4. Discussion, Conclusions, and Suggestions for Future Work

4.1 Discussion

4.1.1 ALT Climatology

Results from a 10-yr climatology indicate that the frequency of ALT occurrence is 26.6% during the warm season (May–September). In a 2-yr climatology, Weisman (1988) found that ALTs occur on 40% of all days during the warm season. Most of the discrepancy between the ALT frequency value from Weisman (1988) and the value shown in the present study can be attributed to how often ALTs were searched for in the climatology. Weisman (1988) recorded the number of “ALT days” during the climatology (i.e., the number of calendar days during which an ALT was recorded at least once), whereas the present study checked for the presence of an ALT every 6 h during the climatology and recorded the total number of ALTs. Results from the present study indicate that 46.1% of all calendar days during the climatology (i.e., 706 out of 1530) would be classified as “ALT days”. The remaining discrepancy can probably be attributed to sampling differences (i.e., a difference in the length of the climatology between the two studies with no overlap in the period of time examined), as well as different data sources and methodology used to define an ALT between the two studies. Weisman (1988) used manually analyzed surface charts from the National Meteorological Center (NMC) to identify ALTs, recording an ALT whenever one of the following three criteria was met: 1) the NMC had analyzed a surface trough over the mid-Atlantic, 2) “baggy isobars” existed over the mid-Atlantic, or 3) an MSLP difference of ≥ 1 hPa existed between the central Carolinas and stations to the east and west. In contrast,
the present study performed an algorithm on CFSR gridded reanalysis data to objectively identify an ALT whenever certain criteria were met (see section 2.2.1). Although the ALT identification algorithm used in this thesis was objective, some subjectivity in the establishment of the criteria and the identification of false alarms could not be avoided. Nevertheless, the results from the ALT climatology seem to reflect an appropriate frequency of warm-season ALTs and are consistent with the ALT climatology of Weisman (1988) once the differences in data and methodology are taken into account.

In the CFSR composite of 13 ALTs whose features were used to derive the climatology criteria (Figs. 3.1a,b), two distinct 1000–850-hPa thermal vorticity minima were evident in the lee of the Appalachians from central Virginia to South Carolina: 1) in the immediate lee of the Appalachians, and 2) just inland of the Atlantic Coast. The negative thermal vorticity implies a warm core in the 1000–850-hPa layer. Assuming hydrostatic balance, the ALT would be expected to be collocated with the two thermal vorticity minima. However, the composite ALT is located between the two thermal vorticity minima. One possible reason for this apparent inconsistency is that the composite procedure, by definition, will smooth signals evident in each of the composite members. An alternative explanation is linked to the unique geography of the mid-Atlantic. The ALT Zone is located between the Appalachians and Atlantic Ocean, which both tend to be climatologically cooler than the ALT Zone during the warm season. As a result, a larger-scale trough would be expected to form within the ALT Zone to satisfy hydrostatic balance. It is likely that smaller-scale troughs appear in the immediate lee of the Appalachians and along the coast. On average, these smaller-scale troughs are likely
superimposed upon the larger-scale ALT, and are better resolved by the 32 km × 32 km NARR than the 0.5° × 0.5° CFSR.

4.1.2 ALT Categorization

ALTs identified in the climatology were categorized according to their relationship to synoptic-scale cold fronts. ALTs that occurred in advance of synoptic-scale cold fronts were also considered prefrontal troughs (PFTs). Manual inspection of instances of the two PFT categories (i.e., ALT categories 3 and 4) revealed that the PFTs were mobile and tied to the movement of the parent cyclone and upstream cold front. Many PFTs evolved according to the conceptual model of prefrontal wind shifts in the lee of the Rocky Mountains shown in Hutchinson and Bluestein (1998), where a lee trough that is initially anchored to the terrain (Fig. 1.5a) moves eastward in association with warm advection to the east of the lee trough (Fig. 1.5b), while an approaching cold front begins to overtake northern portions of the lee trough so that the two features merge at the surface (Fig. 1.5c). Similar lee trough movement has been observed in other studies of troughs forming in the lee of the Rocky Mountains and moving onto the Great Plains (e.g., Gaza and Bosart 1985; Locatelli et al. 1989; Steenburgh and Mass 1994; Martin et al. 1995).

