Convective Storm Structures and Ambient Conditions Associated with Severe Weather over the Northeast United States

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ABSTRACT

This study documents the convective storm structures and ambient conditions associated with severe storms (wind, hail, and tornado) over the northeastern United States for two warm seasons (May–August), including 2007 and a warm season comprising randomly selected days from 2002 to 2006. The storms were classified into three main convective organizational structures (cellular, linear, and nonlinear) as well as several subcategories. The same procedure was applied to the highly populated coastal zone of the northeastern United States, including New Jersey, Connecticut, Rhode Island, and New York. The coastal analysis included six warm seasons from 2002 to 2007. Over the Northeast, severe wind events are evenly distributed among the cellular, linear, and nonlinear structures. Cellular structures are the primary hail producers, while tornadoes develop mainly from cellular and linear structures. Over the coastal zone, primarily cellular and linear systems produce severe wind and hail, while tornadoes are equally likely from all three convective structures. Composites were generated for severe weather days over the coastal region for the three main convective structures. On average, severe cellular events develop during moderate instability [most unstable CAPE (MUCAPE) ~1200 J kg^{-1}], with low-level warm-air advection and frontogenesis at the leading edge of a thermal ridge collocated with an Appalachian lee trough. Severe linear events develop in a similar mean environment as the cellular events, except that most linear events occur with a surface trough upstream over the Ohio River valley and half of the linear events develop just ahead of progressive midlevel troughs. Nonlinear severe events develop with relatively weak mean convective instability (MUCAPE ~460 J kg^{-1}), but they are supported by midlevel quasigeostrophic (QG) forcing for ascent.

1. Introduction

The investigation of severe convective weather over the northeastern United States (hereafter referred to as Northeast) has received less attention than that in the central United States. This is likely because of the fewer number of severe weather events over the Northeast as compared to the central Great Plains and Midwest (Brooks et al. 2003; Doswell et al. 2005). The Northeast can experience severe warm season (May–August) storms, which can pose a large threat to life and property, especially in the highly populated New York City (NYC) coastal zone (New Jersey, New York City, Long Island, Connecticut, and Rhode Island), where the population density (~493 people per square kilometer) is 24 times greater than that in Oklahoma.

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Severe weather has caused millions of dollars in damage as well as loss of life over the Northeast. For example, on 29 May 1995, the F3 (using the Fujita scale) Great Barrington, Massachusetts, tornado killed 3 people, injured 29, and caused $35 million in damage (LaPenta et al. 2005; Bosart et al. 2006). On 21 May 1998, an F3 tornado passed through Mechanicville, New York, injuring 68 people and causing $71 million in damage (LaPenta et al. 2005). More recently, on 8 August 2007, an EF1 tornado (using the enhanced Fujita scale) touched down on Staten Island, New York, with no warning lead time, with a second touchdown (EF2) in Brooklyn, New York, about 10 min later (National Weather Service, Upton, New York).

Several studies have investigated the synoptic conditions that support severe weather over the northeastern United States. Giordano and Fritsch (1991) examined the synoptic and thermodynamic conditions associated with strong tornadoes (≥F3) and flash flooding events over the mid-Atlantic. A majority of strong convective events had 500-hPa southwest flow, cyclonic directional wind shear through the boundary layer, enhanced low-level moisture, and convective available potential energy (CAPE) exceeding 3000 J kg^{-1}. Strong tornadoes were shown to occur primarily on the warm side of frontal boundaries, while heavy rain events developed on either side of the boundary. Johns (1982) examined warm season severe weather outbreaks over the United States, including the Northeast, which develop under 500-hPa northwesterly flow. These outbreaks occur with 850-hPa warm-air advection, conditional instability, and a 500-hPa short-wave trough embedded within the northwesterly flow that can help provide midlevel ascent (Johns 1984). Over New England and eastern New York during the warm season, relatively strong (F2 and F3) and violent (F4 and F5) tornadoes form ahead of a surface cold front and occur more frequently under 500-hPa westerly and northwesterly flow than southwesterly flow (Johns and Dorr 1996).

The elevated mixed layer (EML), a layer of enhanced lapse rates above the surface that originates over the higher terrain of the western United States (Carlson and Ludlam 1968), is often associated with severe weather over the Northeast. The most violent tornadoes in the Northeast are often associated with an elevated mixed layer (Johns and Dorr 1996). Farrell and Carlson (1989) discussed the importance of elevated instability during the 31 May 1985 tornado outbreak that occurred over parts of Pennsylvania and New York. Banacos and Ekster (2010) showed that the horizontal advection of EMLs from the western United States toward the Northeast is the dominant reason for the existence of EMLs over the Northeast.

The complex topography of the Northeast has been shown to influence the development of severe weather. Wasula et al. (2002) linked the spatial distribution of severe events over New England to the influence of terrain under southwesterly and northwesterly 700-hPa flow. More specifically, it has been suggested that terrain channeling plays an important role in tornadogenesis for a number of events in New England by accelerating the surface flow and thus increasing shear in the lowest kilometer. On 29 May 1995 in Great Barrington, tornadogenesis occurred due to the merger of flow channeled up the Hudson River valley with accelerated flow down the Catskill Creek (Bosart et al. 2006). The 31 May 1998 Mechanicville tornado formed as a supercell interacted with southerly flow up the Hudson River valley (LaPenta et al. 2005).

Previous literature has highlighted the synoptic conditions that support severe weather over the Northeast as well as the influence of terrain on convection, though the focus was primarily on tornadoes. More understanding is needed of the organizational convective structures capable of producing the various severe weather types (strong wind, hail, and tornadoes) over the Northeast, as well as the associated synoptic patterns, instability, and vertical shear with each severe convective structure. For the central United States, Gallus et al. (2008) identified nine convective structures (i.e., cellular, linear, nonlinear) and discussed the risk of severe weather (wind, hail, tornadoes) posed by each. Duda and Gallus (2010) expanded the analysis to include the development of severe weather by supercells over the central United States. Lombardo and Colle (2010) followed the methods of Gallus et al. (2008) to identify various convective organizational structures over the Northeast during two warm seasons (May–August), though their focus was on all convective storms. Therefore, there has been no systematic study identifying the convective structures associated with severe weather over the northeastern United States.

The coastal marine environment may modify the distribution of severe convective storms over the Northeast (Murray and Colle 2011), but this has not been well studied from a convective structure and ambient condition perspective. Murray and Colle (2011) showed that severe weather over eastern Long Island develops with a low-level trough positioned along the coastline, with low-level westerly flow advecting conditionally unstable air from the inland areas over the island. Presently, there is no work addressing the ambient conditions associated with severe weather from different convective structures along the densely populated coastal region of the Northeast.

Overall, this study will address the following motivational questions:

- What is the type and frequency of severe weather associated with various convective organizational structures over the Northeast? How does this compare to the central United States?
- How does the type of severe weather produced by specific convective organizational structures over the entire northeastern United States compare with that over the Northeast's southern coastal region?
- What are the lifting mechanisms and thermodynamic conditions associated with severe weather over the coastal region, and how do they vary between convective organizational structures (i.e., cellular, linear, nonlinear)?

Section 2 describes the data and methods used in this study. Section 3 highlights the severe weather type associated with each convective organizational mode. Section 4 presents the synoptic and thermodynamic conditions associated with severe weather produced by each type of organized convection. Northeastern U.S. severe weather

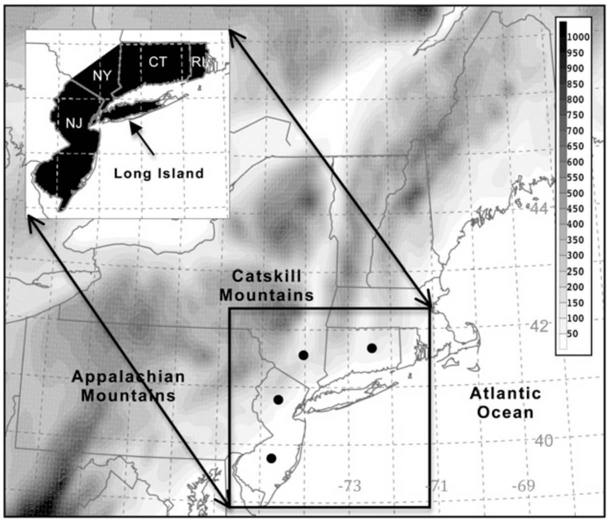

FIG. 1. The northeastern United States and its coastal domains (see black region in inset panel) as used in this study. State abbreviations in the black box are NJ = New Jersey, NY = New York, CT = Connecticut, RI = Rhode Island. The four points used for average box-and-whisker plots (Fig. 12) are also shown. The latitude and longitude of these points are (39.8°N, −74.7°W) in southern NJ, (40.7°N, −74.5°W) in northern NJ, (41.5°N, −74.0°W) in NY, and (41.7°N, −72.6°W) in CT. Terrain is gray shaded every 50 m.

is compared to events over the central United States in section 5. The detailed synoptic and thermodynamic patterns associated with the severe convective types over the northeastern United States could not be compared to those in the central United States, since Gallus et al. (2008) did not complete a synoptic breakdown associated with the various severe convective structures. Rather, we make several qualitative comparisons of various parameters between the Northeast and other studies investigating central Great Plains convection. Conclusions and future work are discussed in section 6.

2. Data and methods

Severe weather climatology

This paper classifies the organizational structures of convection over a domain covering the northeastern United States (Fig. 1) using the approach described in Lombardo and Colle (2010) and Gallus et al. (2008). For this study, the Northeast includes land areas only, excluding the Atlantic Ocean, since severe reports are typically only reported over land (Fig. 1). In Lombardo and Colle (2010), the convective structures over the northeastern United States were categorized through the manual examination of 2-km National Operational Weather Radar (NOWrad) reflectivity imagery every 15 min over two warm seasons (May–August), including 2007 and a second warm season of days randomly selected from 1 May to 31 August 2002 to 2006. The aggregate season was generated to compensate for the relatively large interannual storm frequency variability (Murray and Colle 2011). The dataset was used in this study, except that only those convective storms that produced severe weather were included in this climatology. Similar to Lombardo and Colle (2010) and Gallus et al. (2008), the convective storms were categorized into three types of cellular convection (individual cells, clusters of cells, and broken lines), five types of quasi-linear systems (bow echoes, squall lines with trailing stratiform rain, lines with leading stratiform rain, lines with parallel stratiform rain, and lines with no stratiform rain), and nonlinear systems (cf. Fig. 2 in Lombardo and Colle 2010).

