed in section 3. We caution that because of how we defined 00 h and the fact that our tornado and null events were widely dispersed across Florida, the composites discussed in sections 3b and 3c serve as regional analyses of synoptic-scale patterns. That is, they are not intended to identify variations within Florida. We also caution that our synoptic-scale composite means and anomalies in sections 3b and 3c inherently vary from case to case, which we briefly address in section 5. Finally, our mesoscale parameter-space methodology is detailed in section 4a.

3. Synoptic-scale analysis

a. Teleconnections

Studies have examined the impact of various natural oscillations [e.g., El Niño Southern Oscillation (ENSO), Madden–Julian Oscillation (MJO), Arctic Oscillation (AO), Global Wind Oscillation (GWO), etc.] on United States tornado occurrences (e.g., Hagemeyer 1997, 2010; Cook and Schaefer 2008; Thompson and Roundy 2013; Allen et al. 2015; Gensini and Marinaro 2016; Sparrow and Mercer 2016; Cook et al. 2017; Molina et al. 2018; Tippett 2018). In their climatological study of United States cold-season (November–February) tornadoes, Childs et al. (2018) found correlations between increased tornado counts and negative ENSO (La Niña) as well as positive AO. The correlation between increased cold-season tornado frequency and La Niña was also found by Cook and Schaefer (2008) and Cook et al. (2017), particularly at higher latitudes. However, the domains in both studies encompassed everywhere east of the Rockies, not just Florida, where Hagemeyer (1997, 2010) found a positive correlation between positive ENSO (El Niño) and tornado event frequency. To that end, Molina et al. (2018) recently found that moderate to strong La Niña events are typically associated with relatively lower frequencies of conducive environments for tornadoes in Florida. In contrast, El Niño events were associated with higher chances of conducive tornadic environments across the Southeast.

In this study, we limit our brief teleconnection analysis of tornado events to ENSO and AO. We evaluated ENSO and daily AO for each Florida event (Table 1). For ENSO, we tabulated both the NOAA Multivariate ENSO Index (MEI; Wolter and Timlin 2011) and the Climate Prediction Center (CPC) Oceanic Nino Index (ONI, https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). To be consistent with CPC definitions and previous work, ONI values ≥0.5 were defined as El Niño; values ≤ 0.5 indicated La Niña (Tables 1 and 2). For AO, we used daily data from the CPC archive (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml). Daily data were used to measure AO strength during tornado events, as AO exhibits more short-term variability than ENSO. Daily AO also facilitates a comparison with Hagemeyer (2010). In Tables 1 and 2, again to be consistent with CPC definitions, orange and blue shading is used for AO index values greater and less than 0.5, respectively.

We used the aforementioned ONI thresholds to determine the total number of positive and negative ENSO cases during our tornado events. Of the 33 tornado events, 12 occurred during El Niño and six occurred during La Niña (Table 1).

Table 1: The date of each tornado event, two-month mean MEI and CPC ONI, and daily AO index. Gray shading indicates nighttime outbreaks, while orange and blue shading indicate the ONI/AO threshold was met for positive and negative ENSO/AO events, respectively.

Date	MEI	CPC ONI	Daily AO Index
19830202	2.931	1.9	–2.071
19830423	2.812	1.3	0.772
19830516	2.498	1.1	0.555
19840227	–0.509	–0.4	–0.146
19840409	0.39	–0.4	–0.947
19860208	–0.183	–0.5	–2.196
19860314	0.028	–0.3	–1.484
19890501	–0.393	–0.6	0.952
19900510	0.652	0.3	–3.842
19910303	0.399	0.2	0.24
19910425	0.449	0.3	0.067
19920205	1.886	1.6	–0.702
19930313	0.987	0.5	0.997
19930405	1.408	0.7	0.739
19940103	0.352	0.1	–0.298
19940302	0.159	0.2	0.356
19960202	–0.566	–0.8	–2.637
19970423	0.527	0.3	–0.505
19970428	0.527	0.3	–0.904
19980216	2.777	1.9	0.283
19980217	2.777	1.9	–0.006
19980222 19980223	2.777	1.9	–0.352
19980309	2.751	1.4	1.449
19990102	–1.039	–1.5	0.886
20010329	–0.548	–0.4	0.337
20030327	0.83	0.4	1.086
20030425	0.413	0	0.245
20061225	0.965	0.9	1.425
20070202	0.537	0.3	–0.717
20070302	0.125	0	–1.349
20080307	–1.552	–1.2	1.501
20110331	–1.554	–0.8	–1.55
20160216	–0.11	2.2	0.947

For the AO thresholds stated above, 11 occurred during the positive phase and 12 occurred during the negative phase. We also calculated the mean ONI and AO index values for negative and positive cases. During El Niño cases, the mean ONI was +2.17, while for La Niña cases it was –0.9. For AO, the positive and negative mean event values were 1.028 and –1.48, respectively.

Table 2: As in Table 1, but for the null events.

Date	MEI	CPC ONI	Daily AO Index
20030221	0.6	0.6	0.128
20030222	0.6	0.6	0.128
20050322	0.8	0.4	–1.348
20050326	0.8	0.4	–1.348
20050327	0.8	0.4	–1.348
20050406	0.1	0.4	–0.046
20050422	0.2	0.4	–0.046
20060102	–0.7	–0.8	–0.17
20060113	–0.7	–0.8	–0.17
20070414	–0.4	–0.2	0.544
20080303	–1.5	–1.2	0.586
20080511	–1	–0.8	–1.205
20090218	–0.8	–0.7	–0.672
20090402	–0.8	–0.2	0.973
20110415	–1.7	–0.6	2.275
20121225	–0.1	–0.2	–1.749
20141223	0.3	0.7	0.413
20160121	1.9	2.5	–1.449
20170102	–0.4	–0.3	0.942
20170121	–0.4	–0.3	0.942
20170122	–0.4	–0.3	0.942
20170207	–0.4	–0.1	0.34
20170403	–0.2	0.3	–0.089
20170405	–0.2	0.3	–0.089
20170524	0.2	0.4	–0.73
20180320	–0.8	–0.6	–0.941
20180414	–1.3	–0.4	0.544
20190418	0.3	0.8	–0.255
20190419	0.3	0.8	–0.255

For the null events (Table 2), six events occurred during El Niño and seven during La Niña, although four of the six El Niño events were two sets of two events that occurred on consecutive calendar days. In terms of AO, eight and nine events occurred during positive and negative regimes, respectively. In El Niño cases, the mean ONI was +1.0, while it was –0.78 for La Niña events. For AO, the positive and negative mean event values were 0.97 and –1.19, respectively. Overall, slightly more null events occurred during La Niña, which corresponds to the more poleward cyclone tracks in our synoptic composites (sections 3b and 3c), as well as previous work on ENSO and tornado events (e.g., Eichler and Higgins 2006; Cook and Schaefer 2008; Cook et al. 2017). As in the tornado events, AO results were inclusive, with a nearly equal number of positive and negative cases.

Our analysis supports findings by Hagemeyer (1997; 2010), Cook and Schaefer (2008), Cook et al. (2017), and Molina et al. (2018) that tornado events in Florida are more likely during El Niño than La Niña due to an enhanced subtropical jet stream and the associated synoptic-scale flow patterns. Hagemeyer (2010) also concluded that negative AO may indicate that the jet stream pattern is more favorable for tornadoes in Florida, as cold air tends to plunge equatorward during such events. In contrast, Hagemeyer (2010) found that positive AO was associated with severe weather off the United States east coast (e.g., the 29 March 2010 Grand Bahama tornado). However, Hagemeyer's (2010) study was limited, given that he only examined one season, and our AO results are also inconclusive.

Overall, our ENSO statistics show that the findings from past studies (e.g., Cook and Schaefer 2008; Cook et al. 2017; Childs et al. 2018) of La Niña being associated with increased cold-season tornado counts across the United States likely should not be applied to Florida. These discrepancies are likely due to the different regional impacts of specific jet stream and synoptic-scale patterns. Specifically, La Niña tends to be associated with farther poleward storm tracks east of the Rockies and a weaker subtropical jet stream (Eichler and Higgins 2006; Cook and Schaefer 2008; Cook et al. 2017), which is likely unfavorable for tornado events in Florida but more favorable for events farther north (e.g., our null events). These results also correspond to our synoptic composites in sections 3b and 3c. A summary of typical ENSO and AO patterns associated with Florida and other U.S. cool-season tornado events based on prior work (e.g., Hagemeyer and Schmocker 1991; Hagemeyer 1997, 2010; Cook et al. 2017; Childs et al. 2018; Molina et al. 2018) is shown in Table 3.

Table 3: ENSO and AO patterns typically associated with Florida and other U.S. (east of the Rockies) cool-season tornado events, respectively, based on previous studies (e.g., Hagemeyer and Schmocker 1991; Hagemeyer 1997, 2010; Cook et al. 2017; Childs et al. 2018; Molina et al. 2018).

	Florida	Other U.S.
ENSO	El Niño	La Niña
AO	Negative	Positive

Finally, our teleconnection analysis featured a relatively small sample size (33 tornado and 29 null events) for a limited geographical area (Florida). As it is, only a small portion of our study and serves as a complement to the synoptic-scale analysis presented in sections 3b and 3c, our intent is not to make broad statistically significant conclusions. Potential future work on the relationship between teleconnections and Florida tornado events is briefly discussed in section 5.

b. Large-scale composites: Tornado events

The relationship between jet streaks and severe convective storms has been studied for decades. The interaction of upper- and lower-tropospheric jet streaks can play a role in the development of organized convective systems (Fawbush and Miller 1952, 1954). Upper-tropospheric jet streaks can enhance upper-level divergence and large-scale ascent (Uccellini and Johnson 1979). Meanwhile, the low-level jet (LLJ) can help to advect lower-tropospheric warm and moist air. In some cases, the LLJ is coupled to an upper-tropospheric jet streak (Uccellini and Johnson 1979). Jet streaks can also help create vertical wind shear, another key ingredient for severe convection.

The impacts of jet stream location on tornado occurrences also long has been studied (e.g., Skaggs 1967). For Florida, Hagemeyer (1997) concluded that a stronger than normal jet stream over the Southeast could provide increased 0–6-km vertical shear. Through proximity soundings, he also found that a jet streak moved across or near the Florida Peninsula during most tornado events. An enhanced subtropical jet over the Gulf of Mexico tends to promote extratropical cyclone formation, which can help provide the necessary ingredients for severe convection over Florida. In addition, the left exit region of a subtropical jet streak and/or right entrance of a polar jet streak over Florida are associated with differential positive vorticity advection (DPVA) and increased forcing for ascent.

Figure 2 shows NARR 250-hPa wind speed and geopotential height composites at –24, –12, –06, and 00 h; 700–400-hPa layer-averaged ω is also plotted to analyze large-scale vertical motion. Figure 2a (–24 h) shows two composite mean 80-kt jet streaks located over the eastern United States, with one located south of Texas near the composite longwave trough axis and the other over the Appalachians. As a result, the divergent left exit and right entrance of the equatorward and poleward jet streaks, respectively, are located over Alabama. Figures 2b and 2c (–12, –06 h) show that both jet streaks expand and become more intense over time. At 00 h, Fig. 2d shows the left exit and right entrance regions of the equatorward and poleward jet streaks, respectively, located over northern Florida, promoting strong deep-layer vertical wind shear. This coupled jet divergence region over Florida is also associated with larger negative ω (-4×10^{-2} Pa s^{-1}) values (ascent).

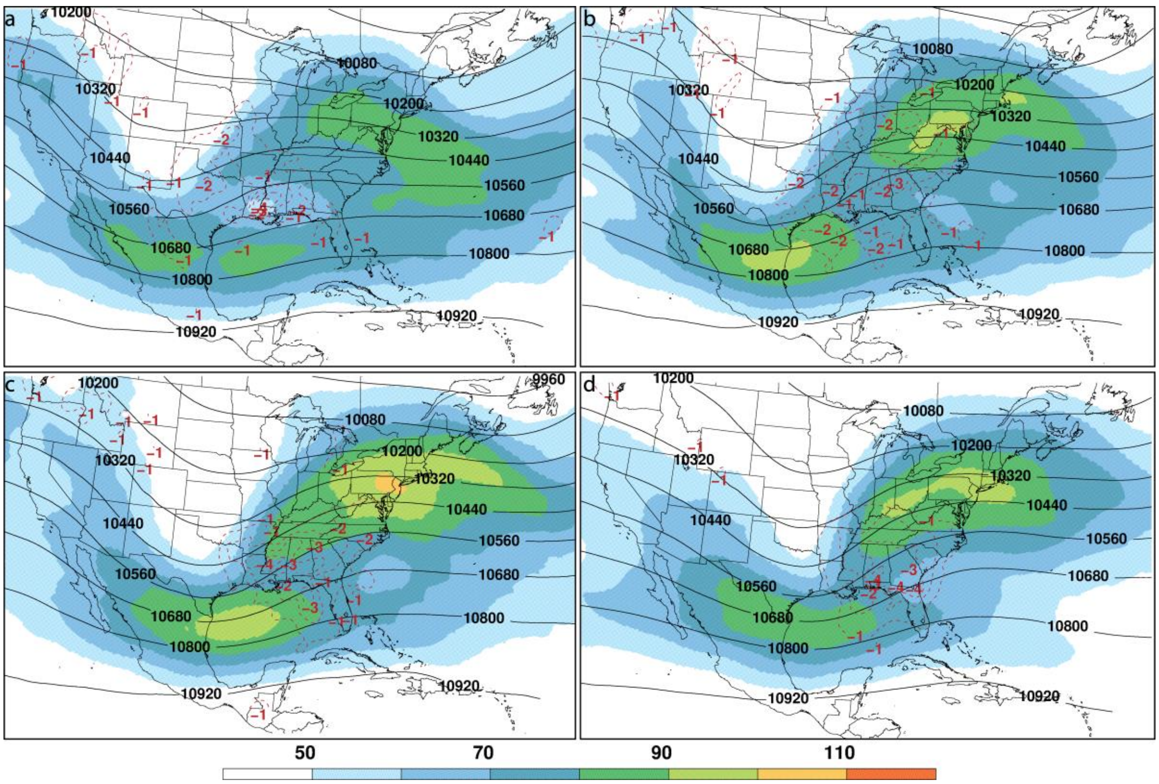


Figure 2: For the tornado events, NARR composite mean 250-hPa wind speed magnitude (kt, shaded; 1 kt = 0.51 m s^{-1}), geopotential height (m, solid black contours), and 700–400-hPa layer-averaged omega ($\times 10^{-2}$ Pa s^{-1}, negative values plotted with red dashed contours) at: a) –24, b) –12, c) –06, and d) 00 h. *Click image to enlarge.*

Pattern recognition of synoptic-scale features is an important forecast tool for severe weather events. To investigate 500-hPa height patterns associated with our tornado events, Fig. 3 shows monthly-weighted anomalies and composite means. Gridpoints with statistically significant anomalies at the 95% and 99% confidence intervals, according to the Student's *t*-test, are hatched and dotted, respectively. At –24 h, Fig. 3a shows a significantly anomalous 500-hPa trough located over the Rockies. By –12 h, a significantly anomalous downstream ridge appears near the Carolinas and the upstream trough is deeper than at –24 h (Fig. 3b). From –24 h to 00 h, both geopotential height anomalies become stronger, particularly the downstream ridge. The negative geopotential-height anomaly associated with the upstream trough grows from –40 to –70 m, as the trough also becomes more negatively tilted (Fig. 3).