Sanders (1999) presented a conceptual model that was similar to the conceptual model of Hutchinson and Bluestein (1998), except that quasigeostrophic theory was used to predict that the PFT would move faster than the cold front, thereby increasing the separation between the two features. Both conceptual models feature a PFT that moves eastward, but the difference between the two models lies in the initial formation of the
PFT and the subsequent movement of the cold front. In the model presented by Hutchinson and Bluestein (1998), the PFT formed orographically (i.e., downsloping winds caused lee troughing), and at a later time, a cold front overtook northern portions of the PFT. In contrast, orography did not play an explicit role in the conceptual model presented by Sanders (1999). Also, the conceptual model presented by Sanders (1999) showed an initial front without a PFT, while at a later time the PFT formed and moved eastward relative to the front as the front dissipated.

Both of these conceptual models could apply to the ALTs observed in the present study. During the climatology, many category 2 ALTs (i.e., non-PFTs) became category 3 ALTs (i.e., PFTs) as a synoptic-scale cold front approached. Also, as mentioned above, portions of some category 3 and 4 ALTs were overtaken by the approaching cold front. Both of these interactions between the ALT and the cold front fit the conceptual model of Hutchinson and Bluestein (1998). Alternatively, some of the cold fronts associated with category 3 ALTs stalled or dissipated while the ALT itself moved eastward, a progression that fits the conceptual model of Sanders (1999). However, category 4 ALTs cannot fit the conceptual model of Sanders (1999), since by definition, in category 4, the cold front passes through the entire ALT Zone and does not dissipate.

4.1.3 Distributions of Severe Convective Storms in the Mid-Atlantic

A pronounced maximum in storm report frequency was found during the midafternoon and evening hours, with maxima at 2100 and 2200 UTC, whereas a minimum was found during the overnight and early morning hours (Fig. 3.6). Many prior studies have found similar diurnal variability in severe convective storms in the
mid-Atlantic using radar (e.g., Koch and Ray 1997; PA07; Lombardo and Colle 2010; MC11) and/or lightning data (e.g., Reap and Orville 1990; Weisman 1990b; Orville and Huffines 2001; Zajac and Rutledge 2001; MK05; MC11) as a proxy for convective storms. The present study, however, is the first one to specifically examine the diurnal variability of severe convective storms over the mid-Atlantic. Zajac and Rutledge (2001) showed that the diurnal lightning activity cycle was very pronounced between the Appalachians and the Atlantic Coast during the warm season, whereas the diurnal cycle is not the dominant mode of temporal variability in areas farther west such as the Great Plains and Upper Midwest (see their Fig. 10b). In fact, the diurnal maximum in lightning over the Great Plains and Upper Midwest occurs during the late evening and overnight hours, which can be attributed to the numerous nocturnal MCSs that move across these regions during the warm season (McAnelly and Cotton 1989). The lack of storm reports during the overnight hours in the present study suggests that severe nocturnal MCSs are rare to the lee of the Appalachians. This assertion is backed by the results of MK05, who studied warm-season lightning distributions in an area centered on the Appalachians in North Carolina. They found that warm-season MCSs were rare in their region of study, and most of those that did occur stayed to the west of the Appalachians.

Despite the diurnal cycle being the dominant mode of variability in convective storms in the mid-Atlantic, several studies have found an eastward-propagating convective signal (e.g., Orville and Huffines 2001; MK05; PA07; MC11). In particular, PA07 and MC11 each found a favored convective initiation region along and in the immediate lee of the Appalachians in the early afternoon hours, with the convection progressing eastward through the afternoon and evening (see their Figs. 7 and 11,
respectively. MK05 attributed the preferred convective initiation region over the Appalachians to upslope flow and lower-tropospheric convergence. The present study found storm report maxima during the 6 h following an ALT in the immediate lee of the Appalachians (i.e., just inside the western boundary of the ALT Zone; Fig. 3.8). These storm report maxima are likely related to the preferred convective initiation regions and eastward-propagating convective signal found by PA07 and MC11. In an average sense, storms that initiate over the Appalachians and move eastward can be expected to strengthen upon reaching a more strongly heated boundary layer and a more convectively unstable air mass at lower elevations compared to over the Appalachians.