The severe weather days for the 2007 and aggregate warm seasons were identified utilizing both the Storm Prediction Center (SPC) and National Climatic Data Center (NCDC) storm report archives. Over the Northeast, there were 310 severe weather events (2912 reports) over 118 days during the two warm seasons. A severe event is defined when a convective element produces at least one report of severe weather. Within one event, multiple reports may be recorded. Each storm report was manually matched to the convective structure that produced it. To increase the sample size of northeastern U.S. tornadoes, tornado reports were included for years when there is available NOWrad data (May–August 1996–2007), thus increasing the number of tornado reports from 56 (2002–07) to 229 (1996–2007). Due to the differing record lengths between the tornado dataset (12 warm seasons) and the wind/hail dataset (2 warm seasons), it should be noted that a direct comparison could not be made between these datasets.

The convective classification was repeated for severe weather events over the Northeast's southern coastal region, which includes New Jersey, Connecticut, Rhode Island, and several counties in southern New York (Fig. 1). For this coastal region, a similar identification and matching procedure was performed as described above for the Northeast; however, all six full warm seasons were used (May–August) from 2002 to 2007 in order to increase the sample size for the relatively small domain. In total, there are 256 severe events (1196 reports) over 166 days. For the coastal tornado events, an expanded dataset of tornado reports was generated from May to August of 1996–2007, which increased the number of the coastal tornadoes from 19 (2002–07) to 41 (1996–2007). As with the Northeast data, the coastal tornado data and wind/hail data could not be directly compared with the coastal wind/hail results given the different sets of years used.

Spatial composites of the ambient conditions were generated for the severe events over the coastal region. Since the impacts of the Northeast interior terrain on severe convection have been well documented (Wasula et al. 2002; LaPenta et al. 2005; Bosart et al. 2006), we focused our larger-scale composites near the less well-studied coastal region. To evaluate the synoptic and thermodynamic conditions that support severe weather over the coastal zone, spatial composites were constructed using the North American Regional Reanalysis (NARR) at 32-km grid spacing (Mesinger et al. 2006) for cellular (49 events), linear (45 events), and nonlinear (15 events) severe events from 2002 to 2007. For the composites, we used the closest 3-h NARR time prior to the first severe weather report of a particular convective element. Since the coastal area of interest is relatively small, compositing with respect to geography preserves most of the flow structures associated with each event type while still relating the atmospheric features to various terrain and coastal features (i.e., Appalachian Mountains, Atlantic coastal boundary). Variables such as 2D Miller (1948) frontogenesis and horizontal temperature advection are plotted at the levels in the lower troposphere at which the magnitudes are maximized.

Box-and-whisker plots were generated to illustrate the spread of the magnitude of particular atmospheric variables (e.g., most unstable CAPE, vertical shear) for each severe event type with the same convective structure. Rather than calculating area-averaged values over the full coastal domain (shaded area in Fig. 1), which would include some values over water interpolated to the coast areas given NARR's 32-km grid spacing, the atmospheric variables were taken from four representative points within the center of the coastal zone (Fig. 1), and those values were then averaged. These four points were moved to other inland locations within the coastal region, and the results did not change. Most unstable convective available potential energy (MUCAPE) is found by calculating CAPE using the equivalent potential temperature (θ_e) in each 30-hPa layer from 0 to 180 hPa above the surface and retaining the maximum CAPE value. Wind shear values are calculated using a vector difference between two layers (e.g., 0–1 km).

3. Northeast convective storm structures and severe weather

Figure 2 shows the percentage of severe events produced by each of the nine convective organizational structures over the Northeast. While linear structures are the least common organization mode, composing only a fifth of all convective modes (see Fig. 3 in Lombardo and Colle 2010), they are responsible for one-third of all severe events (Fig. 2). Conversely, approximately half of all warm season convection organizes into cellular structures (Lombardo and Colle 2010), but they contribute to only ~39% of the severe events (Fig. 2). Nonlinear systems compose about one-third of all summertime convection as well as severe events.

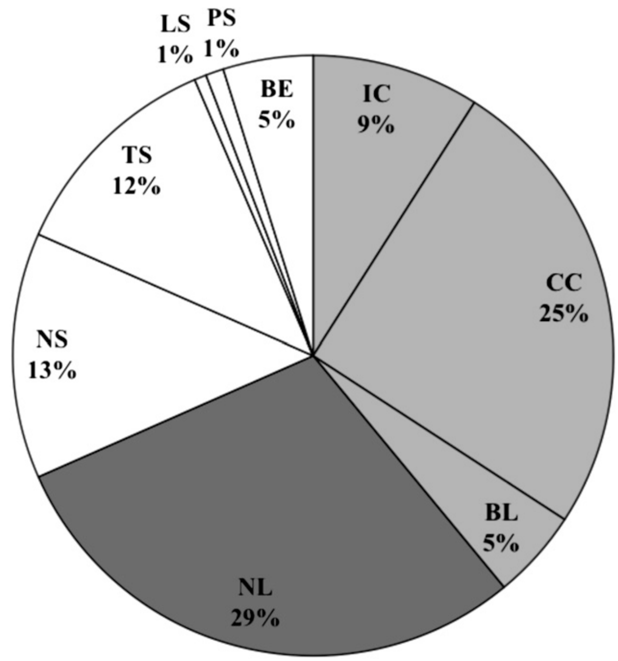

FIG. 2. Percentage of severe events over the northeastern United States produced by each of the nine convection structures, including isolated cells (IC), clusters of cells (CC), broken lines (BL), nonlinear (NL), no stratiform linear (NS), trailing stratiform linear (TS), leading stratiform linear (LS), parallel stratiform linear (PS), and bow echoes (BE), examined during the 2007 and aggregate (2002–06) warm seasons (May–August). Cellular events are lightly shaded, nonlinear events are darkly shaded, and linear events are not shaded.

Figure 3 illustrates the number of severe events, separated into severe wind, hail, and tornado events, associated with each of the nine organizational structures over the northeastern United States. A bootstrap method (Zwiers 1990) was applied to the distribution of each type of severe event (wind, hail, tornadoes) to test for statistical significance between the nine groups (e.g., clusters of cells, nonlinear). For each severe event type, a new distribution of convective structures of the same size was generated 1000 times by randomly selecting from the original sample. The 95% confidence intervals for each convective structure were determined by finding the 2.5th and 97.5th percentiles of the sum of severe events (e.g., wind) produced by that particular convective type of the 1000 resamples. When comparing the results from the various severe weather types, if the 95% confidence intervals

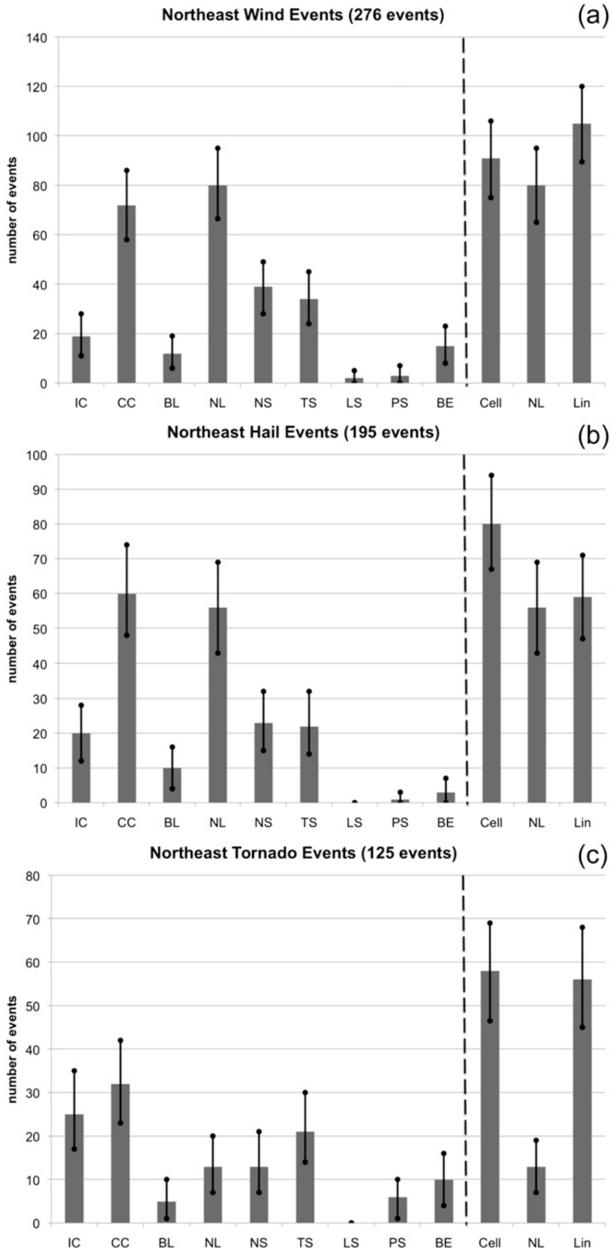

FIG. 3. Number of northeastern U.S. severe (a) wind and (b) hail events from the 2007 and aggregate (2002–06) warm seasons (May–August), and (c) tornado events from the 1996–2007 warm seasons for each of the nine convective types individually and grouped into the three main organizational types (cellular, nonlinear, linear). Error bars (solid black) mark the range of the 95% significance level.

between the organizational structures do not overlap, the results are significantly different.