Meanwhile, the positive geopotential-height anomalies in the downstream ridge increase from 10–70 m between –12 and 00 h (Figs. 3b–d) and become significant at the 99% confidence level by –06 h (Fig. 3). If lower-tropospheric PVA is typically small, the 500-hPa composite mean pattern suggests strong DPVA over Florida by 00 h (Fig. 3b), indicating forcing for ascent.

Another key feature is the subtropical ridge over eastern Cuba that strengthened between –12 and –06 h (Figs. 3b,c). Overall, the downstream anomalous-ridge environment promotes southerly flow over Florida prior to the event, which helps to advect heat and moisture. We discuss this further in subsequent paragraphs.

Moisture is a key ingredient for tornado events (e.g., Thompson et al. 2012), both in terms of high surface dewpoints and tropospheric integrated water vapor (precipitable water). Precipitable water (W) is defined as:

$$W = \frac{1}{\rho g}\int_{P1}^{P2} q\, dp \qquad (1)$$

where g is the gravitational acceleration, ρ is the density of liquid water, q is specific humidity, and dp is the differential representing the change in pressure between two pressure levels. Larger precipitable water in the atmosphere equates to high specific humidity in the troposphere, which is typically concentrated in the lower troposphere and favorable for severe convection.

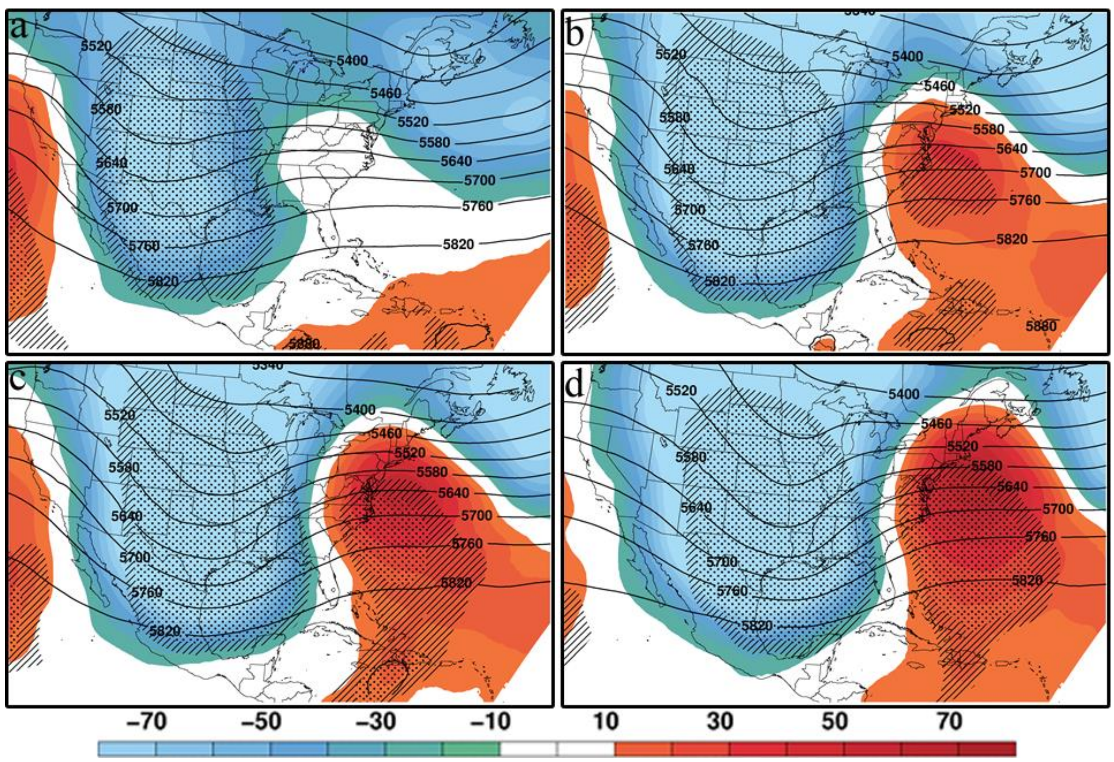


Figure 3: For the tornado events, NARR 500-hPa geopotential height monthly-weighted composite anomalies (m, shaded) and composite mean (m, solid black contours) at: a) –24, b) –12, c) –06, and d) 00 h. Grid points with statistically significant anomalies at the 95% and 99% confidence intervals according to the Student's *t*-test are hatched and dotted, respectively. *Click image to enlarge.*

Figure 4 shows composite mean sea-level pressure (MSLP) and W anomalies. At –24 h (Fig. 4a), a 4–6-mm statistically significant W anomaly is located over the central Gulf of Mexico. As time progresses, larger W anomalies are observed to the north and northeast of the composite MSLP cyclone center. Between –12 and –06 h, Figs. 4b and 4c show that W anomalies increase from 4–6 mm to 6–8 mm. At 00 h, Fig. 4d indicates a large W anomaly (10–12 mm) over Florida as moist air surges poleward ahead of the composite MSLP cyclone. Despite the anomalously large W values over Florida, Rasmussen and Straka (1998) suggested that hydrometeor loading (and thus the degree to which tornadoes are rain-wrapped) is more related to the anvil-relative wind profile.

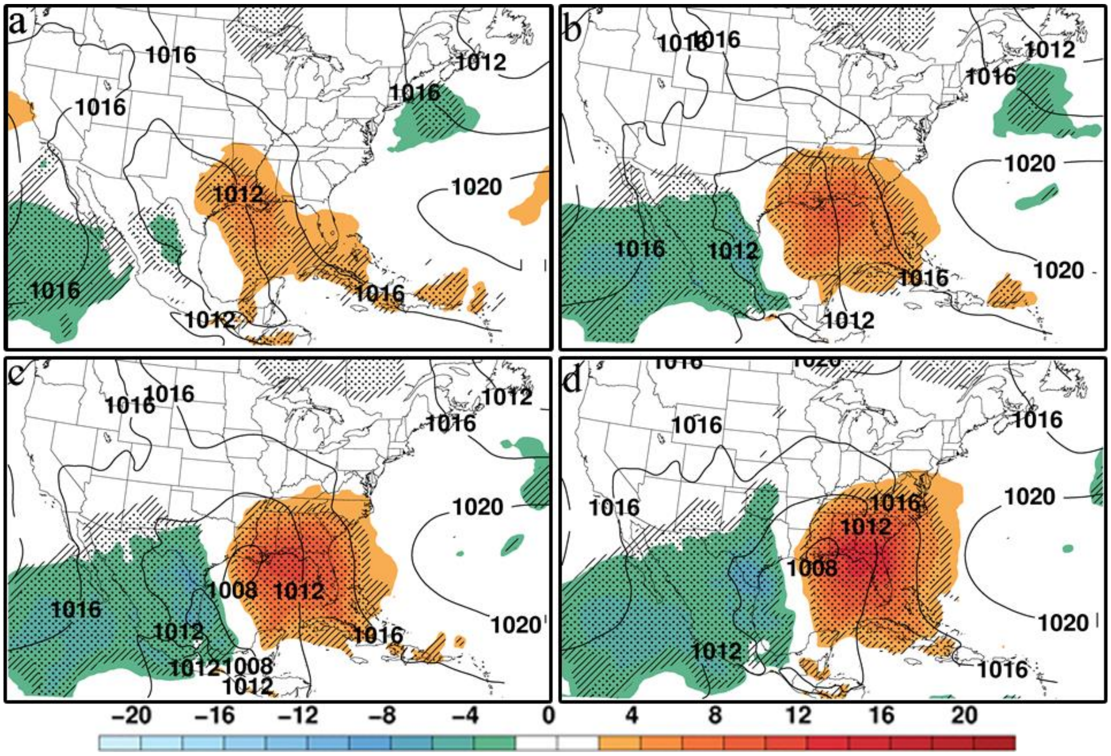


Figure 4: For the tornado events, NARR monthly-weighted composite anomalies of precipitable water (mm, shaded) and composite mean MSLP (hPa, solid black contours) at: a) –24, b) –12, c) –06, and d) 00 h. Grid points with statistically significant anomalies at the 95% and 99% confidence intervals according to the Student's *t*-test are hatched and dotted, respectively. *Click image to enlarge.*

In their Great Plains study, Kis and Straka (2010) found the LLJ to be crucial for nocturnal tornadoes. They defined the LLJ as a relatively narrow band of wind stronger than the background 850-hPa geostrophic flow, with a minimum threshold of 30 kt (15 m s^{-1}). To help investigate the LLJ structures associated with our tornado events, Fig. 5 shows 850-hPa θ_e composite means and anomalies, as well as 850-hPa mean winds from –12 to 00 h. Figure 5a shows 15–20 kt (7.7–10 m s^{-1}) southwesterly winds and θ_e anomalies of 8–10 K over the central Gulf of Mexico, associated with the composite mean θ_e ridge. From –06 to –03 h (Figs. 5b,c), wind direction remains from the southwest; however, wind magnitude increases to 25 kt (13 m s^{-1}), advecting larger heat and moisture values (10–12 K anomalies) poleward toward Florida. In addition, the θ_e ridge orientation evolves from south-north to southwest-northeast. At 00 h (Fig. 5d), θ_e reaches its maximum value over the Florida Peninsula and the northeastern Gulf (12–16 K anomalies). Furthermore, the 850-hPa winds reach a maximum of 30 kt (15 m s^{-1}) from the southwest over Florida. The large θ_e anomalies over Florida in Fig. 5d suggest that very anomalously warm and moist air is present during tornado events, which supports Hagemeyer's (1997) findings.

c. Large-scale composites: Null events

Figure 6 presents 250-hPa composites for the null events, to compare to the tornado composites in Fig. 2. At –24 h (Figs. 2a, 6a), the tornado and null events feature a relatively similar composite mean upstream trough centered over the south-central United States, although the associated jet streak is slightly more pronounced in the tornado composite. More substantial differences between the tornado and null event patterns are evident from –12 h onward (Figs. 2b–d, 6b–d). The null events feature a less-amplified upstream trough located farther to the north than the corresponding feature in the tornado events. Furthermore, the associated upstream and downstream jet streaks are 10–20 kt (5–10 m s^{-1}) weaker in the null events. The weaker upstream jet streak at 00 h in the null events (Fig. 6d) ostensibly is a factor in weaker deep-layer (0–6-km) vertical shear

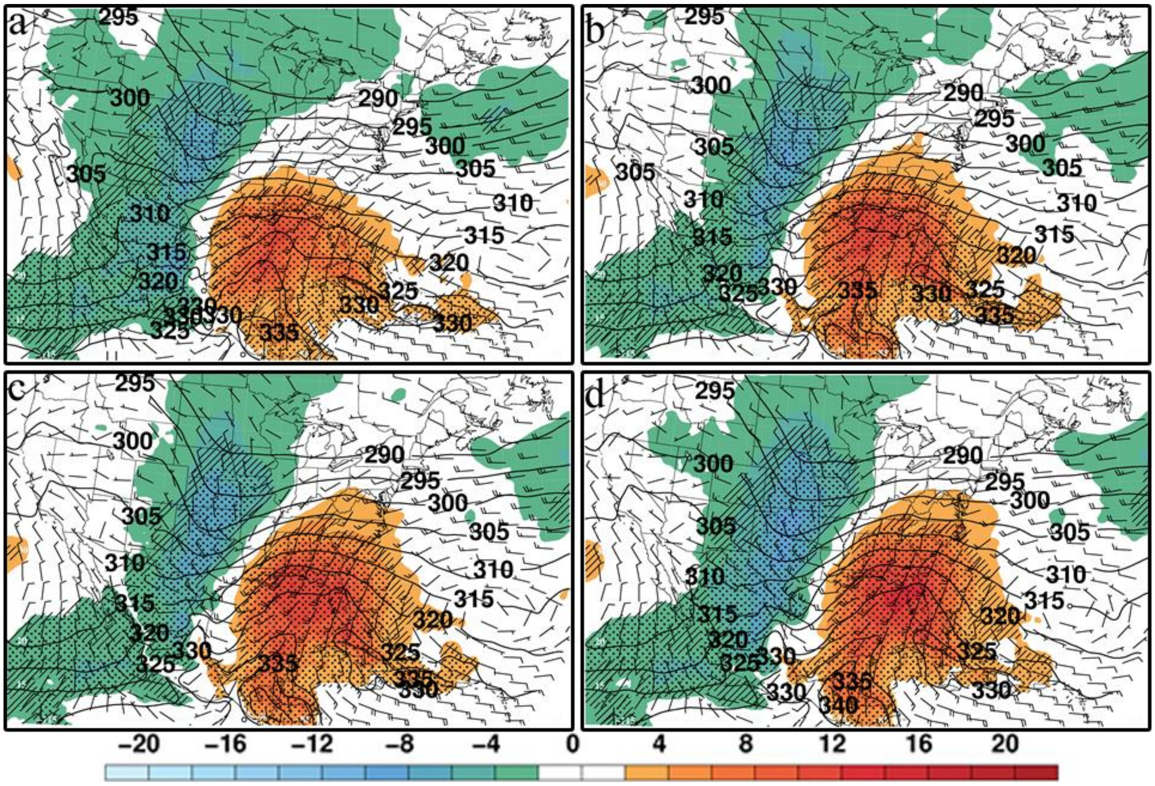


Figure 5: For the tornado events, NARR 850-hPa θ_e monthly-weighted composite anomalies (K, shaded) and means (K, solid black contours), and 850-hPa composite mean wind (kt, barbs) at: a) –12, b) –06, c) –03, and d) 00 h. *Click image to enlarge*.

over Florida (section 4b). In addition, the coupled divergence region (left exit and right entrance of the upstream and downstream jet streak, respectively) is located farther north in the null events than in the tornado events (Figs. 2d, 6d). As a result, the associated ascent over Florida is also weaker. We speculate on the role of the jet-streak positions on surface cyclogenesis in subsequent paragraphs.

