4. Discussion

4.1 Climatology

Past studies have produced spatial frequency maps of severe thunderstorm winds (e.g., Kelley et al. 1985) and gradient winds (e.g., Lee and Myrick 2000, Lacke et al. 2007) that included the NE; however, no study has specifically focused on the frequency of thunderstorm and gradient winds during the cool season. Cool-season thunderstorm-wind days were found to be maximized west of the Appalachian Mountains, in the Ohio Valley, and in eastern Pennsylvania and New Jersey, which is consistent with the results of Kelley et al. (1985). Gradient-wind days were found to be maximized along the Atlantic coast, which is consistent with Lee and Myrick (2000); along the shores of Lake Erie, which is consistent with Lacke et al. (2007); and along the eastern slopes of the Appalachian Mountains. The fact that high-wind days are more frequent closer to the Atlantic coast is likely a reflection of the tendency for surface cyclones to rapidly strengthen just off of the Atlantic coast near the NE as determined by Sanders and Gyakum (1980, Fig. 3). The relative maximum on the eastern slopes of the Appalachian Mountains is likely a reflection of downslope high-wind events.

A total of 335 high-wind events impacted the NE from 15 October 1993 through 31 December 2008. Pure gradient events were maximized, compared to hybrid and pure convective events, during the cool season with 165 (49%) events impacting the NE from 15 October 1993 through 31 December 2008. Pure gradient events maximized during the October 1997 through April 1998 cool season, which is consistent with Lee and Myrick's (2000) climatology of nonconvective high-wind events that impacted southern New England from 1993 through 1999. Lee and Myrick's (2000) climatology indicates that over 80 nonconvective high-wind events occurred in 1997, whereas the present study indicates that 19 pure gradient events occurred from October 1997 through April 1998 (Fig. 3.5a). The difference can be attributed to the following: 1) Lee and Myrick (2000) defined a high-wind event as the occurrence of any single high-wind report, whereas in the present study a high-wind event is defined as a series of high-wind reports; and 2) Lee and Myrick (2000) included all months of the year, whereas the present study only considers the months from October through April. Hybrid events were maximized during the October 2005 through April 2006 cool season and were minimized during the October 2001 through April 2002 and October 2002 through April 2003 cool seasons. Pure convective events were maximized during the October 2001 through April 2002 and October 2007 through April 2008 cool seasons. No pure convective events occurred during the October 1996 through April 1997 cool season. Pure gradient and hybrid events occur throughout the cool season; however, pure convective events tend to occur in April and October. Hybrid events were found to accumulate the largest number of high-wind reports on average, which suggests that hybrid events have the greatest societal impact compared to the pure gradient and pure convective events.

4.2 Composite analysis

One goal of the composite analysis was to identify the mechanisms responsible for the production of high winds in each quadrant of surface cyclones associated with pure gradient and hybrid high-wind events. For pure gradient events, high winds were evenly distributed in each quadrant, but the maximum occurred in the southwest quadrant, which is consistent with the results of Niziol and Paone (2000). The southwest quadrant is characterized by strong flow in the PBL in the presence of near dry-adiabatic PBL lapse rates. Subsidence, likely associated with cold advection, transports momentum into the PBL, where it is likely mixed down to the surface by turbulent eddies. A strong pressure gradient, steep low-level lapse rates, subsidence, and cold advection are consistent with features identified by Kapela et al. (1995) and Niziol and Paone (2000) in their cool season high-wind studies. The pure gradient southeast composite surface cyclone center tracks northeastward through southern Canada, which is consistent with the findings of Niziol and Paone (2000). Another common surface cyclone track is along the Atlantic coast, which is consistent with the results of Lee and Myrick (2000).

For the hybrid events, the initial NE reports occurred most frequently in the southeast quadrant of a surface cyclone (Fig. 3.4b). The hybrid southeast composite surface cyclone center tracks northeastward through southern Canada (Fig. 3.22), which is consistent with the results presented by Niziol and Paone (2000). A composite cross section (Fig. 3.16) shows a layer of potential instability between the surface to 850 hPa, ascent, and 50 kt wind speeds at 700 hPa located at the leading edge of a cold front, which are features consistent with the necessary conditions, as determined by McCann (1978), for convective storms to produce high winds at the surface in the absence of lightning. Ascent in the presence of potential instability is conducive to the development of thunderstorms and thunderstorm-related downdrafts. The hybrid southeast composite resembles the dynamic pattern favorable for the development of squall lines with extensive bow echo-induced damaging winds described by Johns (1993, Fig. 1.4) in that the threat area from Johns (1993) and the hybrid southeast initial NE report are located in the southeast quadrant (Fig. 3.15a) of a northeastward moving surface cyclone (Fig. 3.22b). The hybrid southeast composite (Fig. 3.15d) lacks a subtropical jet that is present in Johns (1993) dynamic pattern. An explanation for this difference is that Johns (1993) studied events that occurred in the Southeast U.S. and were thus farther equatorward compared to the events analyzed in the present study.

