A PRELIMINARY STUDY OF INVERTED-V SOUNDINGS AND DOWNSTREAM SEVERE WEATHER IN NEW YORK AND PENNSYLVANIA

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Abstract

Severe weather outbreaks associated with inverted-V thermodynamic profiles over the northern mid-Atlantic region can be difficult to anticipate, due to the low convective available potential energy (CAPE) often present in these environments. To further understand the relationship between inverted-V soundings and severe weather over New York and Pennsylvania, a study of severe weather events in this area was conducted. The goals of the study were: (1) to examine a group of major severe weather events associated with upstream, observed inverted-V sounding profiles; (2) to develop insight into the characteristics of the environments associated with these events; and (3) to examine the utility of observed, upstream soundings for anticipating these events.

During the period of study, it was found that just less than 40 percent of major severe weather events in the study area occurred with a subjectively-determined, upstream inverted-V profile, based on data from the 1200 UTC Buffalo and/or Pittsburgh sounding sites. Additional analysis from a set of objectively determined events indicated that the majority of these cases occurred during the warm season and were associated with a large number of damaging wind reports. Linear convective events within this group were especially dominated by damaging wind reports, while non-linear convection was associated with a more even distribution of damaging winds and other types of severe weather. The majority of these outbreaks were associated with progressive surface cold fronts or surface troughs. Examination of the observed soundings from these cases indicated that they were

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mostly associated with small amounts of CAPE, moderately large downdraft CAPE (DCAPE), and a wide range of forecast CAPE (FCST CAPE, based on surface conditions modified for afternoon heating). A wide range of 0-3 and 0-6 km mean wind speeds was found, with values less than 50 kt. Observed storm motions were mostly faster than the mean wind. Composites and corresponding anomalies of the synoptic-scale patterns associated with these events indicated mid-tropospheric troughs over the northern Great Lakes and ridges over the Ohio Valley and mid-Atlantic region; strong mid-tropospheric zonal wind flow over the lower Great Lakes; large, positive lower-tropospheric temperature anomalies over the northern mid-Atlantic region; and corresponding large, negative lower-tropospheric relative humidity anomalies. Finally, a subset of major events characterized by little to no FCST CAPE was identified. It was found that the above-listed characteristics of the major events were particularly pronounced for these events.

Two case studies of convective events associated with upstream, observed inverted-V soundings are examined. The cases are shown to illustrate conditions associated with a major event and to compare and contrast those conditions with an event that produced little severe weather. The similarity in some of the fields associated with these two events demonstrates that it can sometimes be difficult to discriminate between major and minor events a priori in an operational setting. However, it is shown that diagnostics associated with the strength of the meso-scale and synoptic scale forcing associated with these cases may be useful to discriminate between a major and minor event.

1. Introduction

Environmental temperature and moisture profiles characterized by steep lapse rates and increasing relative humidity with height in the lower troposphere, capped by a moist layer in the mid troposphere, are known as “inverted-V” profiles (Beebe 1955). Convective storms forming in these well-mixed environments frequently produce strong to severe convective wind gusts resulting from the evaporative cooling and strong downdraft potential associated with such a profile (Bluestein 1993).

Wakimoto (1985) found that inverted-V thermodynamic profiles are an important environmental precursor to dry microbursts over the High Plains of the central U.S. Corfidi et al. (2006) studied severe convective wind storms associated with dry lower-tropospheric conditions occurring in a wide-range of locations around the U.S. Composite soundings for the cases in their study were not as moist in the mid-troposphere as a classic inverted-V profile, however many of the features associated with inverted-V soundings were present; most notably, dry air near the surface, and steep lapse rates (greater than 7 °C km^{-1}) from 850-500 hPa. Twelve cases were examined based on data availability and knowledge of the events by the authors. Seven of these events occurred in the mid-Atlantic region, with three events occurring at least partially in Pennsylvania. In addition to dry low-levels and steep low-level lapse rates, the cases were characterized by convective available potential energy (CAPE) values lower than what is often present with significant severe weather outbreaks over the eastern and central U.S. (Lapenta et al. 2002), making them a challenge to anticipate in an operational setting. These systems were typically initiated by strong mesoscale forcing for ascent and were maintained by a thermodynamic and kinematic environment favorable for downdraft-dominated, forward- propagating convective wind storms. The systems appeared to be composed of bands of downwind-directed microbursts, with propagation playing a disproportionately strong role in system movement relative to advection. Evans (2010) examined a large collection of convective events occurring over the northern mid-Atlantic region with environments characterized by low mixed-layer convective available potential energy (MLCAPE) and high deep-layer shear (LCHS). Significant correlations between event severity, lower-tropospheric lapse rate magnitude, and lower-to-mid tropospheric dew point depression during the warm season were identified for these events, implying that lower-tropospheric inverted-V profiles may be a key ingredient for a substantial percentage of major LCHS severe weather events in the study area.