The 500-hPa geopotential height composites elucidate two key large-scale pattern differences between the tornado (Fig. 3) and null events (Fig. 7). First, the anomalous upstream 500-hPa trough is considerably farther north and less amplified in null events. Second, the anomalous downstream ridge is farther north and more amplified early in the composite evolution (i.e., at –24 and –12 h). These differences suggest that in the null events, the strongest DPVA ahead of the composite mean trough is located well north of Florida at 00 h (Fig. 7d), partially supported by the location of the largest ascent values at the same time (Fig. 6d). In addition, the 500-hPa Rossby wave train reaches peak intensity sooner in the null events than in the tornado events, as evidenced by the earlier appearance of the anomalous downstream ridge (Figs. 3, 7). This result has implications on lower-tropospheric cyclogenesis, which we discuss next.

The null events (Fig. 8) feature a MSLP minimum farther north than the tornado events (Fig. 4) for the entire composite evolution. This corresponds to the relative locations of the aforementioned mid-upper tropospheric trough and jet streaks (Figs. 6, 7). At –24 h, the MSLP composite mean cyclone is stronger in the null events (Figs. 4a, 8a), in association with the earlier-maturing upper-tropospheric pattern (Fig. 7). By 00 h, the null-event MSLP cyclone is located over the Tennessee Valley (Fig. 8d), while the corresponding feature in the tornado events is located near the central Gulf Coast (Fig. 4d). The primary impact from this location difference is in the lower-tropospheric/surface wind direction over Florida, which is more backed (i.e., south-southeast vs. south- southwest) in the tornado events than in the null events.

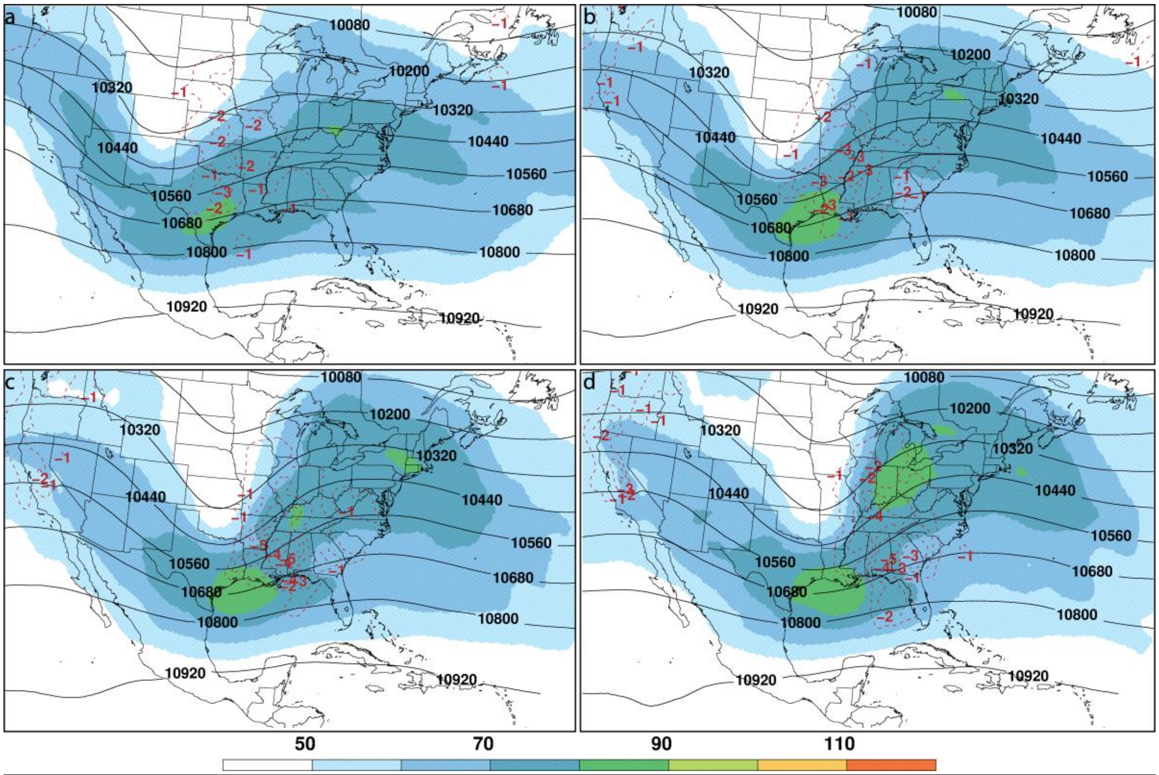
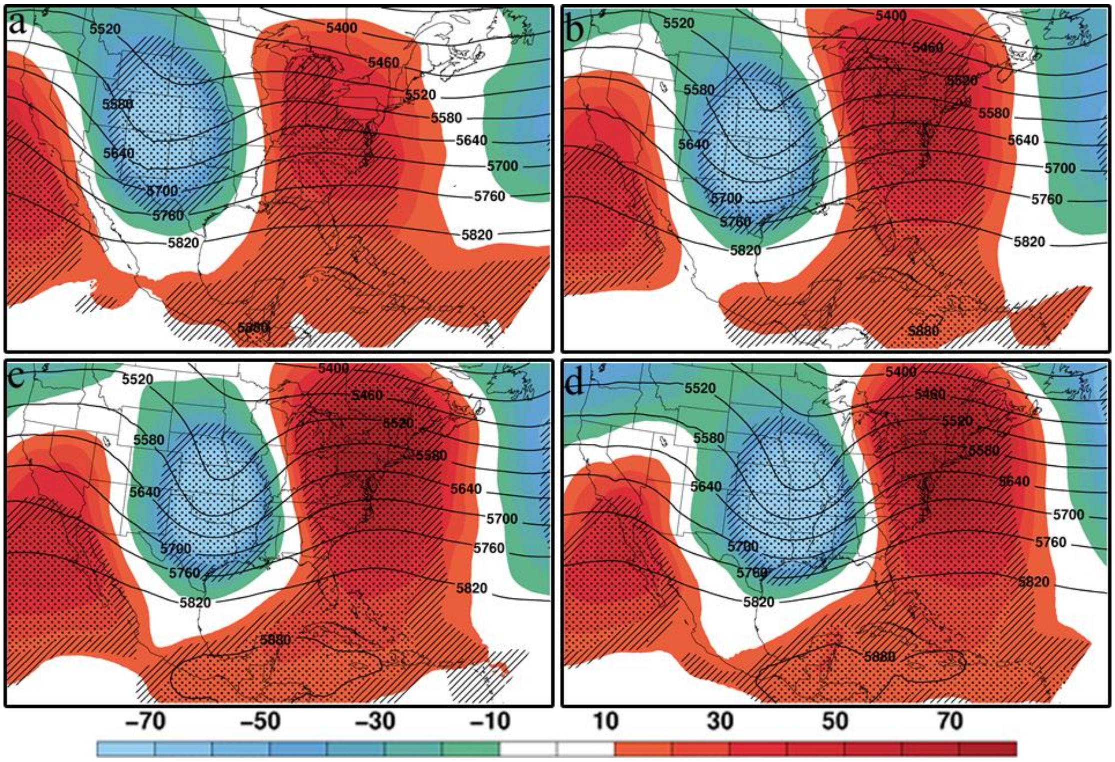


Figure 6: As in Fig. 2, but for the null events. *Click image to enlarge*.

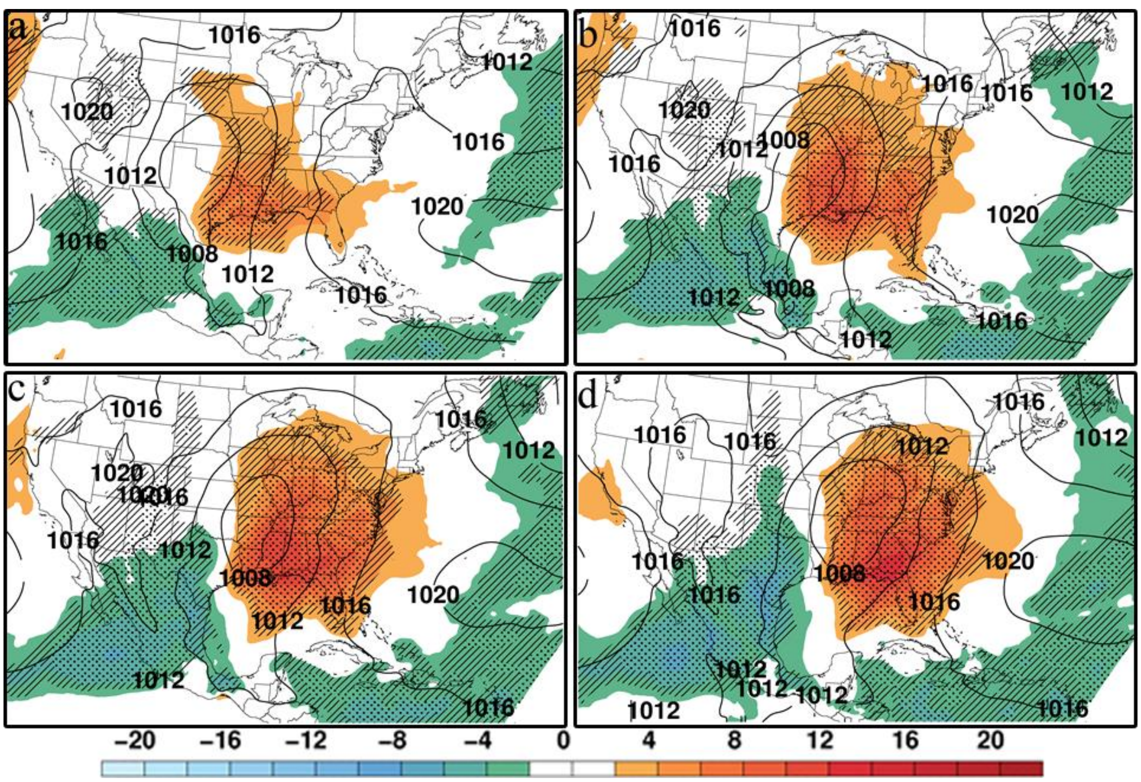
Examinations of NARR composite soundings (not shown) for each set of events support this assertion, which we discuss further in terms of SRH in section 4c.

The tornado and null events exhibit similar statistically significant positive precipitable-water anomalies (8–12 mm) over Florida at 00 h (Figs. 4d, 8d). Positive anomalies extend farther poleward in the null events (Fig. 8), corresponding to the associated synoptic-scale composite height/pressure features. While the overall magnitudes of the precipitable-water anomalies over Florida are similar between the tornado and null events, location differences for the maximum anomaly may be associated with the preponderance of null events that occurred in the Florida Panhandle (Fig. 1c), compared to the majority of tornado events that occurred in Central Florida (Fig. 1a).

There are several key differences in LLJ and θ_e structures between the tornado (Fig. 5) and null (Fig. 9) event composites. First, statistically significant positive θ_e anomalies are located farther north in the null events throughout the composite evolution, corresponding to the relative locations of synoptic-scale pressure/height features. Second, the magnitudes of the θ_e composite anomalies *and* means are considerably smaller in the null events. At 00 h over Florida, the null events (Fig. 9d) feature 6–8 K positive anomalies and mean values near 320 K. In contrast, the tornado events at the same time (Fig. 5d) exhibit 12–16 K positive anomalies and mean values greater than 325 K. Tornado events therefore evidently feature larger values of lower-tropospheric heat and moisture than null events. Finally, while the LLJ over Florida at 00 h is of similar magnitude between the two composites (Figs. 5d, 9d), it is southwesterly in the null events compared to south-southwesterly in the tornado events. In the tornado events (Fig. 4d), the LLJ orientation in combination with south-southeasterly surface flow results in larger lower-tropospheric SRH values (Fig. 8d). We discuss this point further in section 4c.



<u>Figure 7</u>: As in Fig. 3, but for the null events. *Click image to enlarge.*



<u>Figure 8</u>: As in Fig. 4, but for the null events. *Click image to enlarge.*

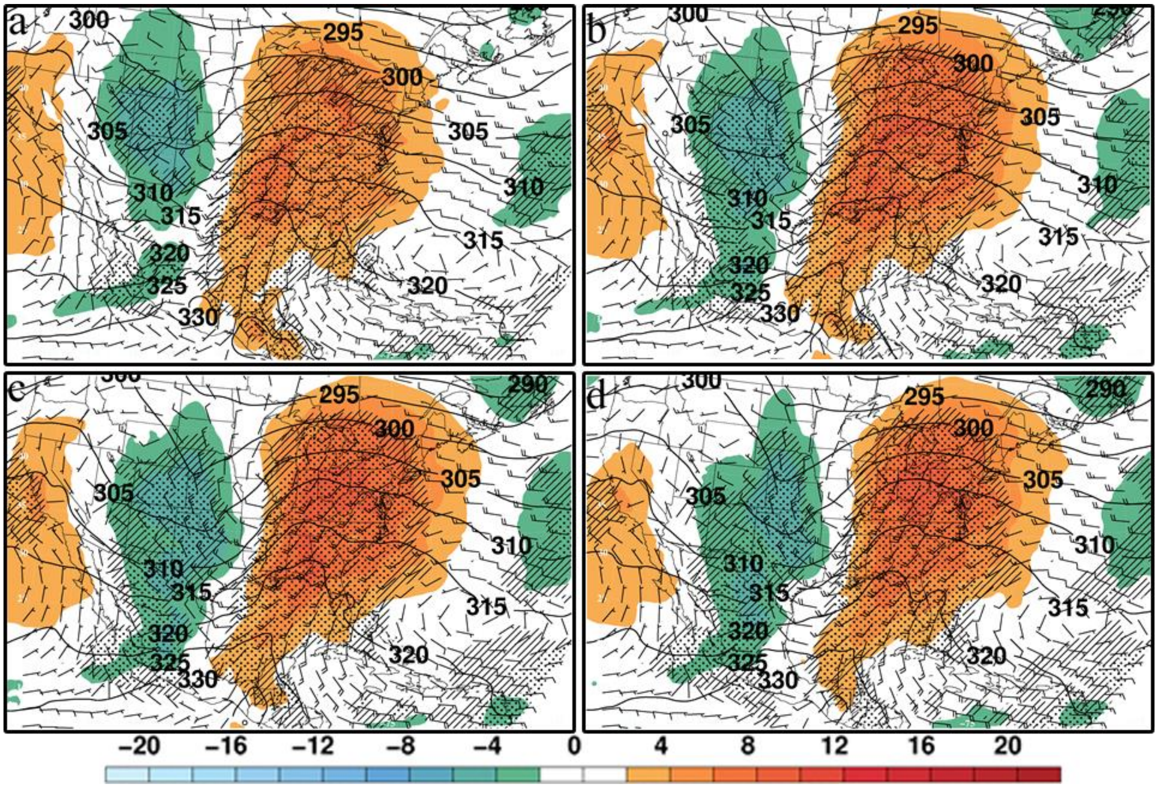


Figure 9: As in Fig. 5, but for the null events. *Click image to enlarge*.