For the pure convective events, the initial NE reports occurred most frequently in association with a 300-hPa trough. The pure convective trough composite consists of surface low pressure center located to the northwest of the initial NE report and warm moist air being drawn poleward east of a cold front. As is the case with the hybrid southeast composite (Figs. 3.15a–d), the pure convective trough composite (Figs. 3.18a–d) resembles the dynamic pattern favorable for the development of squall lines with extensive bow echo-induced damaging winds described by Johns (1993, Fig. 1.4). As is the case with the hybrid southeast composite (Fig. 3.15d), the pure convective trough composite (Fig. 3.18d) lacks a subtropical jet that is present in Johns (1993) dynamic pattern. The pure convective ridge composite consists of low-level warm advection occurring along an 850-hPa baroclinic zone (Fig. 3.20b). The midtropospheric flow is anticyclonic and approximately parallel to a baroclinic zone (Fig. 3.20c), which is consistent with the warm season pattern favorable for the development of bow echoes described by Johns (1993). Johns (1993) states that thunderstorm activity is almost always initiated in a region of warm advection, which is consistent with the location of the initial NE report for the pure convective ridge composite (Fig. 3.20b).

4.3 Case studies

Two high-impact hybrid high-wind events (17 February 2006; 15–16 April 2007) were analyzed to identify mechanisms responsible for the production of high winds during each event. Conceptual models highlighting the important mechanisms responsible for the production of high winds for the 17 February 2006 and 15–16 April 2007 events are presented in Figs. 4.1a,b, respectively. Both events were associated with rapidly deepening surface cyclones and strong MSLP gradients. The 17 February cyclone moved rapidly northeastward through southern Canada, whereas the 15–16 April cyclone stalled over the Atlantic Ocean along the coast of the NE. Due to differences in storm track, the 17 February event was associated with severe winds that occurred more inland compared to the 15–16 April, which was associated with severe coastal winds. Both events were associated with strong isallobaric gradients. The 17 February event was associated with more rapid pressure rises compared to the 15–16 April event.

In both the 17 February and 15–16 April events, high winds occurred in the southwest quadrant(s) of the midlatitude cyclones where PBL lapse rates were approximately dry adiabatic and wind speeds in the PBL were greater than 40 kt. A difference between these two events is that the high winds associated with the 17 February event occurred in conjunction with a cold frontal passage and cold advection, whereas the 15–16 April event was associated with a slow-moving, rapidly deepening surface cyclone whose attendant cold front did not pass over the NE. The mechanism associated with the high winds that occurred in the southwest quadrant of the 17 February cyclone is representative of the pure gradient southwest composite where cold advection and subsidence occur in the presence of strong flow at low levels and near dry-adiabatic

PBL lapse rates. The high winds that occurred in the southwest quadrant of the 15–16 April cyclone at 0600 (Fig. 3.35b) and 1200 UTC (Fig. 3.35d) differ from the pure gradient southwest composite in that the southwest quadrant of the 15–16 April cyclone was not characterized by strong cold advection at 0600 (Fig. 3.33c) and 1200 UTC (Fig. 3.34c).

The 17 February and 15–16 April events also differed in that high winds occurred in the northeast quadrant of the 15–16 April cyclone, whereas high winds did not occur in the northeast quadrant of the 17 February cyclone. Temperature inversions were present near the location of the high winds in the northeast quadrant of the 15–16 April cyclone, which would likely inhibit downward transport of high momentum air to the surface. Despite the likely inhibiting effect of temperature inversions, strong onshore winds did occur most likely because the combination of a strong pressure gradient and reduced friction over the ocean allowed wind speeds at 16 m above the ground to reach 50 kt.