Severe (high) wind is the most common severe weather type over the Northeast (Fig. 3a) totaling 1969 wind reports, or 67.6% of the severe reports from the 2007 and aggregate warm seasons. The numbers of severe wind events for each of the three main convective types (cellular, linear, nonlinear) are comparable. However, differences arise when considering the contribution to severe wind events from each of the individual nine substructures. For cellular structures, clusters of cells produce significantly (95% confidence) more severe wind events than isolated cells, while for linear convection, linear convection with no stratiform and trailing stratiform precipitation produce significantly more (95% confidence) severe wind events compared to the other linear types (leading stratiform, parallel stratiform, and bow echoes). Nonlinear convection is associated with roughly eight or more severe wind events compared to cellular clusters, though this difference is not statistically significant.

Hail reports compose approximately one-third of all severe weather reports (927 reports) over the northeastern United States during the two warms seasons. Cellular convection is responsible for ~1.3 times as many hail events as both linear and nonlinear systems (85% significance level; not shown). Clusters of cells are the primary cellular structures responsible for the hail events, with nonlinear convection producing only slightly fewer (about four) events, although the difference is not statistically significant. Linear systems with trailing stratiform and no stratiform rain are the most common hail-producing linear structures.

For the expanded 1996–2007 year period with 229 tornadoes, Northeast cellular and linear convection produces approximately the same number of tornado events (about nine per year), which is significantly (95% confidence) more than produced by nonlinear systems (about two per year; Fig. 3c). Considering the individual cellular structures, there is no statistical difference between the number of isolated cells and clusters of cells that produce tornado events. The same is true for the five types of linear structures.

To assess the risk of severe weather from each organizational structure, the number of severe reports per event (severe and nonsevere) was calculated for each of the nine convective types over the Northeast (Fig. 4). The number of reports depends not only on the severity of the storm, but also on the storm's areal coverage (e.g., trailing stratiform lines cover a greater area than isolated cells) and the storm's duration. Of the nine convective types (Fig. 4a), lines with trailing stratiform precipitation have the greatest frequency of severe wind (5.9 reports per event), followed by bow echoes (3.3 reports per event). Although convective lines are less common than cellular and nonlinear convection (Lombardo and Colle 2010), linear systems result in more severe wind reports per event at the 99% significance level (not shown). The other organizational structures only produce up to about two reports per event. However, for cellular convection, cellular

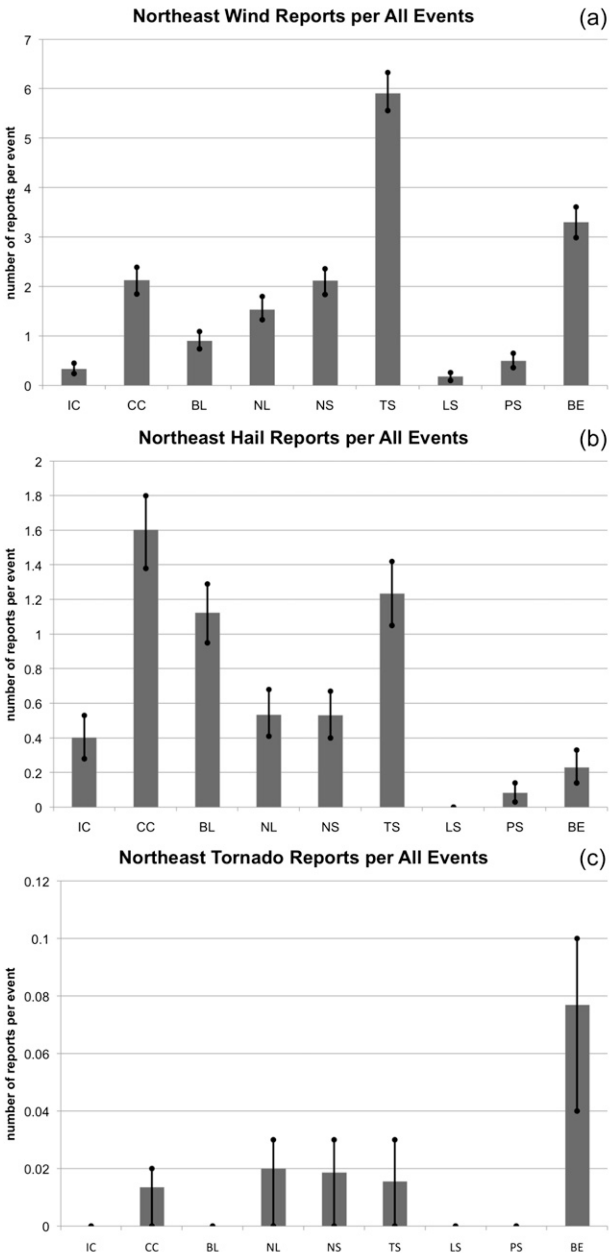

FIG. 4. Number of severe reports per total number of events for each of the nine organization structures over the Northeast using data from the 2007 and aggregate (2002–06) warm seasons for (a) wind (b) hail, and (c) tornadoes.

clusters have 7 times the number of reports per event (2.1) compared to isolated cells (0.3). Therefore, not only are cellular clusters more common than isolated cells (Lombardo and Colle 2010), they are also more likely to produce more severe wind.

Cellular clusters produce the greatest number of hail reports per event [95% level with the exception of trailing stratiform (TS) systems at 90%], with 1.6 reports per event, which, compared to other cellular structures, is 1.5 times greater than for broken lines and 4 times larger than for isolated cells (Fig. 4b). For linear systems, the largest frequency of hail reports is from trailing stratiform lines, followed by lines with no stratiform, bow echoes, and line-parallel stratiform systems. No leading stratiform lines produced hail in our dataset. Nonlinear systems produce only 0.5 hail reports per event. Northeast tornado frequency is dominated by bow echoes (Fig. 4c). Cellular clusters, nonlinear systems, and lines with trailing and no stratiform have similar frequencies, while the remaining convective structures produced no tornadoes in the period of study (Fig. 4c).

4. Coastal convective storm structures and severe weather

a. Distribution

The type of severe weather threat posed by organized convection over the Northeast coastal region (cf. Fig. 1) differs from that of the Northeast as a whole. Over the 2002–07 warm seasons, there are 1196 coastal storm reports: 76.7% for high wind, 21.7% for hail, and 1.6% for tornadoes. As compared to the fractional breakdown of severe weather types over the Northeast, the percentage of severe wind reports over the coastal area is 9.1% larger, the percentage of tornado reports near the coast doubles to 1.6%, and hail reports are ~10% less common over the coastal zone.

Coastal wind events are primarily caused by cells and lines (Fig. 5a), with only ~11% of severe wind events produced by nonlinear convection. Clusters of cells are statistically (95% confidence) the most common cellular structure associated with high-wind events, while linear systems with trailing stratiform and no stratiform precipitation are the most common linear structures (95% confidence).

Cellular convection is associated with the largest number of coastal hail events at the 95% significance level, followed by linear convection, then finally nonlinear convection (Fig. 5b). While clusters of cells produce a larger number of hail events compared to isolated cells, this difference is not statistically significant. Linear structures with trailing stratiform and no stratiform precipitation are the most common linear structures associated with hail events at the 90% significant level (not shown).

Coastal tornado events are not produced by any one preferred convective organizational structure (Fig. 5c). One reason may be the limited sample size of events (41 tornadoes, 27 tornado events), but the results suggest that tornadoes over the Northeast coastal zone are equally likely to develop from cellular, linear, and nonlinear structures.

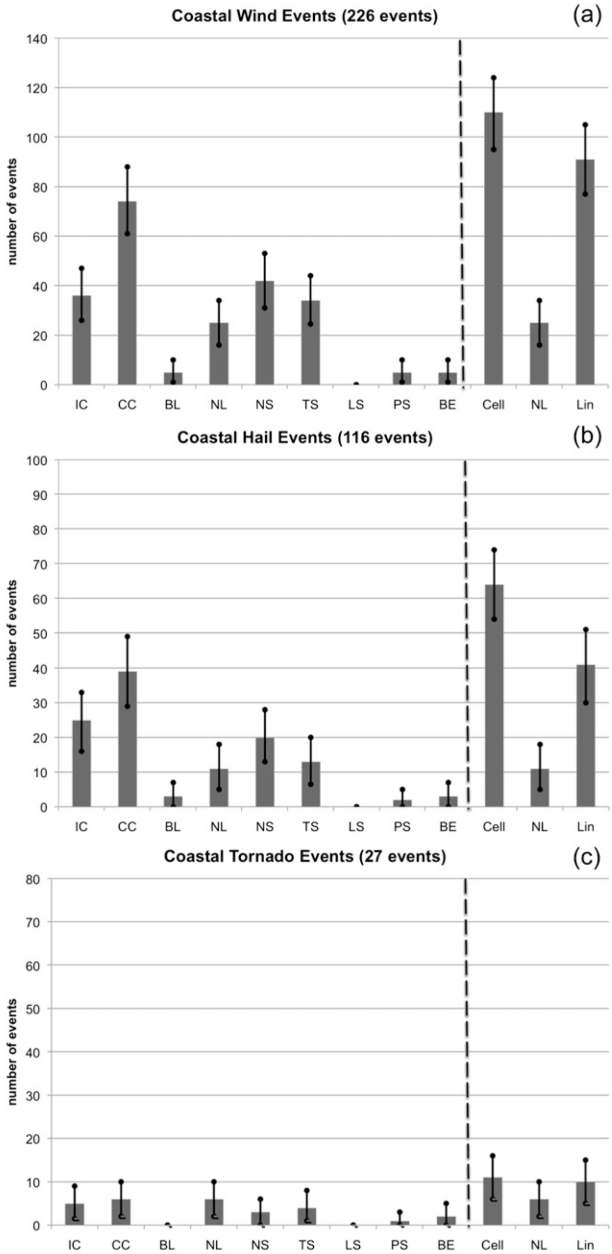

FIG. 5. As in Fig. 3, but for the coastal severe (a) wind and (b) hail events from the 2002–07 warm seasons (May–August), and (c) tornado events from the 1996–2007 warm seasons.