4. Mesoscale analysis

a. Deriving mesoscale parameters from NARR soundings

To analyze the convective parameters discussed in this section, we used NARR-derived soundings produced by the Sounding/Hodograph Analysis and Research Program in Python (SHARPpy; Blumberg et al. 2017). The predecessor to SHARPpy is widely used by NOAA SPC, and SHARPpy automatically calculates all parameters discussed here. For the tornado events, we examined the NARR sounding at the closest 3-h NARR time to each tornado report at the location of that report. We then averaged the values of all convective parameters over all reports within a tornado event. The ranges presented in sections 4b–d use these tornado event average values.

For each null case, we examined the NARR sounding at the closest 3-h NARR time at the location of each hail and wind report in Florida. We then averaged all convective parameter values over all hail and wind reports within a null event. The ranges presented in sections 4b–d use these null event-averaged values.

The values and ranges presented in sections 4b–d generally should be regarded as representing the regional convective environments associated with our tornado and null events (Gensini et al. 2014; King and Kennedy 2019). However, they should not be confused with storm-scale environments, for which the NARR is too coarse to analyze. Here, the NARR serves as a flexible modern replacement for proximity sounding-based environmental analyses (e.g., Hagemeyer and Schmocker 1991; Hagemeyer 1997).

b. CAPE and vertical shear

Figure 10 shows the lowest 100-hPa mean parcel (SHARPpy default) mixed-layer CAPE (MLCAPE) and 0–6-km bulk vertical wind shear (SHR6) for the tornado and null events. For tornado events, MLCAPE (Fig. 10a) has a median value of approximately 600 J kg^{-1} with a maximum near 2000 J kg^{-1}. In the null events (Fig. 10b), the median value is similar to the tornado events, but the maximum is higher (approximately 2400 J kg^{-1}). For SHR6, the tornado event median is approximately 47 kt (24 m s^{-1}) (Fig. 10c), while the null events (Fig. 10d) exhibit a median of around 50 kt (24 m s^{-1}).

However, the tornado events have larger upper- and lower-fence values (top and bottom of each whisker, respectively) of SHR6 (72 and 38 kt or 37 and 19.5 m s^{-1} respectively) than the null events (66 and 22 kt or 34 and 11 m s^{-1}, respectively).

Compared to Great Plains events, cool-season Florida tornado events feature low to moderate MLCAPE and large SHR6. These HSLC results mirror the Southeast results of previous studies, including Sherburn et al. (2016), Cohen et al. (2017), and Anderson-Frey et al. (2019). Specifically, our MLCAPE and SHR6 interquartile ranges in tornado events are very similar to the winter Southeast events of Anderson-Frey et al. (2019). For Florida tornado events, Hagemeyer and Schmocker (1991) found an average dry-season tornado event surface-parcel CAPE of 164 J kg^{-1} with 40 kt (20 m s^{-1}) SHR6. The proximity sounding analysis of Hagemeyer (1997) did not calculate CAPE but found a mean SHR6 value of 45 kt (23 m s^{-1}) across their events.

c. Storm-relative helicity (SRH)

To further gauge tornadic environments, we examine distributions of 0–3-km (SRH3) and 0–1-km SRH (SRH1), commonly used by SPC (e.g., Thompson et al. 2012). Many studies have examined SRH with respect to tornado climatologies (e.g., Rasmussen and Blanchard 1998; Thompson et al. 2003, 2007, 2012; Anderson-Frey et al. 2019). Davies-Jones (1984), Davies-Jones et al. (1990) and Markowski et al. (1998, their Eq. 1) defined SRH as:

$$SRH = \int_0^H (\boldsymbol{v} - \boldsymbol{c}) \cdot \omega \, dz \qquad (2)$$

where H is an assumed inflow depth (3 or 1 km here, respectively), ***v–c*** is the storm-relative wind (environmental wind vector minus the storm motion vector), and ω is the vorticity vector.

Figure 11(a,c) shows that tornado events are characterized by approximate median of 210 and 180 m^2 s^{-2} for SRH3 and SRH1, respectively. The respective medians in the null events (Fig. 11b,d) are approximately 170 m^2 s^{-2} and 150 $m^2 s^{-2}$, both smaller than their tornado event counterparts. Furthermore, upper-fence and 75th percentile values are larger in the tornado events, especially for SRH3 (Fig. 11). The larger SRH values in tornado events correspond to the low-level wind profiles inferred from the MSLP and LLJ composites, as well as composite soundings (not shown). That is, lower-tropospheric wind profiles veer with height more in tornado events.

Our tornado-event SRH3 values resemble the dry-season values of Hagemeyer and Schmocker (1991) and the Southeast event average of Sherburn et al. (2016). Anderson-Frey et al. (2019) studied all tornado events in the Southeast except for Florida but did not analyze 0–3-km SRH. However, our values are ~100–200 m^2 s^{-2} smaller than the average SRH3 observed by Hagemeyer (1997). We note that Hagemeyer (1997) only studied proximity soundings for tornado events in a specific sub-region (east-central Florida), for which they used a higher-end event definition than we do (≥4 tornadoes in 4 h). Finally, our SRH1 interquartile range values are considerably lower than the Southeast winter season ranges of Anderson-Frey et al. (2019). This finding may be in part related to dataset choice (they used the 40-km Rapid Refresh) and/or sounding methodology, but it is likely at least somewhat representative of the differences between cool-season Florida tornado environments and those farther north.

d. Severe composite parameters

The supercell composite parameter (SCP) was defined by Thompson et al. (2003) and analyzed further by Thompson et al. (2012). SCP incorporates MUCAPE (CAPE based on the most unstable parcel in the lowest 300 hPa), effective bulk-wind difference (EBWD), and effective SRH (ESRH):

$$\mathrm{SCP} = \left(\frac{\mathrm{MUCAPE}}{1000\ \mathrm{J\ kg^{-1}}}\right) * \left(\frac{\mathrm{EBWD}}{20\ \mathrm{m}\ s^{-1}}\right) * \left(\frac{\mathrm{ESRH}}{50\ m^2\ s^{-2}}\right). \quad (3)$$

The maximum value for the EBWD term is 1.5 and the EBWD term is set to 0 when EBWD is <10 m s^{-1}.

Thompson et al. (2012) developed the significant tornado parameter (STP) composite index to analyze tornadic environments. We used the version of STP (“effective-layer STP”) that incorporates MLCAPE, mixed-layer convective inhibition (MLCINH), and mixed-layer lifted condensation level (MLLCL):

$$\mathrm{STP} = \left(\frac{\mathrm{MLCAPE}}{1500\ \mathrm{J\ kg^{-1}}}\right) * \left(\frac{\mathrm{ESRH}}{150\ m^2\ s^{-2}}\right) * \left(\frac{\mathrm{EBWD}}{12\ \mathrm{m}\ s^{-1}}\right) * \left(\frac{2000 - \mathrm{MLLCL}}{100\ \mathrm{m}}\right) * \left(\frac{\mathrm{MLCINH} + 200}{150\ \mathrm{J\ kg^{-1}}}\right), \quad (4)$$

where ML refers to the lowest 100-hPa mean parcel. When MLLCL is <1000 m and >2000 m, the MLLCL term is set to 0 and 1, respectively.

In addition, when MLCIN >–50 J kg^{-1} and <–200 J kg^{-1}, the MLCIN term is set to 0 and 1, respectively. Finally, the maximum value of the EBWD term is 1.5 for EBWD >30 m s^{-1} and set as 0 when EBWD <12.5 m s^{-1}. Lastly, STP is set to 0 when the effective inflow base is above the ground. For full details on effective-layer STP, see Thompson et al. (2012).

Figure 12 shows SCP and STP for the tornado and null events. For SCP, tornado events exhibit a median and upper-fence value of approximately 2 and 8, respectively (Fig. 12a). Null events have higher median and upper-fence values at approximately 4 and 10, respectively, although they feature a larger interquartile range (Fig. 12b). The larger SCP values in null events are likely related to the considerably higher CAPE values (Figs. 10a,b). Our results suggest that SCP may not be the most useful parameter in discerning Florida tornado events from null cases, as it can struggle in HSLC environments. In addition, many Florida tornado events are associated with quasi-linear convective systems (QLCSs), not isolated supercells (section 5).

Overall, null cases (Fig. 12d) exhibit slightly larger median and upper-fence STP values than tornado events (Fig. 12c). However, the differences are small with 27% of null cases having an STP of 0, as evidenced by the lower-fence values (Fig. 12d). The tornado event interquartile range is small, suggesting that many events have an STP of near 0.5. Compared to the winter events of Anderson-Frey et al. (2019), our tornado event STP interquartile range is smaller than their 1–2.5. As with SRH, these findings may partially be related to dataset and/or sounding methodology, but also suggest possible differences in tornadic environments between Florida and locations farther north. Our results also indicate that STP, like, SCP, may not be all that useful in discerning Florida tornadic environments from null events. The planned future storm-mode analysis (section 5) should shed more light on why both composite parameters are not that different between the two sets of events.

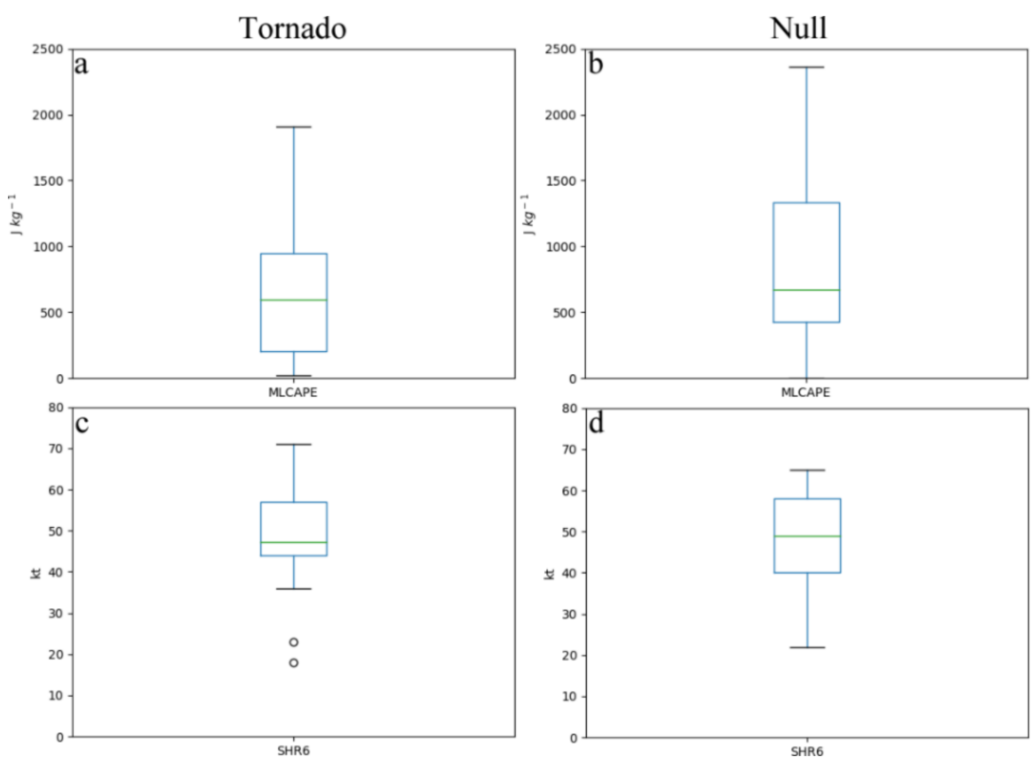


Figure 10: For tornado and null events, box-and-whisker plots of NARR (a,b) MLCAPE (J kg^{-1}) and (c,d) 0–6-km bulk vertical wind shear (SHR6, kt; 1 kt = 0.51 m s^{-1}). Median and outlier values are plotted with a green line and open circles, respectively. The methodology for constructing the plots from NARR soundings is discussed in section 4a.