It was apparent from radar imagery that convective storms formed during the 17 February event and produced strong surface winds; however, the evidence presented for the 15–16 April event suggests, but does not definitively establish, that convective storms led to the development of strong surface winds. McCann (1978) identified the following necessary conditions for convective storms to produce strong surface winds in the absence of lightning: 1) a small amount of potential instability; 2) synoptic-scale lifting; and 3) strong winds between 3 to 5 km above the surface. Ascent occurred in the presence of potentially unstable layers and wind speeds in excess of 50 kt occurred between 3 to 5 km for both the 17 February and 15–16 April events. During the 17 February event, potentially unstable layers developed along a cold front accompanied by a dry-air intrusion and upward-decreasing equivalent potential temperature advection. Frontogenesis was occurring along the cold front (Fig. 4.1a). Ascent, likely associated with frontogenesis, was occurring in the presence of potentially unstable layers. During the 15–16 April event, potentially unstable layers developed in the vicinity of an 850-hPa baroclinic zone located west of the 15–16 April surface cyclone due to a dry-air intrusion and upward-decreasing equivalent potential temperature advection. Frontogenesis was occurring along this baroclinic zone (Fig. 4.1b). Ascent was occurring on the warm side of the region of frontogenesis in the presence of the potentially unstable layers.

As stated above, during the 15–16 April event, an 850-hPa baroclinic zone was located west of the 15–16 April cyclone center similar to the bent-back warm front feature identified as being associated with high winds in studies such as Browning (2004) and Mass and Dotson (2010). Lightning was reported in the vicinity of this baroclinic zone, which suggests the possibility that thunderstorm-related downdrafts were responsible for transporting high momentum air to the surface.

4.4 Conclusions

The objectives of this research were to: 1) diagnose the climatological frequency of high winds in the NE and adjacent regions; 2) construct composite charts that depict the synoptic environments and mechanisms that lead to the production of high winds in the NE; and 3) to examine specific high-wind events that illustrate important atmospheric processes associated with the occurrence of high winds. To accomplish these objectives, 28 867 thunderstorm- and gradient-wind reports were extracted from the NCDC database for 15 October 1993 through 31 December 2008 and stratified into events. An event was defined as any series of greater than or equal to two reports separated by less than or equal to 12 h. Events were categorized as pure gradient, hybrid, or pure convective if the series of reports consisted of only gradient-wind reports, both gradient- and thunderstorm-wind reports, or only thunderstorm-wind reports, respectively. Spatial frequency maps were constructed depicting the percentage of days between 15 October 1993 and 31 December 2008 that experienced high winds. A climatology was developed for high-wind events that impacted the NE for 15 October 1993 through 31 December 2008. Hybrid events were found to produce the highest number of high-wind reports, which suggests that hybrid events have the greatest societal impact compared to pure gradient and pure convective events. Hybrid events whose initial NE report occurred in the southeast quadrant of a surface cyclone were the most common for high-wind events that impact the NE compared to events whose initial NE reports occur in the northeast, northwest, and southwest quadrants.