Banacos and Ekster (2010) examined severe convection in the northeast U.S. associated with deep, well-mixed layers elevated above the boundary layer, and found that significant severe events [defined as hail 2 in. (5.1 cm) in diameter or greater, convective wind gusts of 65 kt (33 m s^{-1}) or greater, and/or tornadoes of EF2 or greater intensity] were frequently associated with elevated mixed layers. Environmental inverted-V profiles as examined in this study can be distinguished from elevated mixed layer events in that the mixed layer associated with the inverted-V profile is based closer to the ground.

The study on inverted-V severe weather events detailed in this paper includes the use of observed soundings to examine the convective environment. The current spatial and temporal distribution of the rawinsonde network in the northern mid-Atlantic region dictates that operational forecasters in Pennsylvania and New York wishing to use morning soundings to anticipate thermodynamic conditions later in the day often examine the 1200 UTC Pittsburgh (KPIT) and Buffalo (KBUF) observed soundings, which are located at the western (usually upstream) edge of Pennsylvania and New York. The state of Pennsylvania extends approximately 500 km (300 mi) east of KPIT and the state of New York extends approximately 600 km (400 mi) east of KBUF. Therefore, a mean flow of 30 to 35 kt is required to transport a 1200 UTC air mass over KPIT or KBUF downstream across all of Pennsylvania or New York by early evening.

The purpose of this study is to build on previous work on convective systems occurring in environments characterized by lower-tropospheric inverted-V thermodynamic profiles, by examining several of these events within an area limited to New York and Pennsylvania. The dry low-levels in these cases typically result in much lower values of surface-based convective available potential energy (SBCAPE) than what is typically present prior to a severe weather outbreak (Lapenta et al. 2002). As a result, these events can sometimes be difficult to anticipate operationally, as the forecaster is left wondering whether the CAPE will be sufficient for any convective storms to develop, and whether any storms that do develop will contain updrafts or downdrafts strong enough to produce severe weather. The challenges associated with these types of environments served as the primary motivation for this study.

A local study of these events will be shown, and characteristics of environments associated with these types of events will be investigated. One goal of this study is to encourage forecasters to utilize observed soundings to anticipate severe convective potential, by demonstrating the relationship between observed, inverted-V lower tropospheric profiles and subsequent downstream occurrences of severe weather.

Section 2 of this paper discusses the data collection and methodology used to discriminate among the inverted-V soundings. Results are summarized in Section 3. Section 4 will show two case studies: one of a significant convective event occurring in Pennsylvania associated with an upstream lower-tropospheric inverted-V sounding, and one where upstream inverted-V soundings were identified, but little severe weather occurred. A summary and discussion is given in section 5.

2. Data and Methodology

In order to identify major severe weather events associated with inverted-V thermodynamic profiles, a large database of severe weather events was developed and then reduced using a combination of subjective and objective criteria. First, days with at least 20 reports of severe weather (wind gusts greater than or equal to 50 kt (26 m s^{-1}), hail at least 1 inch (2.5 cm) in diameter or tornadoes) occurring in Pennsylvania and/or New York were defined as "major" severe weather events. These events were identified from 2005 through September 2010, using the Storm Data publication from the National Climate Data Center [*Storm Data* (NOAA 2005-2010)]. For each case, observed thermodynamic profiles were obtained from the 1200 UTC KPIT and KBUF soundings, from the University of Wyoming online sounding archives (University of Wyoming 2012). In order to determine approximately how often subjectively-indicated inverted-V profiles are associated with downstream severe weather, the 1200 UTC soundings from each case were examined, and an initial, somewhat subjective determination was made about whether one or both soundings exhibited a lower-tropospheric inverted-V profile. This subjective determination was based on identification of a steep, near surface-based lapse rate extending to at least 800 hPa and associated with relative humidity increasing with height. Since 1200 UTC soundings often exhibit shallow, surface-based inversions resulting from radiational cooling, the base of the well-mixed layer was allowed to start as high as 925 hPa. However, soundings with the base of the well-mixed layer above 925 hPa were excluded to avoid identifying "elevated mixed layer" events, similar to those studied by Banacos and Ekster (2010). This procedure resulted in the development of a database of major severe weather events and data from corresponding, observed 1200 UTC KBUF and KPIT soundings, from which some initial conclusions were drawn.