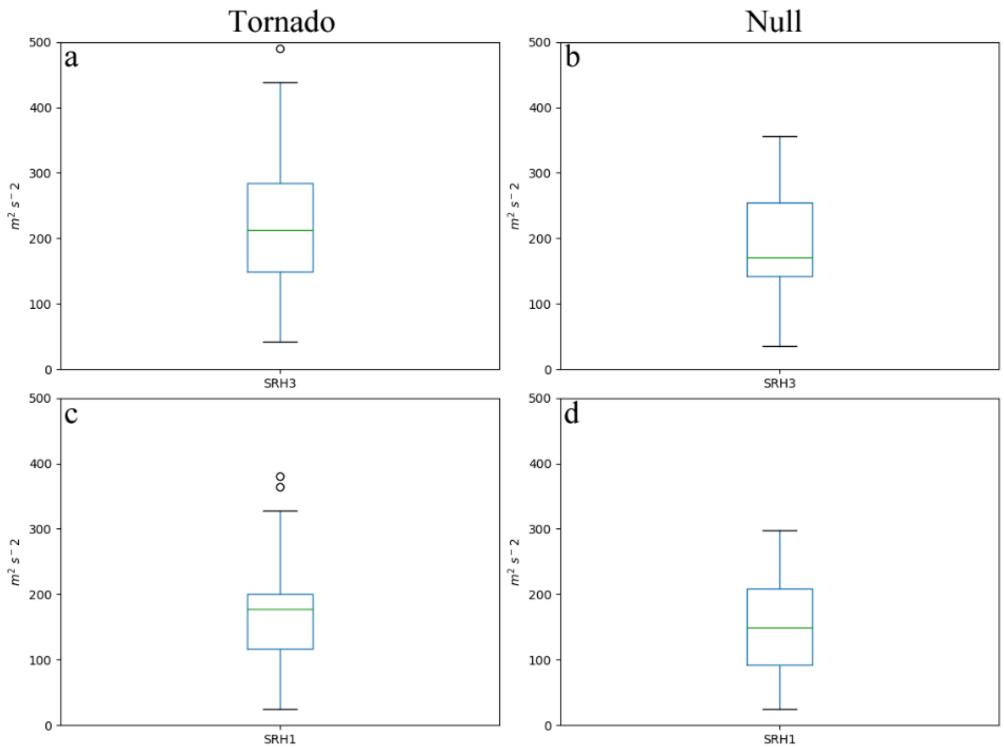


Figure 11: As in Fig. 10, but for NARR (a,b) 0–3-km (SRH3) and (c,d) 0–1-km (SRH1) storm-relative helicity (m^2 s^{-2}).

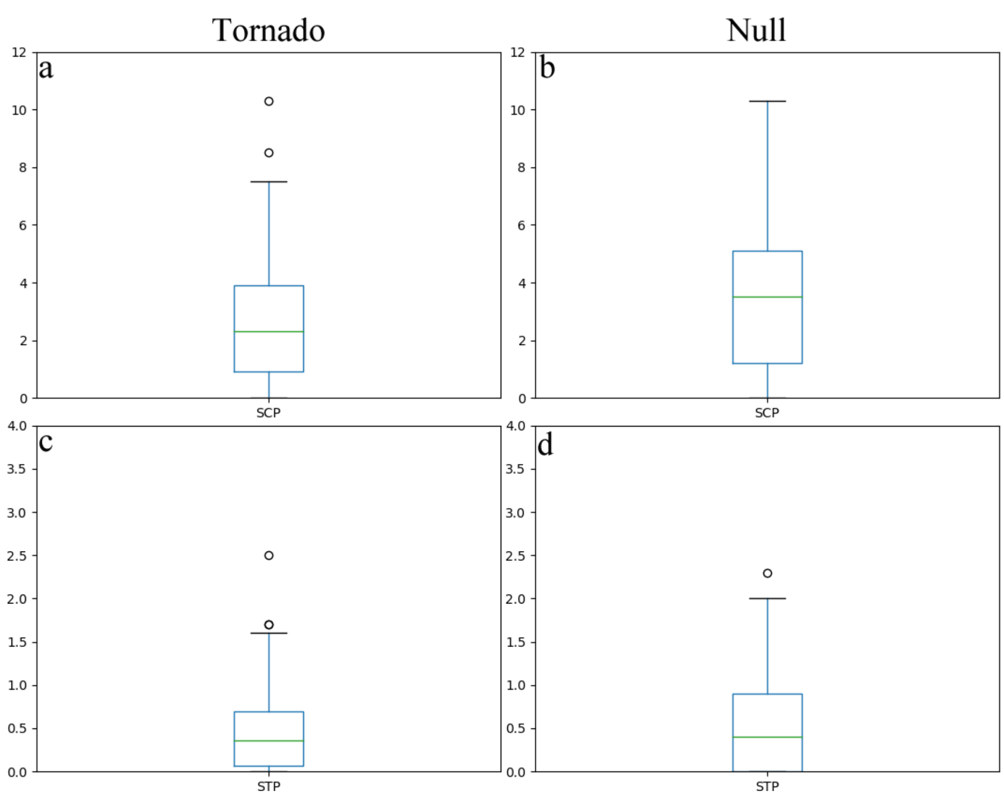


Figure 12: As in Fig. 10, but for NARR (a,b) supercell composite parameter (SCP) and (c,d) significant tornado parameter (STP).

5. Conclusions and future work

This study analyzed the multiscale environmental characteristics of 33 tornado and 29 null events in Florida, using the NARR. We found that more than half of our tornado events occurred during positive ENSO and weak negative AO (Table 1), in agreement with previous studies (e.g., Molina et al. 2018). These results contrast with teleconnection results for cold-season tornado events elsewhere in the United States, for which negative ENSO and positive AO are more conducive for tornadic environments (e.g., Cook et al. 2017). Our null events featured more negative ENSO cases than our tornado events, corresponding to our findings that null events feature more poleward storm tracks. We therefore suggest that Florida (and the Southeast) should be treated differently from other locations when considering the impacts of teleconnection patterns on tornadic environments. One potential avenue of future work is to expand the AO analysis to examine multiple temporal scales, as weekly and or monthly AO indices may exhibit useful relationships with Florida tornado events.

Our synoptic-scale composite analysis (sections 3b and 3c) showed that forcing for ascent over Florida in tornado events was associated with a coupled jet-streak divergence region and DPVA ahead of an upstream, anomalous 500-hPa trough. Null events featured a less-amplified 500-hPa upstream trough. In addition, mid–upper tropospheric features in the null events were located considerably farther north than in the tornado composite, contributing to weaker forcing for ascent over Florida and surface cyclogenesis to the north. Many of the null events did in fact feature tornadoes, but north of Florida (not shown).

Case-to-case variability exists within any composite analysis. This variability does not take away from the conclusions gleaned through the composites, but still can be important to forecasters. To briefly examine the variability in synoptic-scale patterns within our tornado and null events, Fig. 13 presents spaghetti plots of the 5700-m geopotential height contour, with the composite mean contours plotted in red. The 5700-m contour was chosen based on its important composite mean position in both the central U.S. trough and downstream ridge in Figs. 3 and 7. Other contour values (i.e., 5640 m, 5760 m) were tested and results were similar. As is typical in synoptic composites focused on a specific region (e.g., tornado events in Florida), Fig. 13 shows less case-to-case variability closer to 00 h. For the tornado cases, the region of largest variability is in the western U.S. at –24 h (Fig. 13a) and with the speed and amplitude of the central U.S. trough at –12 and 00 h (Figs. 13c,e). The null events appear to have less case-to-case variability at –24 h (Fig. 13b) than do the tornado events, but there are still differences in both the central U.S. trough and the downstream (western Atlantic) ridge. Overall, while Fig. 13 supports our assessments from the composite mean and anomaly plots in Figs. 3 (tornado) and 7 (null), particularly in terms of the anomalously strong central U.S. trough and downstream (western Atlantic) ridge, forecasters should be aware that slight synoptic-scale differences among Florida tornado and null events have and will occur.

Tornado events featured a composite mean MSLP cyclone located in the Gulf of Mexico, while the MSLP cyclone in null events was located over the Tennessee Valley. Combined with a slightly more westerly 850-hPa LLJ, the farther-north null composite MSLP cyclone contributed to weaker lower-tropospheric SRH than in tornado events, for which the surface flow was more backed (south-southeasterly). During tornado events, another important finding was the orientation of the θ_e ridge, as well as higher and more anomalous 850-hPa θ_e values. Overall, the tornado events featured larger values of lower-tropospheric heat and moisture over Florida.

Our mesoscale convective parameter analysis (section 4) demonstrated that Florida tornado events largely fit the HSLC paradigm found by several recent Southeast tornado environment studies (e.g., Sherburn et al. 2016; Anderson-Frey et al. 2019). In fact, the null events exhibited higher median and maximum MLCAPE values than tornado events, but smaller SHR6. All measures of vertical wind shear (SHR6, SRH3, SRH1) exhibited higher median and 75th percentile values in the tornado events than in the null cases. Meanwhile, both composite parameters (SCP and STP) were similar between the two event sets, suggesting that composite parameters may not be as useful in discriminating between Florida tornadic and null environments as they are in the Great Plains.

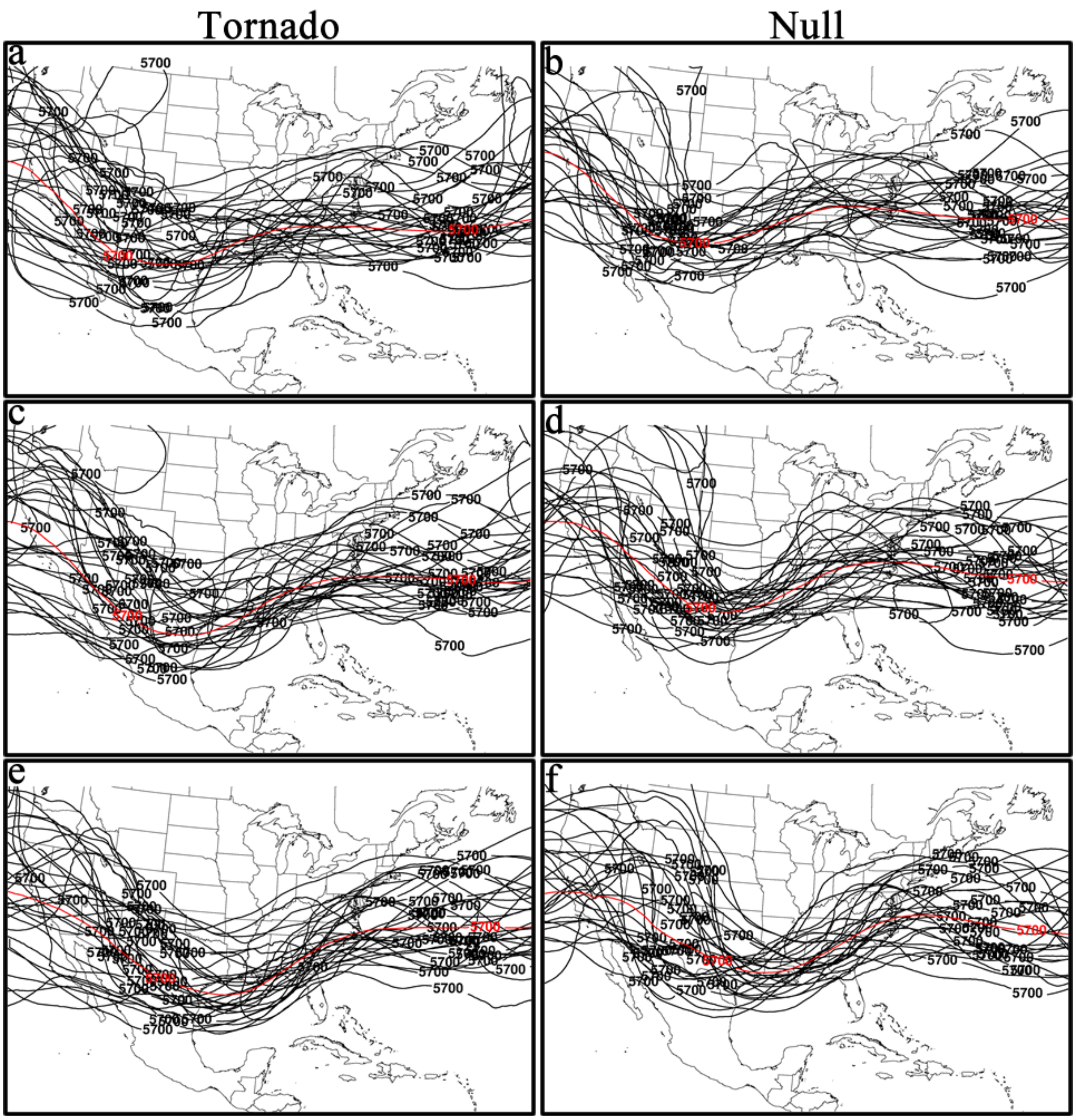


Figure 13: For the (left) 33 tornado and (right) 29 null cases: Spaghetti plots of the 5700-m geopotential height contour at: a,b) –24, c,d) –12, and e,f) 00 h. Each solid black line represents one case, and the solid red line is the composite mean (as in Figs. 3 and 7 for the tornado and null cases, respectively). *Click image to enlarge.*

One issue we faced in this study was the NARR 32-km horizontal grid spacing. Although it was sufficient for the multiscale environmental analysis and allowed us to investigate cases over four decades, localized features such as convergent surface boundaries and sea breeze obviously could not be discerned. As models and reanalysis data continue to improve, future work should include a closer examination of small-scale features. Future work should also explore predictability aspects of Florida tornado events, especially in terms of numerical models.

Cohen et al. (2015, 2017) found that boundary-layer processes such as mass, heat, and momentum fluxes are crucial to convective evolution in Southeast tornado events, especially those with marginal instability. Comparing our environmental analysis to numerical weather prediction output could yield further insight into the role of the planetary boundary layer in Florida events, and elucidate localized effects such as sea breezes and land-sea interfaces.

The role of the surrounding waters in Florida is also unclear. In their study of the 1998 Florida event, Wasula et al. (2007) determined that the ocean shelf maintaining a certain amount of cold water would allow potential convergence zones to develop. To that end, sea breezes occurring later in the cool season (i.e., April–May) may help to develop localized boundaries that enhance mesoscale forcing for ascent and SRH. In addition, some recent studies (e.g., Lee et al. 2016; Molina et. al. 2016, 2018) have examined how Gulf of Mexico sea-surface temperatures (SSTs) modulate U.S. tornado activity; a similar analysis of near-Florida SSTs (including the Atlantic Ocean) for Florida tornado events would be interesting. An additional mesoscale environment question is whether precursor cloud coverage due to advection may help retain a warm boundary layer at night, as most of our tornado events occurred overnight and in the early morning.

Perhaps the most crucial future-work issue is storm-mode analysis of tornadic and null events. It is important to investigate whether events are more associated with isolated supercells or QLCSs, and how the multiscale environments differ between various storm modes. Previous studies (e.g., Collins et. al. 2000; Smith et. al. 2012; Thompson et al. 2012) examined various storm modes associated with tornadoes, including the corresponding environmental parameter spaces. Any future storm-mode analysis for Florida tornado and null events should use the radar-based partitioning methodology of Smith et al. (2012), to separate supercellular and QLCS events. Such a study will allow for the environmental analysis in this study to be placed in additional context and increase multiscale understanding of Florida tornado events.