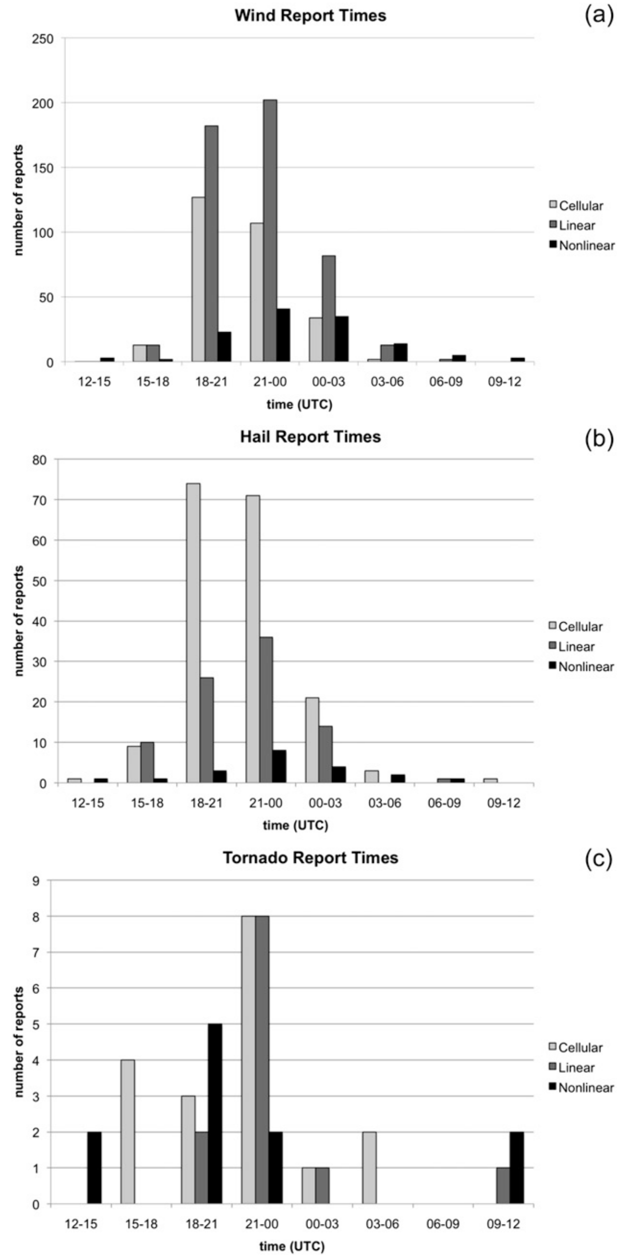

FIG. 6. Number of severe weather reports over the coastal zone plotted as a function of time of day (3-h bins) for cellular, linear, and nonlinear convective organizational structures from May to August 2002–07 for (a) wind and (b) hail, and (c) from May to August 1996 to 2007 for tornadoes.

b. Diurnal variations in coastal severe weather

The distribution of the three types of coastal severe weather reports is examined as a function of time of day (Fig. 6). Most (~75%) severe wind and hail reports occur from 1400 to 2000 eastern daylight time (EDT; 1800 to 0000 UTC), with a tail in the distribution toward the late-evening hours of 2000–2300 EDT (0000–0300 UTC; Figs. 6a and 6b). The diurnal distribution for the tornado reports is less clear (Fig. 6c), though the 2100–0000 UTC maximum for all structures is statistically significant (95% level). While linear convection produces tornadoes almost exclusively from 1800 to 0000 UTC, cellular convection can become tornadic between 1500 and 0600 UTC, with a maximum from 2100 to 0000 UTC. Nonlinear systems produce tornadoes at any time of the day, with no clear temporal maximum.

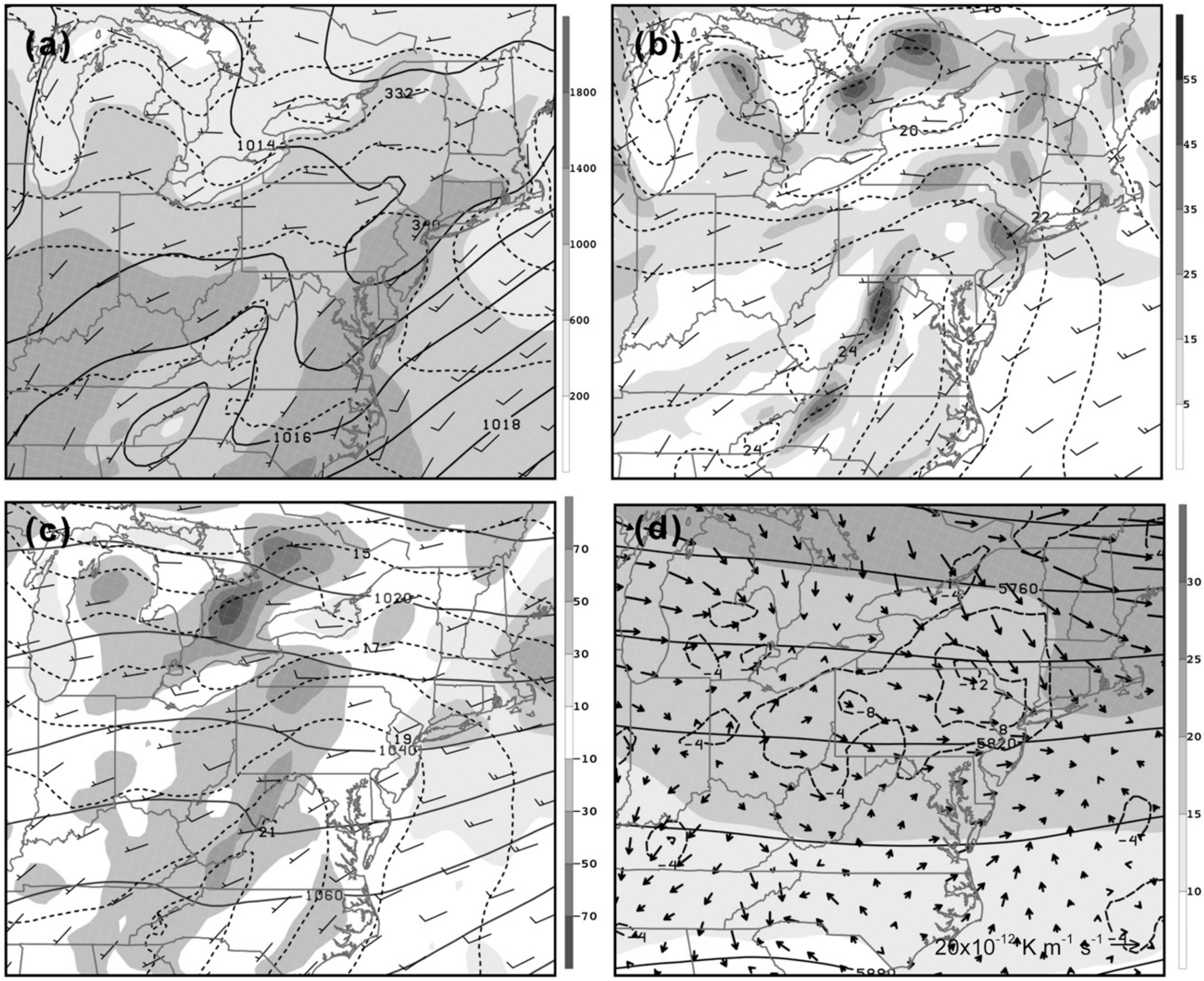

FIG. 7. Spatial composites for the severe cellular events near the coast at $t - 0$ h of (a) sea level pressure (solid every 1 hPa), MUCAPE (shaded every 400 J kg^{-1}), equivalent potential temperature (dashed every 4 K), and 1000-hPa winds (full barb = 5 m s^{-1}); (b) 950-hPa frontogenesis [calculated then composited; shaded every 1×10^{-2} K (100 km)$^{-1}$ (3 h)$^{-1}$], 950-hPa temperature (dashed every 1°C), and 950-hPa winds (full barb = 5 m s^{-1}); (c) 900-hPa temperature advection (calculated then composited; shaded every 1×10^{-6} °C s^{-1}), 900-hPa geopotential height (solid every 10 dam), and 900-hPa winds (full barb = 5 m s^{-1}); and (d) 500-hPa geopotential height (solid every 20 dam), 500-hPa **Q** vectors (10^{-12} K m^{-1} s^{-1}), 300-hPa wind magnitude (shaded every 5 m s^{-1}), and 800–400-hPa layer-averaged omega (dashed, 10^{-4} Pa s^{-1}).

c. *Composites*

1) CELLULAR STORMS

Certain organized convective structures are related to different severe weather types over the coastal zone. For example, hail is most often produced by cellular convection, while severe wind is primarily caused by cells and lines. Therefore, it would be useful to identify the environments that support severe weather associated with the three main organizational convective structures (cellular, linear, nonlinear). Figure 7 shows the NARR composite fields at the closest 3-h time prior to the coastal cellular severe events. During these events ($t - 0$ h), there is a surface pressure trough in the lee of the Appalachians (Fig. 7a), which is a persistent feature during the past 24 h (not shown). A manual investigation of the individual events in the composite revealed that for ~38% of cellular severe events, this trough was not associated with a surface cold front, but rather a lee trough or some other type of inverted or mobile trough. Of the remaining events, 17% were associated with a surface cold front, 19% formed along the warm side of a stationary front, 11% along a warm front, 12% near a surface anticyclone, and 3% occurred after cold frontal passage (not shown).