During 6-h periods beginning at 1800 UTC with at least one active grid box, nearly twice as many storm reports occurred, on average, when an ALT was present at 1800 UTC (17.0) than when an ALT was absent at 1800 UTC (9.3). This result is linked to increased MUCAPE at sounding locations near the ALT Zone at times when an ALT was present compared with times when an ALT was absent (Figs. 3.13a,b). Furthermore, the spatial distribution of storm reports during the 6 h following an ALT shows that the ALT Zone is a favored location for storm reports compared with locations outside of the ALT Zone (Fig. 3.8). MC11 showed a similar result in their composite of convectively active warm-season days over the mid-Atlantic and northeastern U.S., since an ALT was evident in their composite (Fig. 1.8c). Furthermore, MC11 found that 65% of days with lightning frequency over two standard deviations above the mean in northern Chesapeake Bay were associated with a PFT to the lee of the Appalachians. The present study hypothesizes that, at first-order, a surface trough in the lee of the Appalachians (i.e., an ALT or PFT) can be considered a “marker” for an axis of convective instability, due to
the collocation of the ALT or PFT with a lower-tropospheric thermal maximum. As a result, the presence of an ALT or PFT can serve as an alert to forecasters for the potential of active severe convection.

4.1.4 Convective Environments Characteristic of the ALT Zone

A comparison of MUCAPE values between observations derived from radiosondes and two reanalysis datasets (CFSR and NARR) revealed that both reanalyses consistently underestimated MUCAPE values relative to the observations (Figs. 3.14a–d). Part of the discrepancy between the observations and the reanalyses could be due to the differing methods of calculating MUCAPE between the three sources. It is also possible that the MUCAPE underestimation in the reanalyses is partially due to difficulties in accurately parameterizing the boundary layer. If that is the case, the reanalyses may also underestimate surface temperature, dewpoint, and derived variables such as TeD. As a result, caution should be exercised when attempting to interpret these reanalysis-derived boundary layer variables quantitatively.

MUCAPE and VWS were calculated at the location of the first daily storm report for each ALT Zone sector. These values did not show much skill in differentiating between days with more or less than five active grid boxes; however, for each sector, a line can be drawn within MUCAPE/VWS phase space below which few to no storm reports occur (Figs. 3.11a–c). The underestimation of MUCAPE in the NARR gives added confidence that this line separates environments that may be conducive for severe convective storms from environments that are not conducive for severe convective storms.
4.1.5 Composite Analysis

Prior works (e.g., Benjamin and Carlson 1986; Steenburgh and Mass 1994; Hobbs et al. 1996; see their sections 4c, 6d, and Fig. 1, respectively) have shown that Rocky Mountain lee troughs can act as boundaries between dry air to the west of the trough associated with westerly downslope winds and moist air to the east of the trough that is advected poleward by southerly winds. It is reasonable to assume that the downsloping westerlies would suppress convection to the west of the lee trough. However, the present study does not show suppressed convection in the immediate lee of the Appalachians; in fact, the immediate lee of the Appalachians is the location of the storm report maxima during the 6 h following the presence of an ALT (Fig. 3.8). A possible reason why severe convection is not suppressed in the immediate lee of the Appalachians during ALT days is evident upon examination of the 10-m wind fields of the initial ALT composite (Figs. 3.1a,b). In this composite, winds between the Appalachians and the ALT are southwesterly, not westerly. Manual inspection reveals that 8 of the 13 1800 UTC composite members (62%) exhibited 10-m meteorological wind directions of 180°–240° (i.e., between southerly and west-southwesterly) over the majority of the portion of the ALT Zone that lies between the Appalachians and the ALT. The lack of westerly winds between the Appalachians and the ALT likely means that drier air that has descended from the Appalachians does not make it far, if at all, into the ALT Zone (although a trajectory analysis would be needed to confirm this hypothesis).

Meteorological wind directions of 180°–240° at 10 m in the immediate lee of the Appalachians are evident to a degree in the 2S and 3S composites as well (Figs. 3.16b,c, 3.17b,c). Manual inspection of the members of 2S and 3S reveals that 77% and 71% of
the members, respectively, exhibit 10-m meteorological wind directions of 180°–240° over the majority of the portion of the ALT Zone that lies between the Appalachians and the ALT. The 6 June 2002 case study also showed meteorological wind directions of 180°–240° over the majority of the ALT Zone both to the east and the west of the ALT (discussed further in the next section).