ACKNOWLEDGMENTS

The authors thank NOAA SPC for freely available archived storm reports and NOAA National Centers for Environmental Information (NCEI) for the NARR data. Teleconnection data were downloaded from the NOAA CPC archives. Storm reports were mapped using ESRI's ArcGIS. The composite analysis was performed using Unidata's General Meteorological Package (GEMPAK) Version 7.4.3 and Python, including the SHARPpy. This research was partially supported by the Embry-Riddle Aeronautical University Applied Aviation Sciences department. Finally, the authors express their great gratitude toward Victor Gensini, Ariel Cohen and Ashton Robinson Cook, the three reviewers whose insightful comments and advice resulted in a considerably stronger manuscript.

APPENDIX A

Table A1: Dates and time periods (UTC) of tornado events from the first to last tornado report. Shaded boxes represent nighttime occurrences.

Date	Time (UTC)	Number of Tornadoes
19830202	0330–1220	14
19830423	0230–1330	8
19830516	0830–1330	4
19840227	0735–1336	4
19840409	1150–1300	4
19860208	0635–1145	4
19860314	0417–1245	10
19890501	0358–1300	4
19900510	0832–1315	4
19910303	0720–1250	8
19910425	1317–1530	6
19920205	0210–1925	6
19930313	0000–0010	4
19930405	0000–0230	6
19940103	1245–1530	6
19940302	0331–1330	5
19960202	1658–1800	4
19970423	0610–1310	22
19970428	0955–1200	5
19980216	0835–2145	6
19980217	0326 - 0630	6
19980222 19980223	1445–0130	10
19980309	0019–0500	8
19990102	0430–2235	9
20010329	0905–1017	6
20030327	1320–1646	8
20030425	0355–1305	7
20061225	0706–1240	5
20070202	0210–0700	4
20070302	0110–0425	4
20080307	0627–0930	6
20110331	0627–1006	9
20160216	0349–0651	9

Table A2: Dates and time periods (UTC) of the 29 null events from the first to last hail/wind report. The maximum SPC 0600 UTC Day 1 tornado probability (%) over Florida is shown in the right-hand column. Shaded boxes represent nighttime occurrences.

Date	Time (UTC)	Maximum tornado probability (%)
20030221	2337	15
20030222	1200–1200	5
20050322	1200–0630	15
20050326	1200–0930	15
20050327	1640–0200	15
20050406	1200–0500	15
20050422	1200–0255	5
20060102	1200–0230	15
20060113	1300–1058	5
20070414	1200–1130	15
20080303	1200–1115	15
20080511	1200–0315	10
20090218	1300–1050	10
20090402	1238–1000	15
20110415	1200–1022	10
20121225	1425–0640	10
20141223	1215–0256	5
20160121	1252–1030	5
20170102	1200–0704	5
20170121	1204–1158	5
20170122	1215–1017	30
20170207	1520–0420	5
20170403	1200–0505	5
20170405	1239–1145	10
20170524	1255–0610	10
20180320	1711–0155	10
20180414	0315–1158	5
20190418	1407–1159	10
20190419	1200–0903	10

REFERENCES

Agee, E. M., and A. Hendricks, 2011: An assessment of the climatology of Florida hurricane-induced tornadoes (HITs): Technology versus meteorology. *J. Climate*, **24**, 5218–5222.

Allen, J. T., M. K. Tippett, and A. H. Sobel, 2015: Influence of the El Niño/southern oscillation on tornado and hail frequency in the United States. *Nat. Geosci*., **8**, 278–283.

Anderson-Frey, A. K., Y. P. Richardson, A. R. Dean, R. L. Thompson, and B. T. Smith, 2016: Investigation of near-storm environments for tornado events and warnings. *Wea. Forecasting*, **31**, 1771–1790.

——, ——, ——, ——, and ——, 2019: Characteristics of tornado events in the southeastern United States. *Wea. Forecasting*, **34**, 1017–1034.

Ashley, W. S., A. J. Krmenec, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Wea. Forecasting*, **23**, 795–807.

Blumberg, W. G., K. T. Halbert, T. A. Supinie, P. T. Marsh, R. L. Thompson, and J. A. Hart, 2017: SHARPpy: An open-source sounding analysis toolkit for the atmospheric sciences. *Bull. Amer. Meteor. Soc*., **98**, 1625–1636.

Bunker, R. C., A. E. Cohen, J. A. Hart, A. E. Gerard, K. E. Klockow-McClain, and D. P. Nowicki, 2019: Examination of the predictability of nocturnal tornado events in the southeastern United States. *Wea. Forecasting*, **34**, 467–479.

Childs, S. J., R. S. Schumacher, and J. T. Allen, 2018: Cold-season tornadoes: Climatological and meteorological insights. *Wea. Forecasting*, **33**, 671–691.

Cohen, A. E., S. M. Cavallo, M. C. Coniglio, and H. E. Brooks, 2015: A review of planetary boundary layer parameterization schemes and their sensitivity in simulating southeastern U.S. cold season severe weather environments. *Wea. Forecasting*, **30**, 591–612.

——, ——, ——, ——, and I. L. Jirak, 2017: Evaluation of multiple planetary boundary layer parameterization schemes in southeast U.S. cold season severe thunderstorm environments. *Wea. Forecasting*, **32**, 1857–1884.

Collins, W. G., C. H. Paxton, and J. H. Golden, 2000: The 12 July 1995 Pinellas County, Florida tornado/waterspout. *Wea. Forecasting*, **15**, 122–134.

Cook, A. R., and J. T. Schaefer, 2008: The relation of El Niño–Southern Oscillation (ENSO) to winter tornado events. *Mon. Wea. Rev.*, **136**, 3121–3137.

——, L. M. Leslie, D. B. Parsons, and J. T. Schaefer, 2017: The impact of the El Niño–Southern Oscillation (ENSO) on winter and early spring United States tornado events. *J. Appl. Meteor. Climatol.*, **56**, 2455–2478.

Davies-Jones, R. P., 1984: Streamwise vorticity: The origin of updraft rotation in supercell storms. *J. Atmos. Sci.*, **41**, 2991–3006.

——, D. W. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, AB, Canada, Amer. Meteor. Soc., 588–592.

Edwards, R., 2012: Tropical cyclone tornadoes: A review of knowledge in research and prediction. *Electronic J. Severe Storms Meteor.*, **7** (6), 1–61.

Eichler,T., and R.W. Higgins, 2006: Climatology and ENSO-related variability of North American extratropical cyclone activity. *J. Climate*, **19**, 2076–2093.

Fawbush, E., and R. Miller, 1952: A mean sounding representative of the tornadic airmass environment. *Bull. Amer. Meteor. Soc.*, **33**, 303–307.

——, and ——, 1954: The types of air masses in which North American tornadoes form. *Bull. Amer. Meteor. Soc.*, **35**, 154–166.

Gensini, V. A., and W. S. Ashley, 2011: Climatology of potentially severe convective environments from North American Regional Reanalysis. *Electronic J. Severe Storms Meteor.*, **6** (8), 1–40.

——, and A. Marinaro, 2016: Tornado frequency in the United States related to global relative angular momentum. *Mon. Wea. Rev.*, **144**, 801–810.

——, T. L. Mote, and H. E. Brooks, 2014: Severe thunderstorm reanalysis environments and collocated radiosonde observations. *J. Appl. Meteor. Climatol.*, **53**, 742–751.

Hagemeyer, B. C., 1997: Peninsular Florida tornado events. *Wea. Forecasting*, **12**, 399–427.

——, 2010: The 2009–10 El Niño and Florida dry season tornadoes: A reality check for the limits of predictability. NOAA climate prediction S&T digest, 9–14. [Available online at https://repository.library.noaa.gov/view/noaa/9379/noaa_9379_DS1.pdf.]

——, and G. K. Schmocker, 1991: Characteristics of east-central Florida tornado environments. *Wea. Forecasting*, **6**, 499–514.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588–612.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey, 1978: An augmented tornado climatology. *Mon. Wea. Rev.*, **106**, 1172–1183.

Kelly, J. J., and Coauthors, 1998: Central Florida tornado event February 22–23, 1998. NWS service assessment, 37 pp. [Available online at https://www.weather.gov/media/publications/assessments/cntrlfl.pdf.]

King, A. T., and A. D. Kennedy, 2019: North American supercell environments in atmospheric reanalyses and RUC-2. *J. Appl. Meteor. Climatol.*, **58**, 71–92.

King, J. R., M. D. Parker, K. D. Sherburn, and G. M. Lackmann, 2017: Rapid evolution of cool season, low-CAPE severe thunderstorm environments. *Wea. Forecasting*, **32**, 763–779.

Kirkpatrick, C. E., W. McCaul, and C. Cohen, 2011: Sensitivities of simulated convective storms to environmental CAPE. *Mon. Wea. Rev.*, **139**, 3514–3532.

Kis, A. K. and J. M. Straka, 2010: Nocturnal tornado climatology. *Wea. Forecasting*, **25**, 545–561.

Lanicci, J., 2016: A multi-scale analysis of the atmospheric conditions associated with the Daytona Beach tornado of Christmas Day, 2006. *Electronic J. Severe Storms Meteor.*, **11**, (5), 1–44.

Lee, S.-K., A. T. Wittenberg, D. B. Enfield, S. J. Weaver, C. Wang, and R. Atlas, 2016: Springtime U.S. regional tornado outbreaks and their links to ENSO flavors and North Atlantic SST variability. *Environ. Res. Lett.*, **11**, 044008.

Markowski, P., J. M. Straka, E. N. Rasmussen, and D. O. Blanchard, 1998: Variability of storm-relative helicity during VORTEX. *Mon. Wea. Rev.*, **126**, 2959–2971.

McCaul, E. W. Jr., and M. L. Weisman, 2001: The sensitivity of simulated supercell structure and intensity to variations in the shapes of environmental buoyancy and shear profiles. *Mon. Wea. Rev.*, **129**, 664–687.

Miller, R. C., 1972: Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central. Tech. rep. 200 (Rev.), Air Weather Service, Scott AFB, IL, 190 pp. [Available online at https://apps.dtic.mil/dtic/tr/fulltext/u2/744042.pdf.]

Molina, M. J., R. P. Timmer, and J. T. Allen, 2016: Importance of the Gulf of Mexico as a climate driver for U.S. severe thunderstorm activity. *Geophys. Res. Lett.*, **43**, 12 295–12 304.

——, J. T. Allen, and V. A. Gensini, 2018: The Gulf of Mexico and ENSO influence on subseasonal and seasonal CONUS winter tornado variability. *J. Appl. Meteor. Climatol.*, **57**, 2439–2463.

NCEI, cited 2019: U.S. tornado climatology. [Available online at https://www.ncdc.noaa.gov/climate-information/extreme-events/us-tornado-climatology.]

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148–1164.

——, and J. M. Straka, 1998: Variations in supercell morphology. Part I: Observations of the role of upper-level storm-relative flow. *Mon. Wea. Rev.*, **126**, 2406–2421.

Sherburn, K. D., and M. D. Parker 2014: Climatology and ingredients of significant severe convection in high-shear, low-CAPE environments. *Wea. Forecasting*, **29**, 854–877.

——, ——, J. R. King, and G. M. Lackmann, 2016: Composite environments of severe and nonsevere high-shear, low-CAPE convective events. *Wea. Forecasting*, **31**, 1899–1927.

Smith, B. T., R. L. Thompson, J. S. Grams, C. Broyles, and H. E. Brooks, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part I: Storm classification and climatology. *Wea. Forecasting*, **27**, 1114–1135.

Skaggs, R. H., 1967: On the association between tornadoes and 500-mb indicators of jet streams. *Mon. Wea. Rev.*, **95**, 107–110.

Sparrow, K. H., and A. E. Mercer, 2016: Predictability of US tornado event seasons using ENSO and Northern Hemisphere geopotential height variability. *Geosci. Front.*, **7**, 21–31.

Tippett, M. K., 2018: Robustness of relations between the MJO and U.S. tornado occurrence. *Mon. Wea. Rev.*, **146**, 3873–3884.

Thompson, D. B., and P. E. Roundy, 2013: The relationship between Madden–Julian oscillation and United States violent tornado events in the spring. *Mon. Wea. Rev.*, **141**, 2087–2095.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. M. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1243–1261.

——, C. M. Mead, and R. Edwards, 2007: Effective storm-relative helicity and bulk shear in supercell thunderstorm environments. *Wea. Forecasting*, **22**, 102–115.

——, B. T. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part II: Supercell and QLCS tornado environments. *Wea. Forecasting*, **27**, 1136–1154.

Uccellini, L. W., and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective storms. *Mon. Wea. Rev.*, **107**, 682–703.

Wasula, A. C., L. F. Bosart, R. Schneider, S. J. Weiss, R. H. Johns, G. S. Manikin, and P. Welsh, 2007: Mesoscale aspects of the rapid intensification of a tornadic convective line across Central Florida: 22–23 February 1998. *Wea. Forecasting*, **22**, 223–243.

Wolter, K., and M. S. Timlin, 2011: El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *Int. J. Climatol.*, **31**, 1074–1087.

REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Ashton Robinson Cook):

Initial Review:

Recommendation: Accept with minor revisions.

General Comments: The authors present a well-conceived, thorough analysis of cool-season tornado events in Florida that builds upon an extensive amount of previous literature assessing environments supportive of tornadoes. The paper also provides an extensive and thorough review of the literature, while outlining how the current results apply specifically to tornado events in Florida. The novelty of the study and its relevance in understanding patterns related to impactful Florida tornadoes justifies its publication, though a number of revisions are recommended to strengthen the already robust results, clarify a few key aspects of the study, and focus the study on its most important outcomes.

Substantive Comments: The assertion that tornadoes in Florida occur with cells vs. linear systems requires a more-detailed analysis than that presented in the current study. Additional comments provided later in this review.

We agree and this sentence has been removed. Other reviewers also suggested adding a detailed storm-mode analysis to this paper. We essentially had to make a choice between adding the null case analysis or adding a storm-mode analysis. We have completed both, but it is just too much information for one manuscript. We chose to add the null cases to facilitate a comparison with the tornado events. An in-depth analysis of storm mode will be addressed in a future manuscript, which we now explain in section 5.

How are the areal extents of the outbreak (the square boxes in Fig. 1) determined? An extra sentence or two describing this would be helpful. Also, was there a time criteria applied for determining outbreaks? (i.e., 4 tornadoes in a 24-hour period?)