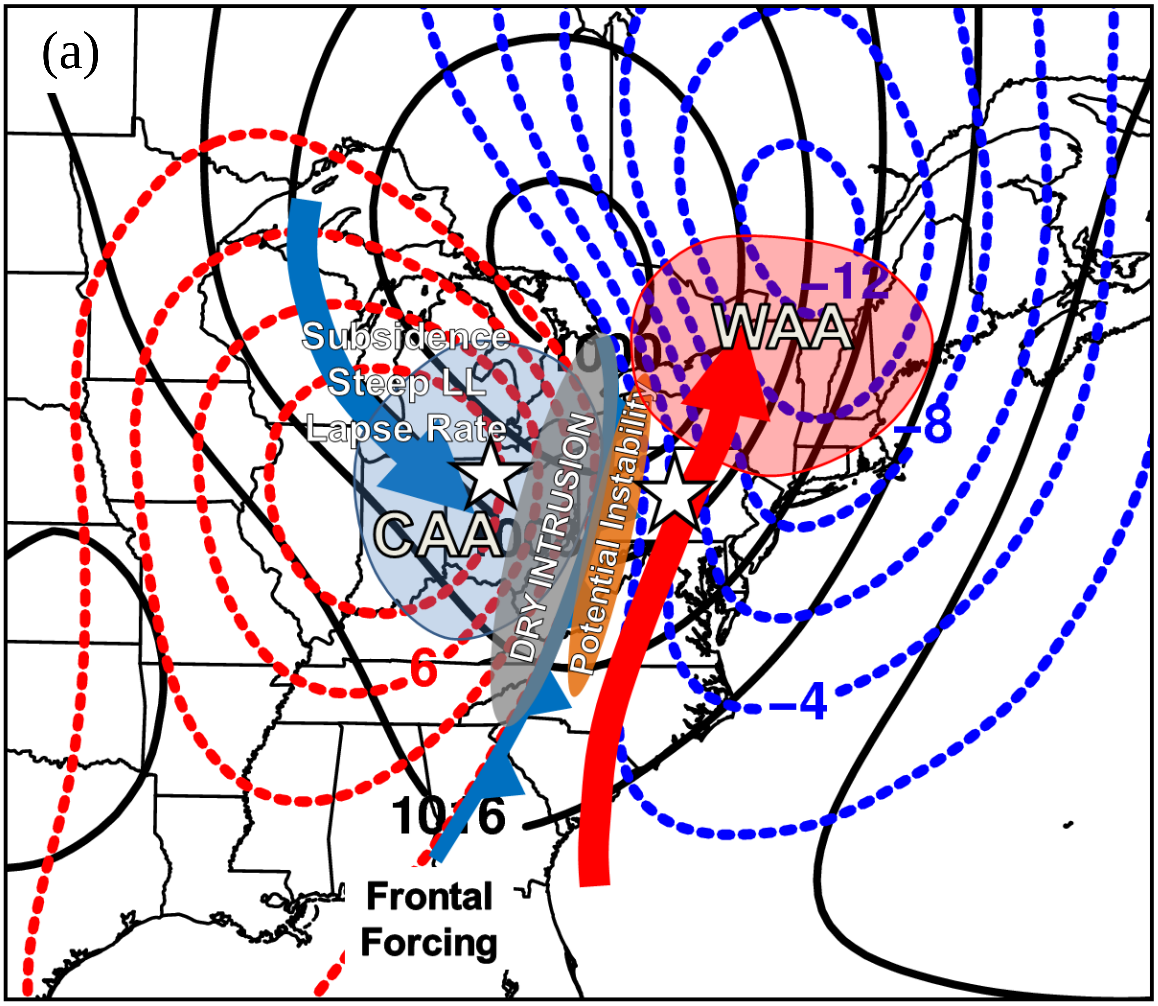
Events were subcategorized based upon the location of the initial NE report relative to a surface cyclone (performed for the pure gradient and hybrid events) or whether the initial NE report occurred in the vicinity of a 300-hPa trough or ridge (performed for the pure convective events). For the pure gradient and hybrid events, composites were constructed for each of the eight subcategories in order to determine the mechanisms responsible for the production of high winds in each quadrant of a surface cyclone. For the pure convective events, composites were constructed for each of the two subcategories in order to determine the mechanisms responsible for the production of high winds in the vicinity of upper-level troughs and upper-level ridges.

Results from composite and case study analyses provided insight into mechanisms that were responsible for the production of strong surface winds. The southwest quadrant of a cyclone was characterized by near dry-adiabatic PBL lapse rates and strong PBL wind speeds, which is favorable for turbulent transport of high momentum air to the surface. In both cases, ascent, likely associated with frontogenesis, was occurring in the presence of potentially unstable layers, which developed as a result of upward-decreasing equivalent potential temperature advection and a dry-air intrusion. As stated in section 4.2, ascent in the presence of potentially unstable layers is conducive to the development of thunderstorms and thunderstorm-related downdrafts.

4.5 Suggestions for future work

This research produced a database of high-wind events that impacted the NE from 15 October 1993 through 31 December 2008. Although the 17 February event had the highest impact in terms of the number of high-wind reports accumulated compared to all other events in the present study, the database contains other high-impact events that are worthy of study. It would be valuable to compile a list of null cases to be studied and compared to cases in the database of high-wind events.