At low levels, the severe cellular storms are supported by moderate instability (mean MUCAPE > 1000 J kg^{-1}), with an axis of warm, moist air (1000-hPa $\theta_e \approx 340$ K) extending over the coastal zone (Fig. 7a). Just above the surface, 950-hPa frontogenesis [$>35 \times 10^{-2}$ K (100 km)$^{-1}$ (3 h)$^{-1}$] is evident at the leading edge of a thermal ridge over northern New Jersey (Fig. 7b), with ageostrophic frontal circulations contributing to the 800–400-hPa layer-averaged omega, causing ascent in the lower levels over New Jersey and southern New York (Fig. 7d), which helped initiate the convective storms (not shown). The magnitude of the composite 950-hPa frontogenesis for cellular events is relatively small in part from the composite smoothing, since there are a couple of events with frontogenesis values $\geq 0.76 \times 10^{-2}$ K (100 km)$^{-1}$ (3 h)$^{-1}$. However, the 950-hPa frontogenesis located over northern New Jersey and southern New York does lead to a maximum in upward motion of -12×10^{-4} Pa s^{-1} at 950–900 hPa (not shown) near this same region, and contributes to the southern area of 800–400-hPa upward motion in Fig. 7d. For those cases in which the frontal forcing is too weak, convection can initiate from upslope flow along the windward terrain slopes over the northeastern United States (Lombardo and Colle 2010), as well as cold pool boundaries from other convection (Weckwerth and Wakimoto 1992).

Slightly east of the coastal frontogenesis maximum and centered over Long Island is a localized area of 900-hPa warm-air advection ($>30 \times 10^{-6}$ °C s^{-1}; Fig. 7c). On average, this warming in the low levels helped destabilize the column (not shown). The composite warm-air advection is maximized at this level (not shown) and develops within the 12 h leading up to the severe event, as 900-hPa winds rotate from westerly to southwesterly and the thermal gradient strengthens at this level.

At 300 hPa (Fig. 7d), the jet maximum ($\sim$20 m s^{-1}) is located $\sim$1000 km poleward of the coastal region of interest, causing weak mid- and upper-level ascent due to ageostrophic jet circulations over northern New Jersey, northeastern Pennsylvania, and eastern New York. Inspection of each cellular event reveals that $\sim$25% develop in conjunction with a 500-hPa midlevel trough in close proximity. However, due to the wide variety of synoptic regimes that exist in the midlevels during these severe coastal events, there is there is no mean trough in the composite field (Fig. 7d). Furthermore, there is **Q**-vector convergence over northern New Jersey, southern New York, and Long Island at 500 hPa (Fig. 7d) highlighting the quasigeostrophic (QG) midlevel forcing for ascent during these events.

2) Linear systems

Twelve hours prior to a severe linear event ($t - 12$ h), there is a surface pressure trough in the lee of the southern and central Appalachians. A second trough, associated with a surface cold front, is $\sim$450 km to the northwest over the lower Great Lakes, with the associated cold advection to the west of the trough (Figs. 8a and 8c). The individual events show that 73% of all linear events have a trough within the Appalachian lee with a frontal boundary to the west at $t - 12$ h, while only 36% of cellular events exhibit this synoptic pattern. An elongated area of 950-hPa frontogenesis [$>55 \times 10^{-2}$ K (100 km)$^{-1}$ (3 h)$^{-1}$] from northeastern Ohio into western New York (Fig. 8b) parallels the cold front, with weak warm-air advection at 900 hPa (10×10^{-6} °C s^{-1}) over New Jersey, Long Island, and southern Connecticut.

By the time of the event ($t - 0$ h), the Appalachian lee trough amplifies in situ, while the surface cold front moves eastward toward the coast (Fig. 9a). The frontal position is less apparent in the composite than at $t - 12$ h, since $\sim$20% of the cold frontal boundaries merge with the preexisting trough in the Appalachian lee, while in a few other cases the front either stalled to the northwest or weakened. A majority (53%) of the severe linear events develop in association with the lee or prefrontal trough, while only 13% develop along the cold front that moves into the lee. The rest develop along a warm front (9%), stationary front (9%), or under a surface anticyclone (13%). Both the 950-hPa frontogenesis maximum (Fig. 9b) and the leading edge of 900-hPa cold-air advection (Fig. 9c) are now located over the Appalachian terrain. The frontogenesis maximum over northern Pennsylvania–southern New York is greater in the linear composite than the cellular composite at the 80% level, indicating that it is a fairly distinguishing feature between the two convective types.

At $t - 0$ h, a thermal ridge extends along the coastal plain from the southeastern United States to the northeast, with average MUCAPE values exceeding 1000 J kg^{-1} over much of the coastal region and a 1000-hPa θ_e between 340 and 344 K (Fig. 9a). A localized region of warm-air advection ($>70 \times 10^{-6}$ °C s^{-1}; Fig. 9c) at 900 hPa is located to the east of a cold front along coastal southern New England, which helps destabilize the lower troposphere (not shown). A maximum in frontogenesis [$>55 \times 10^{-2}$ K (100 km)$^{-1}$ (3 h)$^{-1}$; Fig. 9b] develops over the coastal zone, with the associated ageostrophic circulations providing a mechanism for low-level ascent to support the severe weather (not shown). Approximately one-quarter of the individual linear severe events have larger frontogenesis values compared to the composite value, with the largest contribution to the vertical motion occurring in the lower levels. The magnitude of the temperature advection and frontogenesis averaged over the coastal domain for the composite linear event is not statistically different than the cellular composites. Meanwhile, a broad 500-hPa midlevel trough moves eastward, with

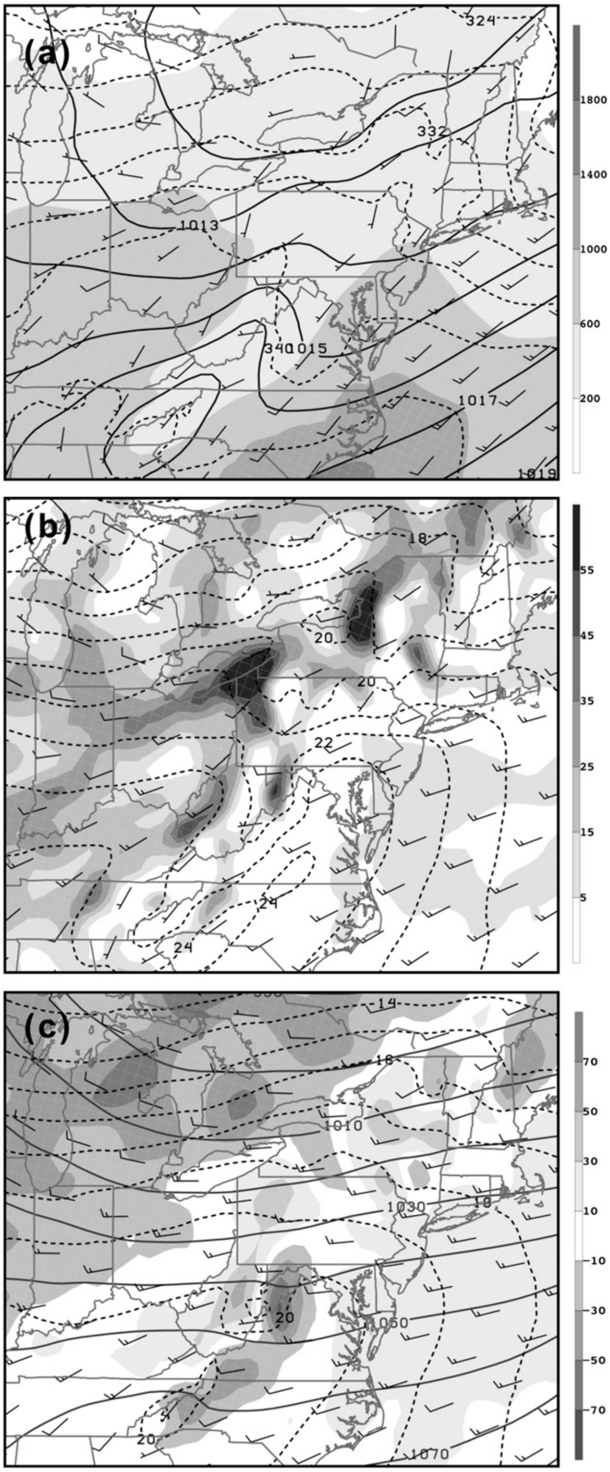

FIG. 8. As in Figs. 7a–c, but for the severe linear events near the coast at $t - 12$ h.

the associated downstream **Q**-vector convergence providing QG mid- and upper-level ascent over the coastal zone (Fig. 9d). Though the magnitude of the **Q**-vector convergence for linear events is 1.5 times larger compared to the cellular composite, this **Q**-vector convergence averaged over the coastal zone is not statistically different from the cellular composites (not shown). Over 80% of all severe linear events in this study develop under westerly to southerly 500-hPa flow, as compared to 60% for cellular events, yielding a more robust midlevel trough in the composite for linear events. However, only ~44% of the linear events are associated with a 500-hPa trough, while the other events either have a trough well to the north or west of the severe convection (~35%) or develop under an anticyclone or with no trough in close proximity (~20%). This large-scale variability during severe convective events is not uncommon. For example, Coniglio et al. (2004) found similar results for derechos that form the east of the Rockies, with the convection developing downstream of a 500-hPa trough (~40%), under a midlevel ridge (~20%), and under zonal midlevel flow (~12%).

At upper levels, linear severe convection develops near the right-entrance region of a 300-hPa jet (>30 m s^{-1}), a favorable region for ascent as indicated by the upward vertical motion at mid- to upper levels (Fig. 9d). Clark et al. (2009) showed that severe weather over the central plains develops within the right-entrance region of an upper-level jet, especially severe wind, as well as along the jet axis in the exit region during hail and tornado events. They showed that there is a thermally direct circulation within the entrance region, with convergence in the lower levels, divergence in the upper levels, and deep ascent through the troposphere, consistent with the four-quadrant jet model.