The database was further refined in a second iteration by an objective criteria for a lower-tropospheric inverted-V sounding. The reason for this second iteration was to develop a smaller subset of cases that would inarguably be considered inverted-V events, for a more detailed analysis. The criteria was based loosely on lapse rate and dew point depression thresholds used by Banacos and Ekster (2010) for their study on elevated mixed layers, with some modifications based on the fact that this study would be examining mixed layers based closer to the ground. Inspection of the soundings in the initial database indicated that the layer from 925 hPa to 800 hPa would best represent the well-mixed lower-troposphere, since surface-based inversions were often present below 925 hPa, and the well-mixed layer above 925 hPa often did not extend very far above 800 hPa. (The depths of the steep lapse rates found in this study, however, were much less than what is typically observed over the western half of the U.S.) Many of the cases from the initial database were removed in this iteration due to barely failing the lapse rate or dew point depression thresholds. The final, objective criteria for an inverted-V sounding were:

A 925 hPa to 800 hPa lapse rate of at least 7.5 °C km^{-1}.

An increase in relative humidity with height through the layer from 925 hPa to 800 hPa.

A maximum dew point depression from the surface to 800 hPa of greater than 7 °C.

A minimum dew point depression from 800 hPa to 500 hPa of 3 °C or less.

The 925 hPa to 800 hPa lapse rate was calculated by computing the temperature difference between the mandatory 925 hPa level temperature and the significant level temperature closest to, but above, 800 hPa. The application of this objective criteria resulted in a "major event" database containing 10 events.

Next, for each event within the major event database, 12-h 500, 1500, and 3000 m above ground level (AGL) forward trajectories were run from the location of the inverted-V soundings, using the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Draxler and Hess 1997; Draxler and Rolph 2011) model with Global Data Assimilation System (GDAS; Kalnay et al. 1996) data, in order to confirm whether the air mass over the observed soundings was being transported to areas that experienced severe weather later in the day. If the majority of 12-h 500, 1500, and 3000 m trajectories extended over both New York and Pennsylvania, then severe reports from both states were logged with the sounding data. If the 12-h trajectories extended across only one state, then only reports from that state were logged and counted toward establishing the event as "major". If none of the trajectories extended across a state where severe weather was reported, then the event was removed from the database. This procedure resulted in the reduction of the major event database to 9 events. For events when both the KBUF and KPIT soundings were inverted-Vs, the database was reduced to data from one sounding site, by eliminating the sounding associated with fewest downstream reports based on the above methodology. One event (17 August 2007) was added to the major event database based on the 0000 UTC 18 August 2007 Albany (KALB) sounding, which clearly indicated an inverted-V profile around the time of severe weather occurrence upstream over central New York. The final result was a database with 10 major inverted-V events.

Finally, a "null" event database was also developed, using a similar methodology as for the major event database, except that a null event was defined as occurring with one to five severe weather reports. The result was a database containing 17 null events. The focus of this paper will be on data from the major events, although some comparisons between major and null events will be briefly described in the results section.

Sounding parameters were obtained from an archive available at the Storm Prediction Center (SPC) in Norman, Oklahoma. The parameters were calculated from the sounding and hodograph analysis and research program (NSHARP; Unidata 2012). Forecast CAPE (FCST CAPE) was calculated from the observed sounding by estimating the afternoon maximum temperature and dew point by assuming a dry adiabatic lapse rate from 850 hPa to the ground, then adding 2 °C for a superadiabatic "contact" layer, and using a mean mixing ratio in the lowest 100 hPa of the sounding. Composite fields and anomalies were calculated based on National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis data obtained from the Earth System Research Laboratory (Kalnay et al. 1996). The mean fields are based on the period from 1968-1996. Composites are daily composites, derived by averaging data from 0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC. Radar animations from the severe weather events were viewed on the National Weather Service's Advanced Weather Interactive Processing System (AWIPS) workstations in order to determine the dominant mode of convection (linear or other) and the storm speed for each event. The dominant mode of convection was determined subjectively from the animations, based on a classification scheme consisting of linear, and non-linear categories. The storm speed was determined using the AWIPS workstation speed tool on observed radar reflectivity animations. Surface data were obtained from the National Centers for Environmental Prediction's (NCEP) Hydrometeorological Prediction Center (HPC) and the Plymouth State University online archives (Plymouth State University 2012).