The present study shows that the ALT does not always mark the location of a sharp wind-shift boundary. In fact, most of the composite members for all ALT categories did not exhibit a sharp wind shift anywhere within the ALT Zone; rather, many showed a gradual backing of the winds from westerly to southerly from the Appalachians to the Atlantic Coast. Manual analysis of the composite members for each of the six severe and nonsevere ALT categories reveals that only 15 of the 112 total members (13%) exhibited a wind shift of > 45° over 100 km anywhere between the Appalachians and the Atlantic Coast. As a result, in almost all of the composite members, the ALT did not act as a sharp dewpoint boundary, as lee troughs originating from downslope flow across the Rocky Mountains sometimes do. Rather, the dewpoint often gradually increased from west to east across the ALT Zone, as depicted in the composite analyses [panel (c) of Figs. 3.15–3.20]. Despite the lack of sharp wind-shift boundaries evident in the reanalyses it is likely that there are often localized wind-shift boundaries whose horizontal scales are too fine to be reproduced by reanalyses. Such a localized wind-shift boundary was evident in the 6 June 2002 case study.

A few speculative comments about the difference between Rocky Mountain lee troughs and ALTs with respect to the sharpness of the wind-shift boundary and the magnitude of the dewpoint gradient are presented below. These differences may be
related to the different geographic characteristics of the Rocky Mountains and the Appalachians. Two main geographical differences are evident: 1) the Rocky Mountains are higher and broader than the Appalachians, and 2) the orientation of the Rocky Mountains is roughly north-northwest to south-southeast from the U.S./Canada border to Colorado, and north to south from Colorado to the U.S./Mexico border, whereas the orientation of the Appalachians is roughly northeast to southwest. As a result, the Rocky Mountains may represent a quasi-infinite barrier, whereas the Appalachians represent a finite barrier around whose southern end air parcels in the lower troposphere may travel [as shown by Weisman (1988, 1990a)]. Because the Appalachians represent a finite barrier, it seems possible for lower-tropospheric trajectories terminating west of the ALT (i.e., between the Appalachians and the ALT) to not have crossed the Appalachians. In this case, the ALT and its associated gradual wind shift may mark the difference between ending locations of southwesterly lower-tropospheric trajectories originating from the Gulf Coast and terminating in the ALT Zone west of the ALT, and southerly lower-tropospheric trajectories originating from the Atlantic Ocean or eastern Carolinas and terminating in the ALT Zone east of the ALT. Because both of these source regions tend to be relatively moist during the warm season, there is not a marked dewpoint drop to the west of the ALT. In contrast, because of the height and orientation of the Rocky Mountains, it seems unlikely to have trajectories terminating to the west of the Rocky Mountain lee trough that do not originate over the higher terrain and dry upon descending to the Great Plains. In addition, since the elevation change from the Rocky Mountains to the Great Plains is much greater than the elevation change from the Appalachians to the
Coastal Plain, the degree of downslope drying is likely greater over the Rocky Mountains/Great Plains region than over the ALT Zone.

Considerable variation was evident among the members of both the severe and nonsevere composites with respect to the locations and amplitudes of upper-tropospheric troughs and ridges, as well as the locations and magnitudes of QG forcing and the nearest surface low pressure center. However, manual inspection of the members of each composite yields certain features that were present in the majority of the members. Some of these features can be used to discriminate between severe and nonsevere days for each category. The features that are evident in the majority of the severe composite members, as well as those that can be used to discriminate between severe and nonsevere days, are shown in conceptual models for ALT categories 2–4 (Figs. 4.1a–c, respectively). For categories 2 and 3, a plume of CAPE that extends poleward throughout the ALT Zone (i.e., approximately 900 km) was the best discriminator between the severe and nonsevere composites. In both 2S and 3S, 82% of the members showed the CAPE plume, whereas in 2N and 3N, only 36% and 12% of the members, respectively, showed the CAPE plume (Figs. 4.1a,b). Other features that appeared in the majority of the members of 2S and 3S were TeD > 20 K over at least half of the ALT Zone (shown in 100% and 88% of the members, respectively) and 10-m meteorological wind directions of 180°–240° over at least half of the portion of the ALT Zone between the Appalachians and the ALT (77% and 71%). The CAPE plume and high TeD values demonstrate some of the convective instability parameters that are necessary for the development of severe convective storms on 2S and 3S days. The 10-m wind direction parameter is linked to
the convective instability parameters for reasons discussed in the previous paragraph (i.e.,
drier air is likely prevented from penetrating into the ALT Zone).