High-resolution numerical simulations of high-impact events could provide insight into the origin of high winds and the mechanisms responsible for transporting high winds to the surface. For example, Clark et al. (2005) simulated the Great Storm of October 1987, and determined, through trajectory analysis, that the high winds at the surface originated in a coherent mesoscale midlevel ‘sting jet’ as described by Browning (2004). Evaporational cooling has been documented to be important for transporting high momentum air to the surface (e.g., Wakimoto 2001; Clark et al. 2005). Numerical simulations of high-impact high wind events could determine the role of diabatic processes in the production of high winds at the surface.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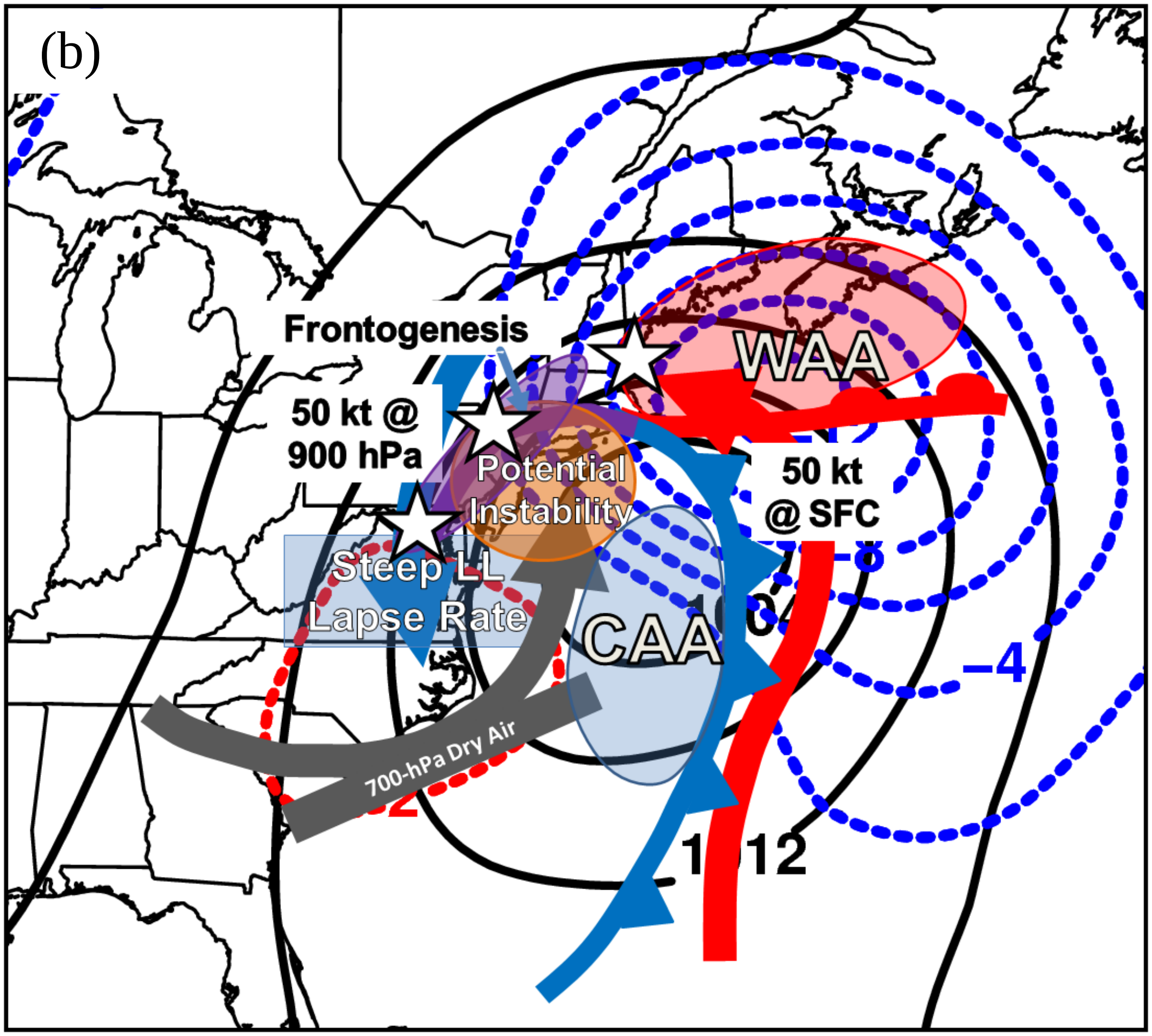

Fig. 4.1 The conceptual models depicting the mechanisms responsible for the production of high surface winds for the (a) 17 February 2006 and (b) 15−16 April 2007 events. For both, MSLP is indicated by the solid black contours, potential instability is shaded in orange, 12-h centered mean sea level pressure change [hPa (12 h)$^{-1}$, dashed; increasing indicated in red, decreasing indicated in blue], regions of warm advection (WAA) and cold advection (CAA) are indicated by the blue and red shaded regions, respectively, and the location of the dry-air intrusion is indicated by the (a) gray shading and (b) gray arrow. The stars denote the locations where high winds occurred. The red and blue arrows represent streamlines at the surface and at 900 hPa, respectively. Frontogenesis is indicated as frontal forcing along the cold front in (a) and is indicated by the purple shading in (b).