3. Results

Application of the methodology shown in section 2 resulted in several findings related to severe weather events associated with upstream, observed inverted-V soundings in the northern mid-Atlantic region.

a. Environmental characteristics

The search for severe weather events from 2005 through 2010, as described in the methodology section, identified 79 days with at least 20 severe reports in New York and Pennsylvania, and 149 days with one to five reports. Examination of the KBUF and KPIT 1200 UTC soundings on these days indicated that 29 of the 79 major events (37 percent) were associated with upstream 1200 UTC profiles that could be considered inverted-V soundings, based on a cursory examination of the lower-tropospheric lapse rate and relative humidity profile. Meanwhile, 56 of 149 null events (38 percent) were associated with upstream, inverted-V soundings. The majority of the major inverted-V events (20) occurred in the summer (June-August), with five in the spring (March-May), three in the fall (September-November), and one in the winter (December-February).

An examination of the major, inverted-V events resulted in the identification of nine major severe weather events when the upstream KPIT or KBUF sounding met the objective criteria for an inverted-V sounding as described in the methodology section, plus one event that was based on the 0000 UTC KALB sounding. The top of the lower-tropospheric mixed layer (the level where the lapse rate decreased with a concurrent decrease in relative humidity, based on visual inspection of the profiles) averaged 704 hPa for these 10 events, indicating a more shallow mixed-layer than what is often observed with an inverted-V sounding over the western half the U.S. (Beebe 1955). A total of 448 severe weather reports were logged downstream from the inverted-V soundings for these 10 events, an average of 45 per event (Table 1). Of these 448 reports, there were 389 severe wind reports (an average of 39 per event, or 87 percent of the total number of severe weather reports), two tornado reports, and 57 large hail reports. Seven of the 10 major events occurred during the summer (June – August), with three events in the spring (March – May). Six of the 10 events were associated with lines of convection, while four were categorized as non-linear (primarily isolated storms or clusters of storms). The six linear events were strongly dominated by damaging wind reports (328 of 341 reports were of damaging winds, or 96 percent), while the other events were associated with a more even distribution between damaging wind and other types of severe weather (61 of 107 reports were of damaging winds, or 57 percent). Seven of the 10 events occurred with progressive cold fronts or troughs, while one event occurred with a stationary front and two occurred with no large-scale surface features analyzed by NCEP's HPC.

Values of several parameters from the upstream inverted-V sounding for these days are summarized in Fig. 1. The number of events depicted is not large enough to allow for any statistically significant conclusions; however, some interesting relationships can be inferred. The 925-800 hPa lapse rates in the study ranged from 7.5 °C km^{-1} to 9.5 °C km^{-1}. An estimated lower-tropospheric lapse rate (calculated by subtracting the surface temperature taken at the closest observing station to the first severe report of the day from the 850 hPa temperature of the observed sounding) indicated a wider range of values, ranging from 9 °C to 15 °C. (Fig. 1a). The distribution of SBCAPE, FCST CAPE and DCAPE (Fig. 1b) indicate that the SBCAPE was low (mostly below 500 J kg^{-1}) for these events, while a larger range was indicated with the FCST CAPE (Fig 1b). The DCAPE values range was relatively narrow, with the majority of cases occurring between 600 and 900 J kg^{-1}. Wide ranges of mean 0-3 and 0-6 km winds were indicated, along with a wide range of 0-6 km bulk shear (Fig. 1c). Interestingly, no cases exhibited a 0-3 km or 0-6 km mean wind speed of greater than 45 kt (23 m s^{-1}). Storm speeds were substantially larger than the mean wind values, indicating that propagation was likely playing a large role in the movement of the storms, in addition to advection.