In 4S, the juxtaposition of a poleward-extended CAPE plume with > 30 kt of
VWS occurred in 65% of the composite members, whereas this juxtaposition occurred in
just 18% of the 4N members (Fig. 4.1c). Greater VWS in category 4 compared with
category 2 and 3 is a signal that convective storms occurring during category 4 days are
more likely to be spatially organized and longer-lived than convective storms occurring
during category 2 or 3 days. Furthermore, TeD > 20 K over at least half of the ALT Zone
occurred in 82% of the members of 4S, whereas it occurred in just 47% of the members
of 4N. In addition to demonstrating the convective instability present in 4S, this result
shows that the thermodynamic environment may still be conducive for wet microbursts
within areas of the ALT Zone that do not have high VWS on 4S days. Recognition of the
aforementioned features that often occur during severe convective storm days, as well as
those that discriminate between severe and nonsevere days, can allow for increased
situational awareness in an operational forecasting setting.

4.1.6 Case Study

The 6 June 2002 severe convective storm event was chosen for analysis in order
to identify mechanisms responsible for severe convective storms and to determine what
role the ALT plays in initiating and sustaining these storms. Several aspects of this event
were similar to the 4S composite (Figs. 3.20a–e). For instance, an upper-tropospheric
trough was present upstream of the ALT Zone at 1800 UTC when the storms were
initiating within the ALT Zone (Fig. 3.22a), although the trough axis and associated QG
forcing for ascent were farther west than in the composite and did not affect the ALT Zone until 2100 UTC (not shown). In addition, the event exhibited a plume of high CAPE that extended poleward throughout the ALT Zone and was juxtaposed with > 30 kt VWS (Fig. 3.25a), and the event exhibited > 20 K TeD over the majority of the ALT Zone (Fig. 3.25b), both of which are features that are evident in the 4S composite (Figs. 3.20d,e).

Prefrontal storms initiated along a wind-shift boundary in the immediate lee of the Appalachians (Fig. 3.24a). This wind-shift boundary occurred where westerly winds over the Appalachians converged with southwesterly winds between the Appalachians and the ALT. Downslope drying did not occur since backward trajectories originating in the lee of the Appalachians did not pass over the Appalachians (Fig. 3.26). As a result of the lack of downslope drying, dewpoints reached 20–24°C and θe values reached 350–365 K in the vicinity of the ALT (Figs. 3.24b,c). As the prefrontal storms moved eastward, they moved into an increasingly convectively unstable air mass in the vicinity of the ALT. A conceptual model is presented for this event in Fig. 4.2. The main features of the conceptual model are: 1) storms initiating along a wind-shift boundary in the immediate lee of the Appalachians, 2) an ALT collocated with a surface θe maximum located east of the storm initiation region, and 3) storms intensifying as they approach the ALT and its associated surface θe maximum. Since ALTs are associated with lower-tropospheric thermal anomalies, given an appropriate amount of VWS, storms moving toward the ALT can be expected to intensify upon encountering an air mass with more convective instability in the vicinity of the ALT compared with the convective initiation region. The fact that the severe composites of ALT categories 2–4 show MUCAPE
increasing from west to east over the ALT Zone adds confidence to this conceptual model.

4.1.7 Applications of Research to Operational Forecasting

This research has attempted to classify ALTs and investigate their association with severe convective storms in order to provide forecasters with enhanced situational awareness when severe convective storms are possible in the presence of an ALT. Knowledge of the expected ALT category on a particular day (i.e., the location of the nearest upstream cold front and its expected progression) can provide forecasters with the expected spatial organization of severe convective storms, and it can point forecasters toward other parameters to examine in order to assess the likelihood of severe convective storms. For instance, on days featuring ALT categories 2 or 3, convection is less likely to be spatially organized relative to category 4, owing to the lack of VWS and QG/frontal forcing for ascent in categories 2 and 3 (with the exception of the area along the portion of the front that passes through the ALT Zone in category 3). Despite the expected lack of spatially organized convection in categories 2 and 3, certain steps can be taken to assess the likelihood and favored locations of severe convective storms. For instance, observed morning soundings and forecast afternoon soundings can be examined to assess the potential for wet microbursts. TeD values > 20 K along with midtropospheric dry air above a column of moist air both support the possibility of wet microbursts in a high-CAPE, low-VWS environment. In addition, deep convection in general will be more likely to occur if there is no capping inversion present. Climatologically favored areas of convective initiation should be considered [i.e., along and in the immediate lee of the Appalachians and along the sea-breeze boundary (when present)], along with favored
areas for storm reports for categories 2 and 3 (Figs. 3.9b,c). Throughout the afternoon as
convective storm occurrence becomes more favorable because of increasing convective
instability, detection of mesoscale surface boundaries and convergence zones is
important, especially if the environment is uncapped and convectively unstable. In that
case, all that is needed to initiate deep convection is a triggering mechanism.