Based on other reviewer comments, we have replaced the word "outbreak" with "event", so as not to confuse readers with official definitions of "outbreak". In addition, the boxes in Fig. 1a for the tornado events were based on our definition of ≥ 4 tornadoes in a 24-h period. Null-event identification (Fig. 1c) is also explained in the revised section 2.

Essentially, the boxes are a measure of the maximum spatial extent of each tornado/null event, with the caveat that all boxes are rectangular. This means that the subset of boxes that extend over bodies of water (e.g., the Gulf of Mexico) do not indicate waterspouts. But they do tend to indicate that a particular tornado/null event occurred over a larger area. The case examples in Fig. 1(b,d) should also assist with interpretation of Fig. 1.

Daily AO can be useful, but perhaps various temporal averages of AO can be beneficial since persistent AO patterns can result in persistent warm or cold advection across the eastern U.S.—the latter having potential to hinder subsequent atmospheric destabilization ahead of any approaching waves across the central U.S.

We agree that longer temporal averages of AO would be interesting to examine for the reasons cited by the reviewer. However, the goal of our limited AO analysis was to compare to the Hagemeyer (2010) results, making an analysis of longer temporal averages somewhat beyond the scope of this paper. We do now mention this potential extension of our teleconnection work in section 5 (future work).

The use of averages among cases is a valid approach to assessing environmental conditions ahead of the outbreaks, although there are probably additional ways to examine the possibility of individual outbreaks not following the overall trends described by averages. Additionally, it is possible that timeframes farther in advance of the outbreaks exhibit higher variability and hence lower averages compared to environments closer to the time of the outbreaks. To address this, I'd at least recommend visual/subjective inspections of the cases (since there are only 33) to identify and talk about specific events that may deviate from the averages. More sophisticated approaches to investigate this involve principal component analysis, self-organizing maps, etc.

We agree that using composite means, particularly in terms of convective parameters, was not the best methodology. We have addressed this concern by revising our mesoscale section (section 4) such that it analyzes the parameter space of Florida tornado events instead of composite means. The new box-and-whisker plots (new Figs. 10–12), an approach that has been used in recent severe convective environment papers (e.g., Anderson-Frey et al. 2019), do a much more complete job in assessing the distribution of convective parameters for our tornado and null events. The text in section 4 has been edited/rewritten accordingly.

A more-detailed analysis of the speed of fronts (an objective stated toward the end of section 1) may be helpful to include in this section, although in my opinion it is not absolutely needed, given the amount of great information provided in other portions of the manuscript.

We have removed this sentence. Frontal speed will definitely be explored as part of our future storm-mode analysis. However, it is beyond the scope of this manuscript.

The use of SCP alone cannot completely determine whether a case or group of cases contains discrete storms or quasi-linear convective modes. Tornado outbreaks often contain both. The assertion being made here would be more effectively made with a broader presentation of the outcomes of radar analysis.

We agree and these sentences have been removed. This issue will be addressed in future work.

[Minor comments omitted...]

Second Review:

Recommendation: Accept with minor revisions.

General Comment: The revisions in the latest submission strengthen an already substantial scientific contribution and I continue to recommend the manuscript for publication with only one minor suggestion for revision and three overall comments on the work. *[Editor's note: Since this was a very helpful suggestion that resulted in a substantive improvement to the manuscript, it is included here.]*

Revision suggestion: The authors address [reviewer's original comment on assessment of outlier events, averaging, and visual inspection of each of the 33 cases] by presenting box-and-whisker diagrams of various convective patterns, which is important but didn't directly address the revision suggestion. Within synoptic composites, there may be individual events that deviate from the averages of the remaining events. These deviations can be important factor for resultant severe weather occurrence, however. Were there specific tornado events that did not follow the average tornado event synoptic composite? (i.e., no geopotential height ridging along the east coast, or no geopotential height trough across the center of the country in advance of a tornado event).

We understand this common concern with composite means/anomalies and apologize for not addressing it in more detail in the first round of reviews. To alleviate the reviewer's concerns, we have produced "spaghetti" charts using the 5700-m geopotential height contour at 00 and −12 h. Each black contour in the four plots below (tornado and null cases, in that order) represents the 5700 m contour at 00 h for each case. The red line in each plot represents the composite mean 5700 m contour. As you can see, there was some minor variability in the upstream trough and downstream ridge, particularly in the null cases. Visual inspections of other times (−24 h, etc.) revealed a similar amount of variability. Admittedly there is more case-to-case variability over the western U.S., upstream of the key trough. However, this feature was not all that important to the synoptic-scale precursors and conditions during our tornado events. Should the *reviewer feel that spaghetti images such as the ones on the next page belong in the manuscript, we would be happy to add them.*

[Editor's note: The spaghetti charts originally appeared in the author's review reply. In consultation of editor and reviewer, we agreed that these would be insightful additions directly to the manuscript, given the common, familiar presence of such visualizations in operational ensembles used by forecasters.]

Section 3b: It is still a bit of a stretch to tie precipitable water content with high-precipitation supercells here.

We have modified the language in this sentence to eliminate the suggestion that high precipitable water values explicitly lead to rain-wrapped tornadoes.

The addition of null events to this analysis strengthens the manuscript substantially. Of particular interest is the notion that null events generally exhibit greater displacement of synoptic forcing away from Florida compared to tornado events. Similarly, the El Niño/La Niña cool-season teleconnection pattern generally shifts surface low tracks southward toward Florida in warm phases and away from Florida in cool phases (Eichler and Higgins 2006; Cook and Schaefer 2008; Cook et al. 2017). To my knowledge, the current study is actually the first to indirectly tie this information to SPC convective outlooks via the null-case definition. The question remains, however: how many of these null cases occur concurrent to La Nina conditions in the Pacific and vice versa?

We have added Table 2 to the manuscript, which repeats the ENSO/AO analysis in Table 1 for the null events. Of the 29 null events, 6 occurred during El Niño and 7 during La Niña, although the El Niño total is a bit biased by two sets of two events that occurred on consecutive days. Nevertheless, it does seem that null events are more characterized by La Niña than tornado events are. We have added a few paragraphs of text to section 3a to explain these results better and put them in context of previous work on this topic. We have also added the Eichler and Higgins (2006) study to the references (the other two studies mentioned by the reviewer were already cited in the manuscript).

[Minor comments omitted...]

REVIEWER B (Ariel E. Cohen):

Initial Review:

Recommendation: Accept with major revisions.

Substantive/Major Comments: The definition of a "tornado outbreak" varies considerably across a variety of contexts, from official forecasts to publications to media usage. However, the lower threshold used in this paper (i.e., 4 tornadoes occurring across the state of Florida within a 24-hour period) is considerably below what most people would link the term "outbreak". The AMS Glossary (http://glossary.ametsoc.org/wiki/Tornado_outbreak) suggests that, "In recent years, Galway (1977) has defined ten or more tornadoes as constituting an outbreak."—Galway, J. G., 1977. Some climatological aspects of tornado outbreaks. *Mon. Wea. Rev.*. **105**, 477–484. This was from a 1977 publication, when tornado reports—especially for weaker tornadoes—were far underrepresented compared to modern practices. As a result, I believe that the use of "outbreaks" in this work should be replaced by the phrase "events" or "episodes" or something less harsh than "outbreaks", or a much higher tornado-count threshold should be used.

Other reviewers also mentioned this point, which is a good one. We have replaced "tornado outbreak" with "tornado event" throughout the manuscript.

Within the extended range of years studied, and especially in May, were there any cases of season-peripheral tropical cyclone tornado episodes? If so, were they manually removed? I feel this needs to be addressed, as tropical cyclones have occurred outside the traditional season and could be associated with a tornado threat.

We examined whether some of our May events may have been associated with early-season TCs, using the NHC archives. During our study period, there were 8 TC cases that affected Florida outside of the typical Atlantic TC season (June–November). However, we found that only one of these were associated with a tornado report and none corresponded to our event dates.

Overall, we chose to focus on non-TC cases to analyze events that were associated with mid-latitude processes. While TC-related cases are interesting, they're often associated with different mechanisms and would have affected the integrity of our synoptic composites. We wanted this study to be an updated version of the Hagemeyer and Schmocker (1991) and Hagemeyer (1997) Florida tornado climatologies, as well as a complement to recent southeast U.S. severe convective environment work (e.g., Anderson-Frey et al. 2019; Childs et al. 2018).

There are two relevant publications that address low-CAPE high-shear tornado environments during the cold season and specifically focus on the southeast U.S. including a portion of Florida:

Cohen, A. E., S. M. Cavallo, M. C. Coniglio, and H. E. Brooks, 2015: A review of planetary boundary layer parameterization schemes and their sensitivity in simulating southeastern U.S. cold season severe weather environments. *Wea. Forecasting*, **30**, 591–612.

Cohen, A. E., S. M. Cavallo, M. C. Coniglio, H. E. Brooks, and I. L. Jirak, 2017: Evaluation of multiple planetary boundary layer parameterization schemes in southeast U.S. cold season severe thunderstorm environments. *Wea. Forecasting*, **32**, 1857–1884.

I make subsequent reference to these publications in the review here, so I encourage the authors to investigate both of these publications and provide some contextualization of their work into the already established near-storm mesoscale environment information that both of these publications demonstrate. This will especially be the case, as latter comments address my concerns regarding the application of a composite analysis to local-convective threat assessment.

We have added these two references to the manuscript and incorporate them into the text at various points, based on our own assessments and the reviewer's comments.

Parcel level/layer comprising CAPE needs to be specified.

McCaul and Weisman (2001) did not specify their parcel level/layer other than to say "bulk CAPE". We will assume for now that this is essentially the same as surface-parcel CAPE, so we have changed the text to "surface-parcel CAPE".

"CAPE" values (for mixed-layer parcel and surface parcel) notably below 800 J kg^{-1} are associated with tornadoes for southeast U.S. cold-season tornado environments—please reference second Cohen et al. document. In fact, of these environments, a large proportion of the distribution is associated with SBCAPE and MLCAPE below 800 J kg^{-1}. This is based on the actual near-storm mesoscale environment relevant to the individual tornado, rather than a regional composite. Please reflect these results. The nonlinear intensification of a perturbation-pressure pattern resulting from the interaction of any updraft and a strongly sheared wind profile can initiate with only a marginal amount of buoyancy present. Favorable shear indeed can drive these non-linear effects with SBCAPE or MLCAPE markedly below 800 J kg^{-1}, prolonging the duration of rotating convection.

We have added a short discussion of the Cohen et al. (2017) results here, emphasizing the reviewer's key point regarding non-linear interaction.

The use of semi-regional composite analysis to address ingredients favoring local-scale tornadogenesis is inherently inconsistent (i.e., inconsistent scales of analysis). Results may be misapplied through comparisons against other climatologies. However, this does not render statistical averages of sounding data at locations well removed from tornado reports relevant to describing the actual near-storm mesoscale environment of the tornado. This is a natural concern with attempting to composite together meteorological parameters characterizing multiple tornado events across the large state of Florida—where many points across Florida may not have been characterized by tornado-favoring environments while tornadoes elsewhere across the state are favored. The disparity between tornado location and representative parameter cannot be rectified when addressing the actual tornado environment, including specification of point parameters. The paper needs to be updated here and elsewhere to reflect these concerns. However, the concept of a larger-scale, synoptic composite can be relevant, as the scale of tornado occurrences across the broader state of Florida is much more comparable to a synoptic-scale-forcing domain. Analogously, individual tornadoes are much more comparable to the local near-storm mesoscale environment forcing, which is not addressed in this paper, and therefore the related parameters are not representative. I also encourage the authors to draw connections to the Cohen et al. works cited above, as they are directly in line with the HSLC regime focused on the Southeast States.

We have largely addressed these concerns through our revisions of the mesoscale section (section 4), with the box-and-whisker plots replacing the previous composite means. The methodology in choosing NARR sounding points to examine mesoscale parameters is now explained in section 4a.

We agree that the choice of sounding points is crucial and not necessarily representative of storm-scale environments. However, our new analysis addresses these issues and our explanation in the text at the start of section 4 better explains the associated caveats. We have also added references to Gensini et al. (2014) and King and Kennedy (2019), who examined and justified the use of the NARR to analyze severe convective environments.

This sentence: "In general, supercell environments are typically characterized by large CAPE and mixing ratios, strong 0–6-km vertical wind shear, low lifted condensation levels (LCLs), and strong ascent–forcing (e.g., Thompson et al. 2012; Anderson-Frey et al. 2016; 2017)," is a generalization and does not account for the vast variability among supercell environments. Low LCLs typically have been linked to more-favorable tornado environments, whereas for supercells alone, LCL heights can vary greatly; and work by Hart and Cohen (Hart, J. A. and A. E. Cohen, 2016: The Statistical Severe Convective Risk Assessment Model. *Wea. Forecasting*, **31**, 1697–1714.) casts question on the use of LCL height for tornado predictability, overall. More concerning, strong ascent tends to support more linear modes owing to the larger number of convective elements developing and interacting with one another; this is at odds with the assertion provided in this paper. As a result, the subsequent conclusion that the capabilities for supercell assessment across Florida is limited needs to be restructured. The notion that individual cells can develop along weak-ascent foci within an adequately buoyant and sheared environment applies to Florida as much as it does anywhere else, and this paragraph and others that make the Florida problem seemingly unique need to be adjusted to make it clear that Florida tornado environments may tend to be skewed to specific parts of the spectra of convective ingredients, but it's the same basic ingredients that must be met for tornadoes in Florida as anywhere else.

We have largely rewritten this paragraph to address the reviewer's concerns. Specifically, we have removed any mention of LCLs and focus on the differences in the parameter space/environments between Great Plains supercellular tornado environments and Southeast tornado environments, including Florida. References to Cohen et al. (2015, 2017) have also been added to this paragraph.

The reference to "vertical wind shear" needs to be modified by a defined layer—even a general description like "deep layer". This comment applies to this section and the remainder of the paper.

The Hagemeyer and Schmocker (1991) and Hagemeyer (1997) studies used 0–6-km vertical shear, as do we (section 4). Therefore, we now use that descriptor throughout the manuscript.