Date	Sounding Location / time	Downstream reports / wind reports	Times (UTC)	Location
6/1/2007	KPIT / 12 UTC	23 / 18	1900 - 0135	PA
6/8/2007	KPIT / 12 UTC	71 / 71	2036 - 0308	PA
6/13/2007	KBUF / 12 UTC	28 / 27	1750 - 2300	PA and NY
6/19/2007	KPIT / 12 UTC	138 / 127	1508 - 0440	PA and NY
6/21/2007	KBUF / 12 UTC	29 / 10	1820 - 2310	NY
8/18/2007	KALB / 00 UTC	28 / 28	2204 - 0255	NY
7/7/2009	KBUF / 12 UTC	31 / 18	1647 - 0415	NY
4/8/2010	KPIT / 12 UTC	32 / 31	2100 - 0151	PA and NY
4/16/2010	KPIT / 12 UTC	44 / 44	1940 - 2315	PA
5/31/2010	KPIT / 12 UTC	24 / 15	1735 - 0343	PA

Table 1. The 10 major events (20 or more reports) in the study.

Fig. 1(a).

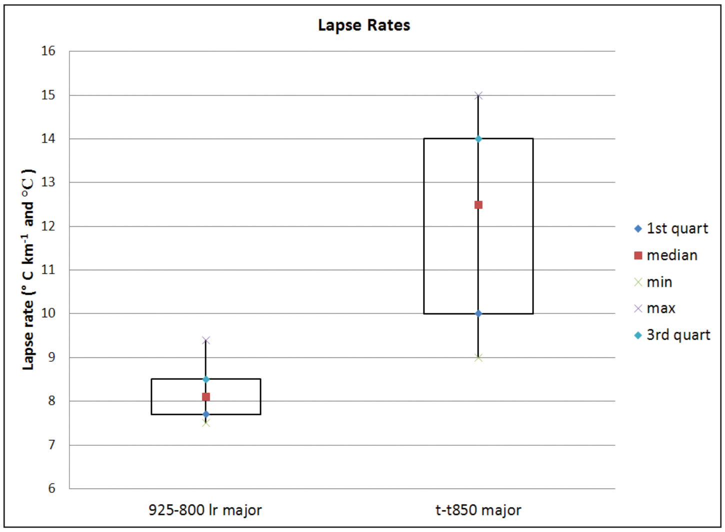

Fig. 1(c).

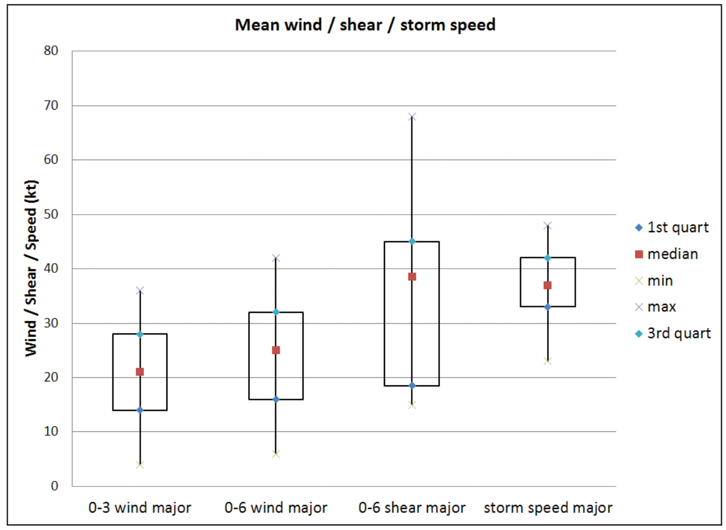

Fig. 1(b).