If a category 4 ALT day is anticipated, the convection can be expected to be more
spatially organized due to greater VWS and QG/frontal forcing for ascent than in
categories 2 or 3. However, severe convection can still develop ahead of the strongest
QG/frontal forcing as seen in the case study (i.e., because of convergence along a
mesoscale surface boundary in an uncapped, convectively unstable environment). As a
result, assessment of wet microburst potential and detection of mesoscale surface
boundaries in the prefrontal air mass (i.e., in the vicinity of the ALT) remains important
in order to identify areas located ahead of the strongest QG/frontal forcing that are still
favorable for severe convective storms. In addition, identifying the collocation of the
poleward-extended CAPE plume with > 30 kt VWS is important in order to pinpoint a
possible threat region for the strongest, longest-lived convective storms (this collocation
occasionally appears on category 3 days, as well). As shown in the case study conceptual
model (Fig. 4.2), knowledge of the location of the convective initiation region with
respect to the location of the ALT and any associated warm/moist axes can be used to
predict whether convective storms will intensify given enough VWS.

In addition to assessing the potential for severe convection based upon ALT
category, consideration of MUCAPE and VWS calculated at the first daily storm report
can be useful in placing a certain day into climatological context. For instance, forecast
values of MUCAPE and VWS valid during the afternoon hours can be compared with box-and-whisker plots of MUCAPE and VWS calculated at the location of the first daily storm report for each ALT Zone sector and month (Figs. 3.12a–f). Specifically, since convective instability is usually present during the mid-Atlantic warm season, VWS values greater than the 75th percentile for each sector during JJA should be taken as a signal that a severe convective storm event is likely, given the presence of a triggering mechanism to initiate deep convection. PA07 support this assertion by finding that “even though instability is usually present in the southeastern United States during the summer, organized convective episodes only occur on days with relatively higher shear” (p. 3722; see also their Fig. 16). In fact, PA07 find that even during the month with the lowest shear (August), the mean VWS value in the mid-Atlantic during convectively active days is still greater than the median VWS value for the entire year. Despite the importance of VWS, however, severe convective storms are still possible in environments of low VWS (especially in environments conducive for wet microbursts), though the convection is less likely to be spatially organized or long-lived. During MS, when VWS is likely to be higher relative to JJA, the expected MUCAPE value may play a more important role relative to its role during JJA. For each sector during MS, MUCAPE values above the 75th percentile (recall that the MUCAPE values presented in Figs. 3.12a–f are calculated from the NARR and are thus likely underestimates) coupled with VWS values above the median should serve as a signal that a severe convective storm event is likely, given the presence of a triggering mechanism to initiate convection.

Additionally, comparison of forecast afternoon MUCAPE and VWS values with scatterplots of MUCAPE and VWS calculated at the location of the first daily storm
report for each sector (Figs. 3.11a–c) can yield insight into the possibility of severe convective storm occurrence. Especially on days in which the environment for severe convective storms seems marginal, comparison of forecast MUCAPE and VWS values with the line on the scatterplot below which severe convective storms are rare can increase confidence as to whether or not severe convective storms are possible.