3) NONLINEAR SYSTEMS

At $t - 12$ h (Fig. 10), a surface trough resides in the Appalachian lee, with a weak north–south θ_e gradient across the Northeast at 1000 hPa (Fig. 10a). There is weak cold-air advection over much of the Northeast, while weak warm-air advection overlies Long Island and southeastern New Jersey, with the maximum located just east of the Maryland and Delaware coasts (Fig. 10b). Meanwhile, a 500-hPa trough is located over the Great Lakes (Fig. 10c), with **Q**-vector convergence downstream of the trough extending over the coastal zone, supplying a mechanism for QG ascent as revealed by the 800–400-hPa vertical motion (Fig. 10c). The core of a 300-hPa jet is located over the southeastern Great Lakes at this time (Fig. 10c).

By $t - 0$ h (Fig. 11), a mean surface low develops over Chesapeake Bay (Fig. 11a), with half of the composite members having a closed surface cyclone in the area. Only 20% of all severe cellular events and 11% of all severe linear events have a closed low in a similar region in the Appalachian lee. The Atlantic coastal plain environment remains weakly unstable compared to 12 h prior

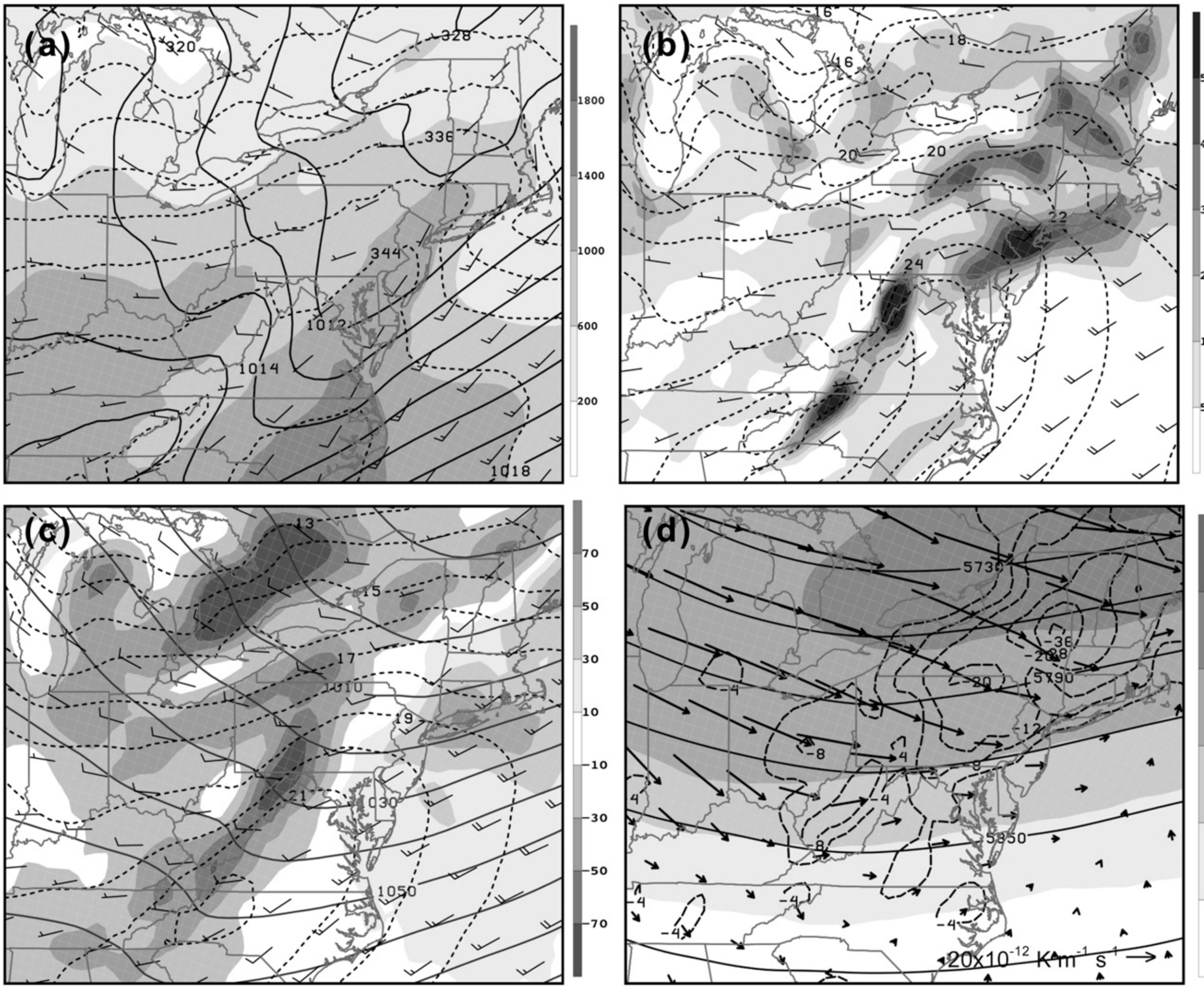

FIG. 9. As in Figs. 7, but for the severe linear events at t −0 h.

(Fig. 10a), with MUCAPE values approaching 600 J kg^{-1} and an average θ_e of ~332 K (Fig. 11a). An elongated area of enhanced 950-hPa frontogenesis [>15 × 10^{-2} K (100 km)$^{-1}$ (3 h)$^{-1}$] extends along the northern and northeastern edge of the surface cyclone from the Maryland–Pennsylvania border westward to southern New Jersey, as well as along a warm frontal boundary over Long Island (Fig. 11b), supporting convective development. Approximately 80% of the individual nonlinear severe events occur in association with stronger frontogenesis compared to the composite value. As the 900-hPa trough over the Atlantic coastal plain amplifies and the surface cyclone develops, warm-air advection develops across New Jersey, Long Island, southern New York, and western Connecticut (Figs. 10b and 11c). Maddox and Doswell (1982) highlighted the role of low-level warm-air advection in initiating and organizing mesoscale convective complexes (MCCs).

At $t - 0$ h, the 500-hPa trough is located ~600 km to the west-northwest of the severe weather reports (Fig. 11d). Manual inspection revealed that 87% of the nonlinear severe events developed with southerly to westerly midlevel flow and ~80% were under the influence of a midlevel trough (not shown). At this time, there is 500-hPa **Q**-vector convergence over the coastal region, especially in northern New Jersey, eastern Connecticut, and Rhode Island, providing mid- and upper-level QG ascent (Fig. 11d). The magnitude of the **Q**-vector convergence over the coastal zone for nonlinear severe events is 2.5 times greater than during linear events and 4 times greater than during cellular events. These differences are statistically significant (95% level), indicating that midlevel forcing is an important ingredient during nonlinear severe events. In conjunction with the 950-hPa frontogenetical lift, localized 900-hPa temperature advection, and the midlevel QG ascent, severe nonlinear convection develops in the right-entrance region of a 300-hPa jet (>25 m s^{-1}; Fig. 11d), which is within a region of ascent at midlevels.

5. Discussion

a. Comparison of convective parameters between the central and northeastern United States

It is well known that both CAPE and vertical wind shear are important parameters in determining the strength and organization of convective storms (e.g., Weisman and Klemp 1982; Parker and Johnson 2000). However, several studies have highlighted the large variability in CAPE and wind shear values in which central U.S. severe storms can develop (Evans and Doswell 2001; Thompson et al. 2003; Cohen et al. 2007). Therefore, while the Northeast composites above (Figs. 7–11) provide a good depiction of the mean dynamic and thermodynamic conditions for the three types of convective structures, there is variance in the flow patterns and convective ingredients that are important, which have been noted by others (Evans and Doswell 2001; Thompson et al. 2003; Cohen et al. 2007). To highlight both the mean and the variability for each convective type near the coast, box-and-whisker plots are shown for MUCAPE and wind shear values averaged for four points over the coastal zone (see Fig. 1). Some of these results are compared with previous studies over the central United States.

The mean MUCAPE values for both cellular and linear severe events near the coast are ~1200 J kg^{-1}, while for nonlinear events the mean is ~460 J kg^{-1} (Fig. 12a), and this difference in MUCAPE is statistically significant at the 95% level. Thompson et al. (2003) found that the mean mixed-layer CAPE (MLCAPE) values for nontornadic supercells and nonsupercells were 1645 and 1280 J kg^{-1}, respectively. Thus, the mean MUCAPE for severe cells near the coast is similar to the average MLCAPE for central Great Plains nonsupercells. For Northeast severe linear events, the mean MUCAPE (1200 J kg^{-1}) is half as large as the mean CAPE observed during mature derecho-producing mesoscale convective systems (MCSs) over the central United States [2394 J kg^{-1}; Coniglio et al. (2004)]. MUCAPE values during coastal Northeast severe linear events (Fig. 12) are more consistent with MLCAPE seen