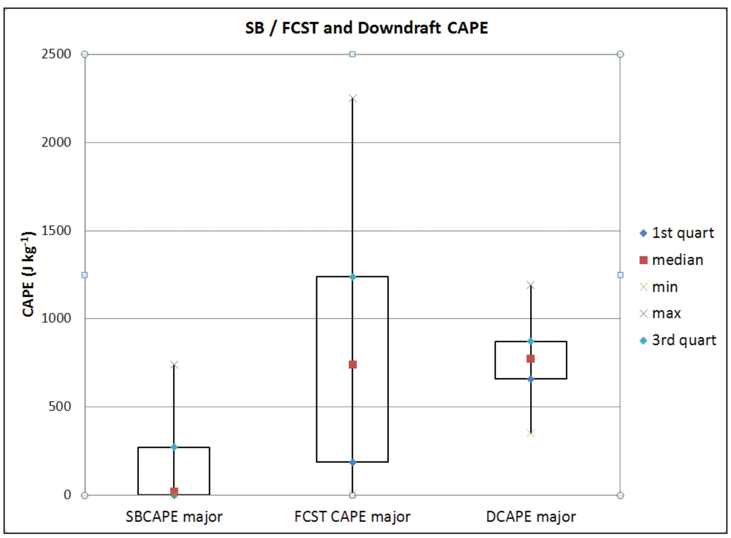

Fig. 1. Box and whisker plot summaries for upstream observed sounding parameters for major events for (a) 925-800 hPa lapse rate (°C km^{-1}) and the difference between surface temperature and upstream sounding 850 hPa temperature (°C) , (b) SBCAPE, FCST CAPE and DCAPE (J kg^{-1}) , and (c) 0-3 km and 0-6 km mean wind, 0-6 km bulk shear, and observed storm speed (kt) . The red dot indicates the median value and the boxes encompass the first and third quartiles. The Xs mark the extremes.

A comparison between sounding parameters from the major event database and parameters from the null event database generally indicated that differences between the major and null events were small (not shown), and were certainly not statistically significant given the small number of cases in each database. The largest difference between the two databases was in the storm speed value, with major events generally associated with larger storm speeds.

To assess the predominant synoptic pattern for the identified major events, composites and corresponding anomalies of several large-scale, lower- and mid-tropospheric fields were produced (Fig. 2). The mean 500 hPa flow for the major events (Fig. 2a) indicates a trough over the northern Great Lakes area and a downstream ridge with anomalously high heights over the mid-Atlantic and northeast U.S. region. The 700 hPa zonal wind major-event composite (Fig. 2b) indicates a band of anomalously high zonal wind speeds across the Great Lakes. The composite 925 hPa relative humidity (Fig. 2c) for the major events was anomalously low over the northern mid-Atlantic region, while the surface temperatures were anomalously high (Fig. 2d). Sea-level pressure and 700 hPa relative humidity composites (not shown), confirmed that these events were associated with pronounced troughs moving east across the Great Lakes region.

A comparison between composites of the large-scale flow pattern associated with major vs. null events indicated somewhat similar patterns; however, the anomalies were larger in the major events (not shown). In addition, the composites indicated that the lower-to-mid tropospheric trough over the Great Lakes was slightly more amplified in the major events than for the null events (not shown).

Fig. 2(a).

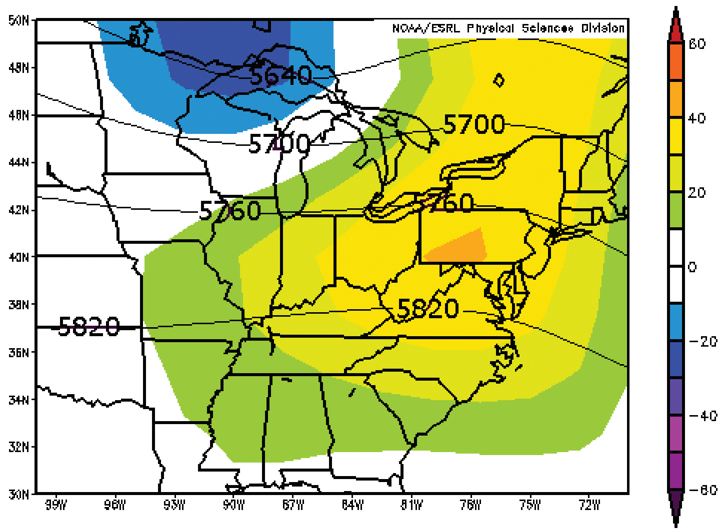

Fig. 2(c).