4.2 Conclusions

The main goals of this thesis were to: 1) establish a climatology of warm-season ALTs in the mid-Atlantic; 2) document the spatial and temporal distributions of severe convective storms in the mid-Atlantic with particular emphasis on the role of the ALT in modulating those distributions; 3) investigate the convective environments characteristic of the ALT Zone; 4) construct composites of ALT events associated with severe convective storms; and 5) study a specific ALT event associated with severe convective storms. To accomplish these objectives, 13 cases of ALTs associated with severe convective storms were analyzed using CFSR data, and three prominent features representative of the 13 cases were identified. The three features were: 1) lower-tropospheric wind components over the Appalachians orthogonal to and downslope of the Appalachians, 2) the ALT itself in the lee of the Appalachians, and 3) a lower-tropospheric thermal ridge collocated with the ALT. An ALT identification algorithm that was based on these three features was performed using CFSR data during 10 warm seasons. ALTs were found to form most often during times of daily and seasonal peak heating. The ALTs identified by the algorithm were categorized based on their relationship to synoptic-scale cold fronts. The frequency of occurrence of each ALT category was dependent on the month. ALTs associated with a total frontal passage from
the Appalachians to the Atlantic Coast (i.e., category 4) were more likely to occur in May and September, whereas ALTs not associated with a total frontal passage (i.e., categories 2 and 3) were more likely to occur during June, July, and August.

A climatological context for severe convective storms was established by determining the spatial and temporal distributions of storm reports in the mid-Atlantic. The spatial distributions of storm reports varied by ALT category. The spatial distributions of storm reports for categories 2 and 3 were qualitatively similar within the ALT Zone, with local maxima in the immediate lee of the Appalachians. Storm reports associated with category 4 ALTs were found to favor the Washington, DC, to Philadelphia corridor. This corridor was collocated with the juxtaposition of a CAPE plume that extended poleward throughout the ALT Zone and > 30 kt VWS. In addition, a larger proportion of storm reports extended to the Atlantic Coast in category 4 than in categories 2 and 3, a result that is likely tied to frontal forcing spreading across the entire ALT Zone in category 4. A marked midafternoon and early evening maximum in storm reports was found in the ALT Zone, as well as a minimum in the overnight and early morning hours. The time of the first daily storm report varied by latitude, with the peak time of the first daily storm report occurring 2 h earlier in the southern portion of the ALT Zone compared with the northern portion.

The convective environments characteristic of the ALT Zone were examined by calculating MUCAPE and VWS at the location of the first daily storm report. Severe convective storms developed in an environment characterized by higher MUCAPE in the southern portion of the ALT Zone compared with the northern portion, whereas severe convective storms developed in an environment characterized by higher VWS in the
northern portion of the ALT Zone compared with the southern portion. In addition, a comparison of observed MUCAPE values revealed that times when an ALT was present were associated with higher MUCAPE values than times when an ALT was absent. This result was linked to the result that nearly twice as many storm reports occurred during the 6 h following the presence of an ALT compared with the 6 h following the absence of an ALT.

Severe and nonsevere composites were constructed for ALT categories 2–4 in order to pinpoint dynamical processes and thermodynamic environments conducive to severe convective storms, and to find features that discriminate between situations that favor and do not favor severe convective storms for each category. A plume of CAPE that extended poleward throughout the ALT Zone was evident in the severe composites of categories 2–4, and in category 4, that plume was juxtaposed with > 30 kt VWS. This juxtaposition was collocated with the maximum in storm reports for category 4 (i.e., the Washington, DC, to Philadelphia corridor). All three severe composites were also characterized by TeD values > 20 K, a threshold value found by Atkins and Wakimoto (1991) to be favorable for the occurrence of wet microbursts. A majority of members of the severe composites for categories 2 and 3 were characterized by 10-m meteorological wind directions of 180°–240° between the Appalachians and the ALT. It is hypothesized that the lack of westerly (downslope) winds in the immediate lee of the Appalachians means that drier air descending from the Appalachians does not progress far into the ALT Zone, so convection is not suppressed in the immediate lee of the Appalachians.

A severe convective storm event associated with an ALT was studied in order to clearly elucidate the dynamical processes and thermodynamic environments associated
with severe convective storms in the presence of an ALT. The event showed features similar to the category 4 severe composite, such as a CAPE plume that extended poleward throughout the ALT Zone juxtaposed with > 30 kt VWS. An extremely convectively unstable air mass was in place over the ALT Zone, characterized by TeD values of 20–35 K and $\theta_e$ values of 345–365 K. Severe prefrontal storms initiated along a wind-shift boundary in the immediate lee of the Appalachians and strengthened upon approaching the ALT and an axis of high $\theta_e$ that was collocated with the ALT. Observed 1200 UTC soundings and model-derived 2100 UTC soundings ahead of the prefrontal storms showed a layer of midtropospheric dry air in an otherwise moist environment, a setup that is comparable to conceptual models for wet microburst-producing storms. A second round of severe alongfront storms developed west of the prefrontal storms and strengthened within the ALT Zone in an environment that had not convectively stabilized in the wake of the prefrontal storms.