The idea that tornado outbreaks occur in association with cold front further reiterates my concern for mixing spatial scales. Inherently, cold fronts are associated with comparatively stronger, more-abrupt ascent than pre-frontal confluence axes/troughs, leading to more contiguous line development. Moreover, typically, the warm sector in which a low-level confluence axis exists is bounded by a cold front on its western and/or northern periphery. So, even if tornadoes are occurring in the warm sector bound by a cold front, the cold front may have little to do with the enhancement or mitigation of tornadogenesis—and often for fast-moving cold fronts, there is a proclivity to undercut incipient updrafts by theta-e deficits (reinforced at the larger scale, making tornadogenesis even more challenging). As a result, the use of the term “association” here and elsewhere in the context of linking Florida tornado events/episodes with cold fronts needs to be modified to account for the appropriate scale of interaction. Just because there’s a cold front around at the larger-scale does not mean that the much smaller-scale tornado processes experience any governing influence by the front, rendering the phrase “association” problematic. This needs to be re-considered here and throughout the manuscript.

We essentially had to make a choice between adding the null cases or adding a more in-depth storm-mode analysis. We have completed both, but it is just too much information for one manuscript. We chose to add the null cases to facilitate a comparison with the tornado events. The storm-mode analysis will be addressed in a future manuscript, which we now explain at the appropriate times in the current paper. In this manuscript, most mentions of fronts, frontal speed, and storm mode have been removed.

The planned storm-mode analysis will include an investigation of the role and speed of fronts. Our early results indicate that Florida tornado events are relatively evenly split between isolated supercell and QLCS events.

PVA is not a forcing term for vertical motion; differential PVA is. Please explain the relationship between the upper- and lower-jet coupling and boosted differential PVA if this description is to be maintained.

Another reviewer had a similar concern. We have edited the text to focus on the upper-level divergence associated with the left exit of a subtropical jet streak and/or the right entrance of a polar jet streak. In addition, we now use DPVA throughout the manuscript. As the reviewer points out, it is DPVA associated with forcing for ascent, not PVA.

As with [a comment above], a concern with the compositing is that the actual magnitudes of averaged variables from the composite analyses do not have direct relevance on any given magnitudes in an instantaneous analysis. Given the large state of Florida and various locations of tornadoes, a different position of say an 80-kt (41-m s^{-1}) cyclonically curved speed maximum for each case will be manifest as a much-reduced speed maximum in the composite analysis. However, this actual magnitude and its qualifier are not representative of any individual case. As such, the verbiage throughout this section needs to reflect the scope of a more regional-scale analysis.

We have adjusted the verbiage throughout section 3 such that it reflects our plots, which are regional composites. We believe the new mesoscale analysis in section 4 also helps to address this issue through the presentation of parameter spaces instead of composite means only.

Theta-e anomalies are not advected. Moisture and heat can be advected, resulting in anomalies, but equations specifying local time derivatives of temperature and mixing ratio address the base variables.

We have edited the theta-e discussion to eliminate mention of “advected anomalies”.

Section 4c provides a very lacking description of what factors were used to assess/assign convective mode, how the radar study was carried out, and how the analyses were performed to yield the assertions. Please remove this discussion, as it is not reproducible in its expression. See publications from Thompson and Smith and others associated with their work for examples of reproducible radar analyses.

The radar discussion has been removed. The storm-mode analysis will be a focus of future work, as now discussed in section 5. Thank you for the reproducible radar analysis citation, we will utilize it in future work.

I would like to see some discussion of improving Florida tornado event/episode anticipation via numerical weather prediction. Both Cohen et al. publications cited above offer ways in which the mass, heat, and momentum fluxes within the planetary boundary layer critically influence convective evolution, and the parameterization of this component of the atmosphere is associated with substantial sensitives in the thermodynamic parameter space for southeast cold-season environments. The relationship between these contentions and observed environments could yield a roadmap forward for identifying ways in which numerical modeling could be improved to better simulate related environments. I'd like to see some discussion tying these concepts together in order to identify future courses for improving numerical weather prediction simulations of these environments – given the increasing role of convection-allowing model guidance. While this may seem to be outside the present scope of the paper, it is a natural follow-on to the composite analysis whose aim it is to identify ways of forecasting this phenomenon. I'm asking for a synthesis of the results in terms of previous work across this regime – not necessarily new research from the authors here.

We have added mention of these issues to the revised conclusions/future work section. We certainly agree that the predictability aspect is a very worthwhile pursuit in future work.

[Minor comments omitted...]

Second Review:

Recommendation: Accept with minor revisions.

General Comment: This is a SERIOUS SERIOUS improvement over what I originally saw. It is truly impressive how much the authors improved their work and very respectfully addressed all reviewers' concerns. This is excellent. I have super-minor edits listed below. No need for me to see this again—great work, everyone!

The authors thank the reviewer for his constructive comments and advice toward improving the manuscript, and we are glad that the revised version is a substantial improvement!

[Minor comments omitted...]

REVIEWER C [Vittorio (Victor) A. Gensini]:

Initial Review:

Recommendation: Revisions required.

Overview:

- The authors present a straightforward synoptic composite analysis of tornado events over Florida spanning the NARR temporal record. They identified 33 cases for examination, using a threshold of 4 tornadoes in 24 hours as an event. Results presented are strongly correlated with our current understanding of synoptic scale conditions that create environments favorable for tornado events.
- I have a number of major and minor comments that I have brain dumped below.
- I found the paper to be well written and free of any major grammatical errors.
- My recommendation is to accept the manuscript pending future revisions.

Major Comments: The authors write, "The goal of the current study is to help forecasters predict tornado outbreaks in Florida by updating the Hagemeyer (1997) proximity sounding climatology using modern reanalysis data." I suggest modification of this sentence, as little/no work is done herein on the prediction angle of these events.

We have changed this to represent that we are investigating tornadic environments in Florida, not predictability. We have also largely rewritten this paragraph to reflect the revised manuscript.

Thirty-three cases were examined, which only compromises ≈0.002% of all days during the study period. The authors state in the abstract, "Results showed that Florida outbreaks were associated with fast moving cold fronts, the divergent exit region of the subtropical jet, a strong negatively tilted mid-tropospheric trough, low cloud bases, and a high-shear low-CAPE environment that is typical of southeastern United States tornado events." Surely there are "null" events that also have such ingredients that fail to produce tornado events across Florida. Relating to Major Comment 1, I would think that this would be an important area to pursue if the authors are truly wanting to, "help forecasters predict tornado outbreaks in Florida" by examining some of the failure mechanisms and null events that may prove to be a majority of the database.

We did in fact examine 29 "null" events in which SPC had ≥5% tornado probabilities for Florida but 0–3 tornadoes occurred in a 24-h period. Although we were originally going to save the null case analysis for future work, reviewer comments made us reconsider and decide to insert them in this manuscript. In section 2, we explain the null event identification methodology. Section 3c details the new Figs. 6–9 (null event synoptic composites) and null event mesoscale parameters are analyzed and compared to tornado events throughout section 4.

Outbreaks have a specific definition in the literature. I'd suggest changing all of your outbreak wording in the manuscript to "tornado events."

We agree and have changed "tornado outbreak" to "tornado event" throughout the manuscript, including the title.

Section 3a: Several references are missing to previous work on ENSO and MJO tornado relationship in the U.S. Would suggest a thorough literature search here to bolster this section. In addition, the GWO has been shown to have a significant relationship to U.S. tornado activity in recent research. I would either a) remove all background discussion except ENSO (given that is all you are examining here) or b) beef up this section to include the full body of previous work that has been performed on teleconnections and U.S. tornadoes (e.g., add in analysis of MJO etc.).

Given the amount of new material that we have added to the manuscript (i.e., the null events), we have decided to take the reviewer's first suggestion and limit this section to largely just discuss ENSO. However, at the beginning of section 3a, we did add references for the GWO (Gensini and Marinaro 2016) and a couple of other recent teleconnection-tornado papers (Molina et al. 2018; Tippett 2018). Molina et al. (2018) is particularly relevant to our ENSO analysis, so we also refer to it later in section 3a. Finally, at the start of the second paragraph of section 3a, we state that we are limiting our teleconnection analysis in this manuscript to ENSO and AO, following Hagemeyer (1997; 2010). While other teleconnections like MJO are certainly interesting, they are not a focus of this manuscript.

Related to Major Comment 2: Is [33 tornado events] a robust-enough sample to say anything meaningful? I do agree that it compares well to previous research, but I'm unsure with a sample size of 33 if the authors can really say anything statistically significant about these teleconnection results. As a forecasting example, given a positive ONI state, what is the likelihood that any given day will be a Florida tornado day?

We agree that our conclusions should not be interpreted as broad statistically significant assessments given the relatively small sample size (33 events). However, we feel it is noteworthy that our ENSO analysis found results similar to other recent studies (e.g., Childs et al. 2018; Molina et al. 2018). We have added a paragraph to the end of section 3a that explains this point and refers the reader to a new brief discussion of future teleconnection work in section 5.

Figure 6: I'm not sure what levels the authors are averaging for their interpretation of MLCAPE. In addition, AGL heights (e.g., 6-km) are not standard NARR levels. Please include the methodology for calculation of these fields so that the study is reproducible.

In the revised manuscript, all mesoscale parameters (section 4) were calculated from the NARR using SHARPpy defaults, which correspond to the SPC definitions of each parameter. For SRH, we now use 0–1- and 0–3-km values instead of ESRH.

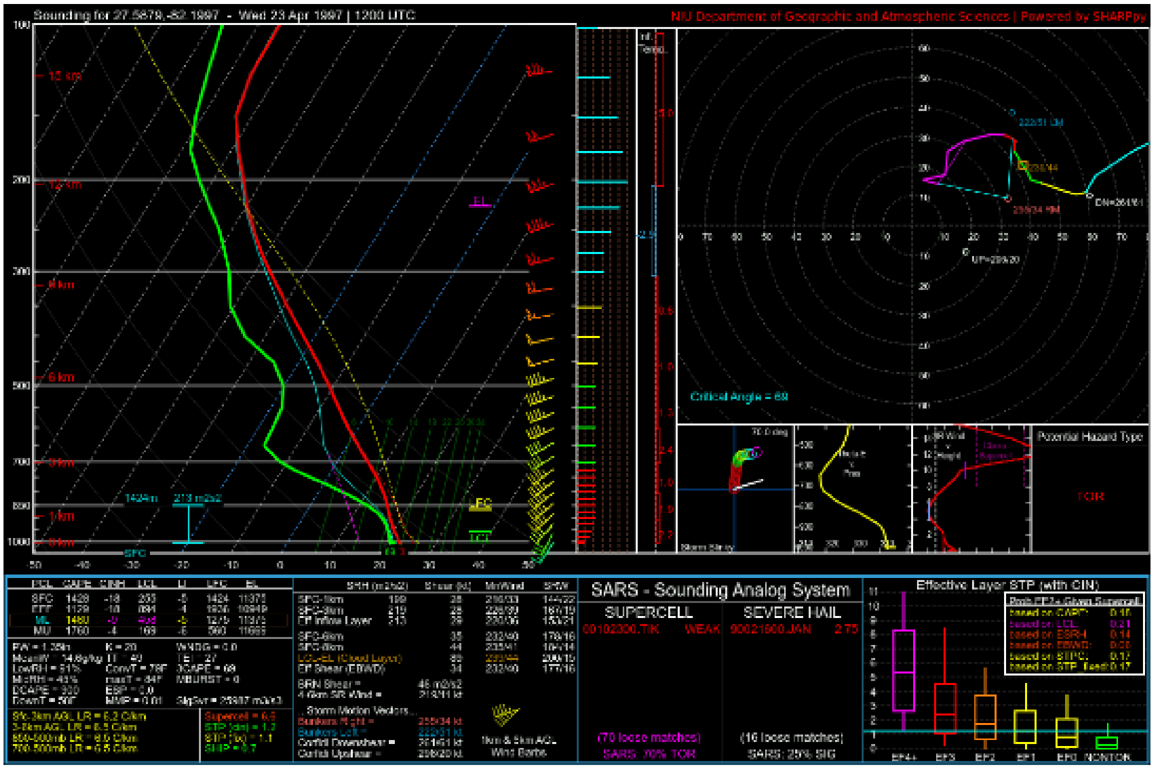
One potential issue that I am seeing is that the authors seem to be drawing conclusions in their results section from the *composite mean* of all cases. I think describing these cases in the context of their entire distribution of values (max, min, stdev, etc.) would be more helpful for potential forecasting applications.

We have addressed this concern by revising most of our mesoscale section (section 4) such that it analyzes the parameter space of Florida tornado events instead of composite means. We feel that the box-and-whisker plots (new Figs. 10–12), an approach that has been used in recent severe convective environment papers (e.g., Anderson-Frey et al. 2019), do a much more complete job of assessing the distribution of convective parameters for our tornado and null events. The text in section 4 has been edited/rewritten accordingly.

I'd suggest that a novel aspect to this paper might be to do further analysis related to storm mode. For example, are there any noticeable differences in the environment between the QLCS and discrete supercell events?

We essentially had to make a choice between adding the null cases or a more in-depth storm mode analysis. We have completed both, but it is just too much information for one manuscript. We chose to add the null cases to facilitate a comparison with the tornado events. The storm mode analysis will be addressed in a future manuscript, which we now explain in section 5.

Section 4d [(former) Fig. 8]. I didn't find these soundings to be particularly helpful as a means to communicate the thermodynamic environment to readers/forecasters. They are (not surprisingly) washed out due the compositing and likely not representative of any one particular event. As one example, I pulled a 1200 UTC NARR sounding from Tampa, FL area for your biggest event (19970423): There are distinct differences that are noted in both the kinematic and thermodynamic fields (available via https://atlas.niu.edu/narr):



My point here is that from a forecasting perspective (going back to the goal of the paper), a composite mean sounding is not likely to be of much help in an operational setting given the inter-event variability in the environment.

Please see our response to Major Comment 7. We believe the new box-and-whisker plots in section 4 address this issue.

I strongly encourage the authors to examine [null] cases and include them in this study. This would add a nice degree of novelty to this study and greatly benefit operational forecasters.

Please see our response to Major Comment 2. We have added the null-event analysis.

[Minor comments omitted...]

Second Review:

Recommendation: Accept.

I found that the authors addressed my major and minor comments in a satisfactory fashion, and thus, I recommend the article for publication. I thank them for the additional work of adding the null events to strengthen their analysis.

The authors thank the reviewer for his constructive comments and advice toward improving the manuscript.