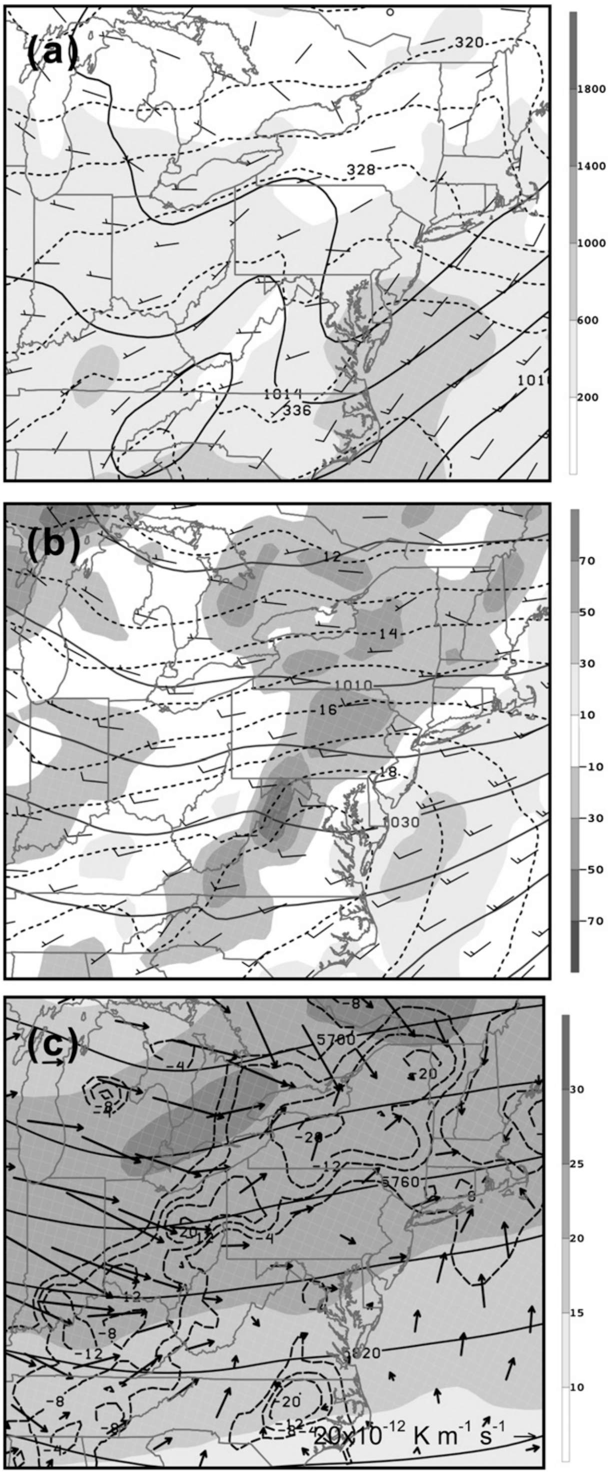

FIG. 10. Spatial composites for the severe nonlinear events near the coast at $t - 12$ h showing (a) sea level pressure (solid every 1 hPa), MUCAPE (shaded every 400 J kg^{-1}), equivalent potential temperature (dashed every 4 K), and 1000-hPa winds (full barb = 5 m s^{-1}); (b) 900-hPa temperature advection (calculated then composited; shaded every 1 × 10^{-6} °C s^{-1}), 900-hPa geopotential height (solid every 10 dam), and 900-hPa winds

←

(full barb = 5 m s^{-1}); (c) 500-hPa geopotential height (solid every 20 dam), 500-hPa **Q** vectors (10^{-12} K m^{-1} s^{-1}), 300-hPa wind magnitude (shaded every 5 m s $^{-1}$), and 800–400-hPa layer-averaged omega (dashed, 10^{-4} Pa s^{-1}).

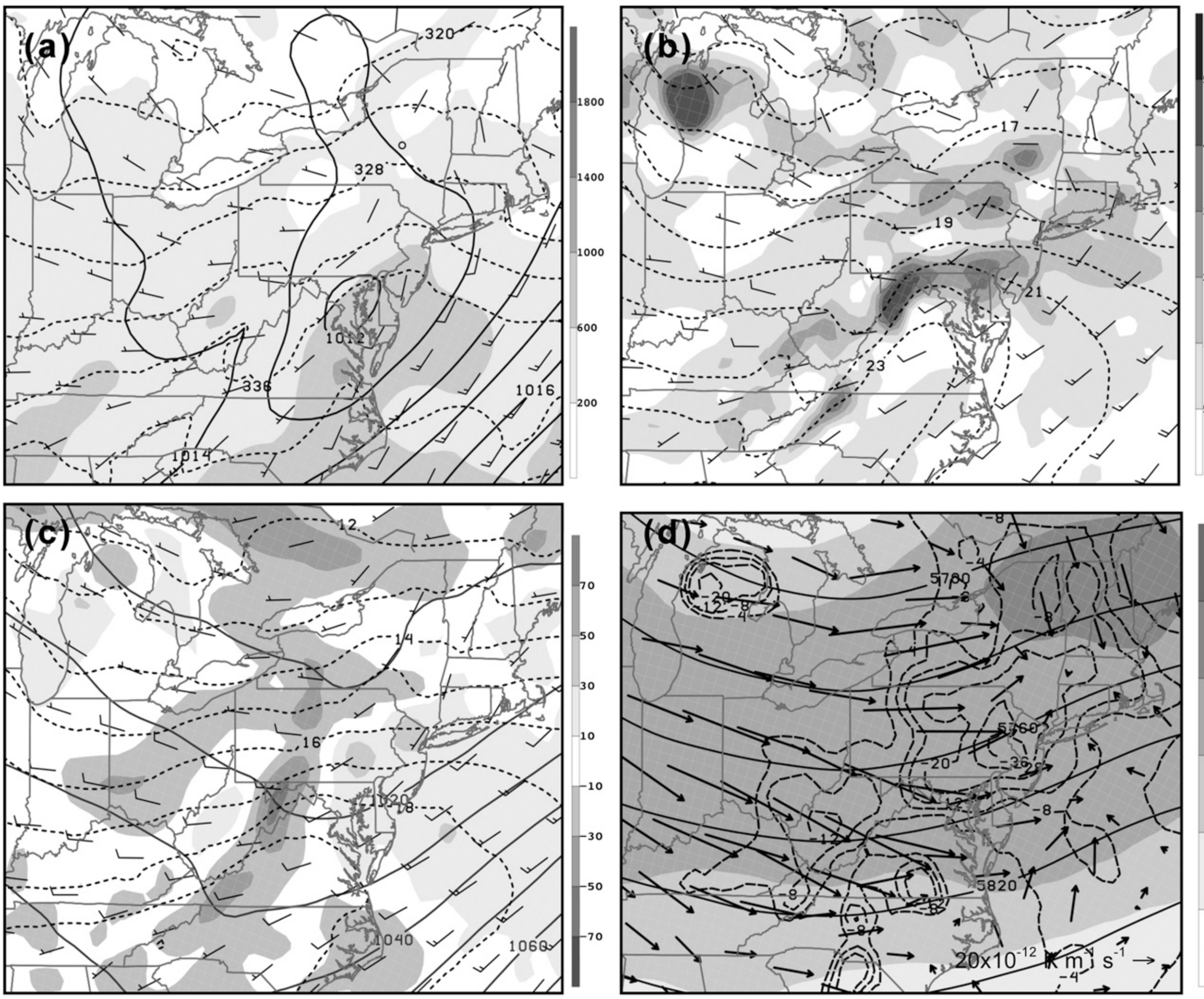

FIG. 11. As in Fig. 7, but for the nonlinear severe events at $t - 0$ h.

during nonsevere MCSs over the central Great Plains (Cohen et al. 2007). However, there is a large range in the MUCAPE values near the coast, with both the linear and nonlinear events occurring with instability as low as a few joules per kilogram. On the other end of the spectrum, coastal Northeast cellular and linear events can develop in 3000 J kg^{-1} of MUCAPE, with nonlinear MUCAPE reaching over 2000 J kg^{-1} for some events.

The average 0–1-km shear during coastal Northeast severe cellular events is a modest ~2.6 m s^{-1} (Fig. 12b), a smaller mean value than for central U.S. nonsupercells [3.8 m s^{-1}; Thompson et al. (2003)]. The mean low-level shear during coastal Northeast severe linear events (4.5 m s^{-1}) is significantly greater (95% level) than severe cellular events, although this mean shear value is smaller than during derecho-producing MCSs in the central and eastern United States [10.6 m s^{-1}; Coniglio et al. (2004)]. Even during weakly forced (500-hPa **Q**-vector convergence) central U.S. derecho events, the mean 0–1-km shear is 1.5 times greater than the coastal Northeast severe linear convection (Coniglio et al. 2004).

An interesting difference between cellular and linear events over the coastal Northeast is the spread of the middle 50% of events (Fig. 12b). The interquartile range (IQR) for all severe cellular events is relatively small, ranging from 1.4 to 2.6 m s^{-1}, while for severe linear events the values range from 2.0 to 7.7 m s^{-1}. Nonlinear severe events have a similar mean 0–1-km shear value (~4.4 m s^{-1}) as the linear events, although the top 50% of the nonlinear shear values are smaller compared to severe linear events. Overall, the spread of 0–1-km shear values for all severe nonlinear events is smaller than the cellular and linear severe events.

The mean deep-layer shear (0–6 km) increases from cellular (~13.4 m s^{-1}) to linear (~14.9 m s^{-1}) to nonlinear