4.3 Suggestions for Future Work

An unanswered problem that arose from this research is quantifying the contribution of orographic effects relative to diabatic effects in ALT formation. On one hand, the presence of lower-tropospheric downslope wind components was a criterion used to define ALTs in the present study. On the other hand, ALTs are more likely to form during times of peak heating, suggesting a link to the diurnal and seasonal heating cycles. Additionally, the downslope flow over the Appalachians was often fairly weak. In cases of weak lower-tropospheric cross-mountain flow, the ALT is less likely to be a result of orographic forcing. A WRF modeling study where terrain and heating could be turned on and off [similar to Benjamin (1986), but specifically with terrain and boundary
conditions characteristic of the mid-Atlantic] could be a step toward answering this problem. It would also be useful to composite ALTs based upon wind direction between the Appalachians and the ALT. It seems likely that the dewpoint gradient in the vicinity of the ALT would be larger with northwest flow (i.e., downslope flow) to the west of the ALT than with southwest flow (i.e., flow not passing over the Appalachians), but this hypothesis should be tested. In such a test, the distribution of severe convective storms could be compared between the two composite categories.

Opportunities for future research also exist in examining PFTs in the northeastern U.S. (i.e., expanding the domain north of the ALT Zone). Anecdotal evidence and conventional wisdom from National Weather Service forecasters in the northeastern U.S. supports the hypothesis that severe convective storms in the northeastern U.S. often occur along or within a PFT. A climatology of PFTs in the northeastern U.S. would yield the frequency of PFT occurrence, and PFTs identified in the climatology could be compared to radar data and/or storm reports to determine the association of PFTs with severe convective storms. A categorization scheme similar to the one developed in the present study could be used to categorize PFTs in the northeastern U.S.

Additional analyses that quantify wet microburst potential could be performed in the ALT Zone. Prior work (e.g., Atkins and Wakimoto 1991; Wheeler and Roeder 1996) has found that the potential for wet microbursts becomes more likely as certain threshold TeD values are exceeded. Since these threshold values appear to be location-specific, a study of TeD values observed before the occurrence of wet microbursts within the three ALT Zone sectors could be performed in order to determine if there is a certain TeD threshold value above which wet microbursts become increasingly likely.
TeD > 20 K over at least half of ALT Zone: 100

10-m wind directions 180°–240° over at least half of the ALT Zone between the Appalachians and the ALT: 77

Poleward-extended CAPE plume: 82 (36)

TeD > 20 K over at least half of ALT Zone: 100

TeD > 20 K over at least half of ALT Zone: 88

10-m wind directions 180°–240° over at least half of the ALT Zone between the Appalachians and the ALT: 71 (47)

Poleward-extended CAPE plume: 82 (12)
Fig. 4.1. Conceptual model of (a)–(c) key features of the severe composites of ALT categories 2–4, respectively. Blue shading indicates areas of MUCAPE > 1000 J kg\(^{-1}\), yellow shading indicates areas of VWS > 30 kt, and red shading indicates areas of Q-vector divergence < \(-3 \times 10^{-15}\) K m\(^{-2}\) s\(^{-1}\). Red (blue) numbers indicate the percentage of severe (nonsevere) composite members that exhibit the indicated feature. Blue numbers are only included for features that discriminate between the severe and nonsevere composites.
Fig. 4.2. Conceptual model based upon the 6 June 2002 severe convective storm event showing MSLP (black contours, hPa), VWS (dark blue contours, ≥ 25 kt), and 10-m winds (barbs, kt). Prefrontal storms (dots colored according to the key in the bottom left of the image) initiate along a wind-shift boundary in the immediate lee of the Appalachians west of the ALT (dashed black line) at $t = t_0$. The ALT marks the location of an axis of high $\theta_e$ (green shading). The storms intensify at $t = t_0 + \Delta t$ upon approaching the ALT and collocated high $\theta_e$ axis.