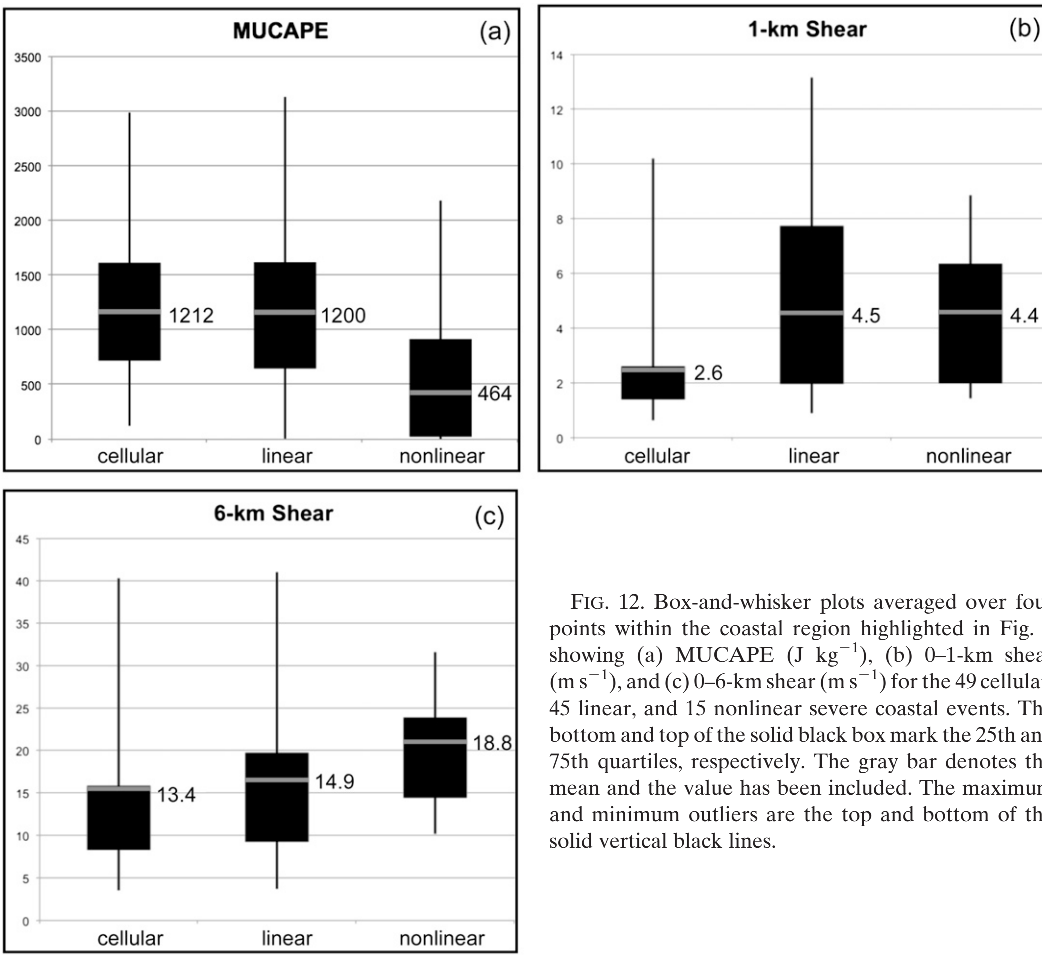

FIG. 12. Box-and-whisker plots averaged over four points within the coastal region highlighted in Fig. 1 showing (a) MUCAPE (J kg^{-1}), (b) 0–1-km shear (m s^{-1}), and (c) 0–6-km shear (m s^{-1}) for the 49 cellular, 45 linear, and 15 nonlinear severe coastal events. The bottom and top of the solid black box mark the 25th and 75th quartiles, respectively. The gray bar denotes the mean and the value has been included. The maximum and minimum outliers are the top and bottom of the solid vertical black lines.

(~18.8 m s^{-1}) severe Northeast coastal events (Fig. 12c). The mean deep-layer shear value for nonlinear events is significantly larger than that for linear events at the 80% level, and significantly larger than for cellular events at the 95% level. Compared to the central United States, the mean deep-layer shear (0–6 km) for coastal Northeast cells is greater than for nonsupercells over the central United States (8.4 m s^{-1}), as noted in Thompson et al. (2003), but still less than the mean-layer shear associated with central U.S. supercells (23 m s^{-1}). Deep-layer (0–6 km) shear values for linear events found in our study are smaller than for both severe and derecho-producing central and eastern U.S. quasi-linear systems (Cohen et al. 2007). Cohen et al. (2007) showed that the IQR of 0–6-km shear for severe central U.S. lines is 14–21 m s^{-1} and is 17–26 m s^{-1} for derecho-producing MCSs, which are more consistent with deep-layer shear seen during severe coastal Northeast nonlinear events (Fig. 12c). The earlier study of Evans and Doswell (2001) found that the middle 50% of derechos that develop east of the Rockies form within 0–6-km shear values of 11.8–20.0 m s^{-1}, which is more consistent with values for severe Northeast coastal linear events.

It should be emphasized that both cellular and linear severe events occur under a wide range of deep-layer shear values (3.6–41.1 m s^{-1}; Fig. 12c), while the spread of deep-layer shear values during nonlinear severe events is smaller (10.2–31.6 m s^{-1}). This suggests that Northeast coastal severe weather can develop under relatively weak deep-layer shear values, a result that is similar to the central Great Plains study of Evans and Doswell (2001), who found that derechos can form in 0–6-km shears as low as 1 m s^{-1}. Typically, these events lack strong synoptic support (i.e., surface cold front, progressive midlevel trough) and they develop in more unstable conditions compared to those events with larger shear values (Evans and Doswell 2001). Approximately 33% of all coastal Northeast severe cellular events and 27% of linear events develop in $<$10 m s^{-1} of deep layer shear. Cellular events with weak ($<$10 m s^{-1}) deep-layer shear are primarily severe wind events, while linear events with weak deep-layer shear can be dominated by severe wind or produce a combination of severe wind and hail. Overall, the complexity of CAPE and shear values can create a potentially difficult forecast situation.

Given the above results, it is apparent that many severe events over the Northeast develop in environments with weaker CAPE and vertical wind shear than the central United States. Forecasting severe weather over the coastal Northeast is a serious challenge given these more subtle conditions compared to those found in the central United States. However, the above composites do help provide some understanding of the basic flow patterns associated with the severe coastal Northeast convection, which can help alert forecasters during more marginal conditions. Furthermore, the role of synoptic-scale lift is important in releasing the more moderate instability during Northeast severe events. Some of the key synoptic forcing mechanisms associated with the three main severe convective structures have been highlighted in the composites (Figs. 7–11), to draw the forecasters' attention to the possibility of severe weather under these regimes.

b. Comparison of severe organizational structures over the central and northeastern United States

Gallus et al. (2008) identified the convective organizational structures responsible for various types of severe weather (wind, hail, tornadoes) over the central United States. The following short discussion will compare the distribution of severe weather over the Northeast to the Gallus et al. (2008) study. Cellular convection over the central United States is responsible for 48% of all severe events, with 26% from isolated cells and 20% from clusters of cells (Gallus et al. 2008, their Fig. 6). Over the northeastern United States (cf. Fig. 2), only 39% of all severe events are from cells, with the majority of severe weather developing from cellular clusters (25%) rather than isolated cells (9%). The fraction of severe events from linear structures is larger over the Northeast (32%) as compared to the central United States (23%). The greatest contribution to this difference is from linear systems with no stratiform precipitation, which are responsible for 13% of all severe events over the Northeast, but only 6% over the central United States. Over both regions, nonlinear severe events produce 29% of all severe events.

The frequency of reports per event can also be qualitatively compared with the central United States. Gallus et al. (2008) found that bow echoes have the largest number of severe wind reports per event over the central United States, while over the Northeast the frequency of severe wind from bow echoes is smaller than for lines with trailing stratiform (Fig. 4). Over the central United States, the highest frequency of small hail (less than 1 in.) is from bow echoes and broken lines, with broken lines producing the highest frequency of severe hail (1–2 in.). Over the Northeast, both clusters of cells and trailing stratiform lines have more hail reports per case than bow echoes. For tornado reports per event, broken lines and lines with parallel stratiform are most likely to cause tornadoes over the central United States, while bow echoes have the greatest number of tornadoes per case over the Northeast.

6. Summary

This study identified the convective organizational structures (i.e., cells, lines, nonlinear) responsible for three types of severe weather (severe wind, hail, tornadoes) over the northeastern United States, as well as a coastal subdomain within the Northeast. Over the northeastern United States, severe wind events are equally likely to be produced by all three of the main convective structure types (cellular, linear, nonlinear), while over the coastal subregion, severe wind is typically from cells and lines. For hail events, Northeast cells are responsible for 1.3 times as many hail events as lines and nonlinear convection. Over the coastal zone, there is a greater prevalence for hail events from cellular convection, with cells producing 1.6 times as many hail events compared to lines, and 5.8 times as many compared to nonlinear convection. Northeast tornadoes are primarily from cells and lines, although no one convective structure is favored to produce tornadoes over the coastal region.

Most of the severe weather over the coastal domain develops during the warmest time of the day, with 75% of all severe wind and hail events occurring between 1400 and 2000 EDT (1800 and 0000 UTC). The development of coastal tornadoes is more evenly distributed throughout the day, although 44% are reported between 1700 and 2000 EDT (2100 and 0000 UTC).

On average, coastal severe cells develop with a surface trough in the Appalachian lee, which is collocated with a low-level thermal ridge, with an average MUCAPE of $\sim$1200 J kg^{-1}. Low-level temperature advection helps to destabilize the environment, while ageostrophic circulations associated with weak frontogenesis near the thermal ridge provide a lifting mechanism to support the developing convection. There is only weak support for ascent in the midlevels and minimal ascent due to jet circulations. On average, cellular events form in 2.6 m s^{-1} of 0–1-km shear, with a deep-layer shear value of 13.4 m s^{-1}.

Severe coastal linear events develop in somewhat similar environments as cellular events on average, although there are some important differences between the two types. At $t - 12$ h prior to the development of severe weather, 73%

of all linear events exhibit a trough in the Appalachian lee with a secondary trough upstream over the Ohio River valley, while only 36% of cellular events show this synoptic pattern. By $t - 0$ h, the magnitude of the frontogenesis associated with this feature for linear events is significantly greater (80% level) than for the cellular events, indicating that ageostrophic circulations from a baroclinic zone just upstream of the coastal zone are important during linear events. Furthermore, almost half of the linear events develop in association with a progressive 500-hPa trough moving toward the coastal zone, while only one-quarter of the cellular events exhibit this feature. Finally, the mean 0–1-km shear during linear events (4.5 m s^{-1}) is significantly greater (95%) than for cellular events.

Nonlinear severe convective events over the coastal region occur within relatively weak average MUCAPE $\sim$460 J kg^{-1}. Approximately half of these events form with a closed surface low over the mid-Atlantic, with a low-level baroclinic zone to the northeast overlying the coastal region. As in the composite cellular and linear events, ageostrophic circulations around the developing baroclinic zone help support the nonlinear convection, while the QG forcing during nonlinear events is significantly (95%) greater than for cellular or linear events. This is supported by the fact that $\sim$80% of all events develop in association with a propagating midlevel trough. Furthermore, the average deep-layer shear value (18.8 m s^{-1}) during these events is significantly greater than during linear (80% level) and cellular (95% level) events.

This work is part of a continuing effort to increase our understanding of warm season convection over the northeastern United States, a region with both complex terrain as well as the Atlantic coastal boundary. While this paper focused on the relationship between severe weather type and convection organizational structures over the Northeast coastal zone, a large amount of work remains to be done to understand the interactions between convection storms and the coastal boundary, including the modification of organizational structures by the Atlantic marine layer.

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