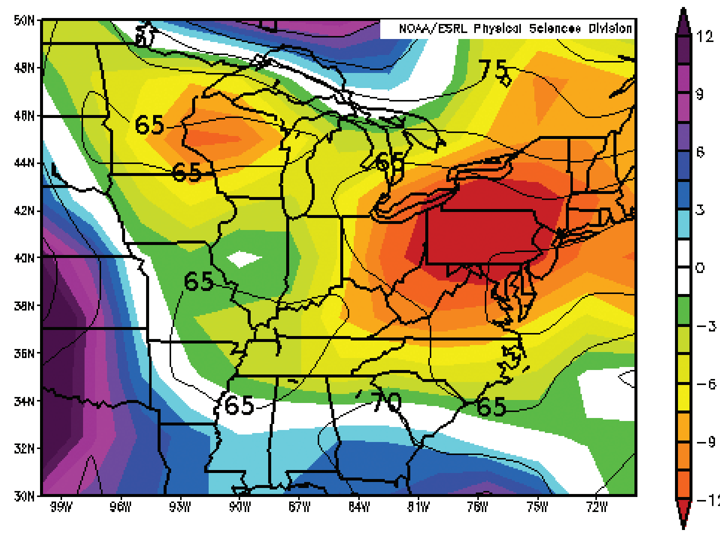

Fig. 2(b).

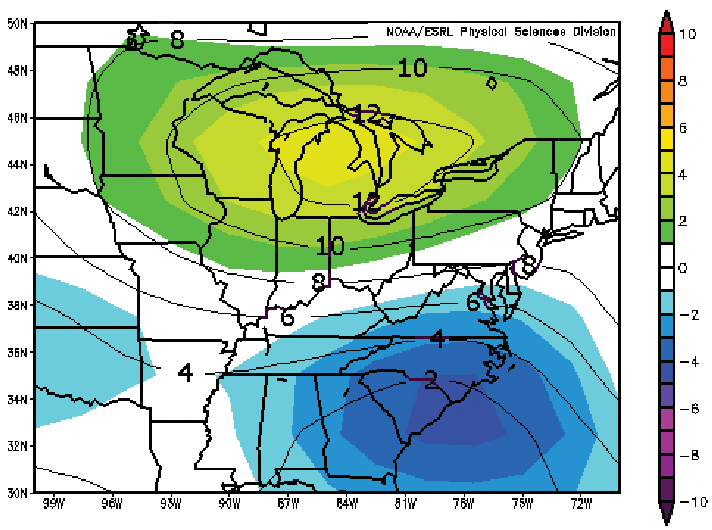

Fig. 2(d).

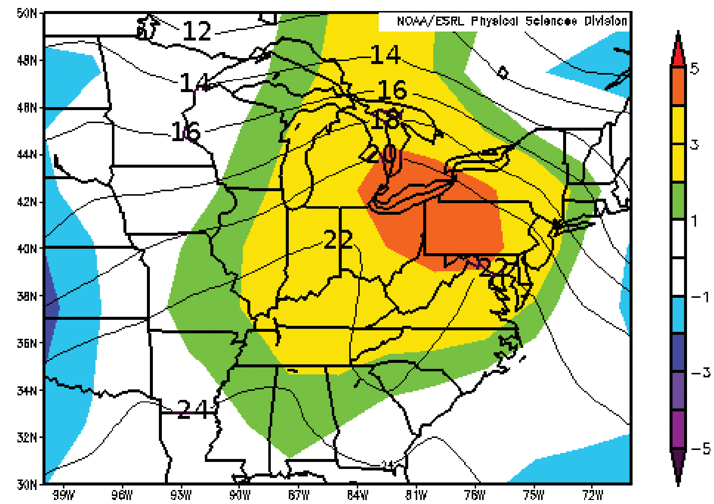

Fig. 2. Composites for the major events in the study of (a) 500 hPa geopotential heights (m, contoured) and anomalies (m, shaded) , (b) 700 hPa zonal wind speed (m s^{-1}, contoured) and anomalies (m s^{-1}, shaded), (c) 925 hPa relative humidity (percent, contoured) and anomalies (percent, shaded), and (d) surface temperature (˚C) and anomalies (˚C, shaded). (from NOAA/ESRL)

b. Major events with large CAPE vs. small CAPE

A closer examination of the 10 major events in this study indicates that these cases can be partitioned into low-CAPE and high-CAPE categories based on the FCST CAPE parameter, and that large differences were observed in several other parameters between these two categories (Fig. 3). A threshold of 500 J kg^{-1} was chosen to discriminate between low-CAPE and high-CAPE cases, based on the distribution of the FCST CAPE data (Fig. 3a). Two of the four low-CAPE events occurred during the spring, while the other two occurred during the summer. Five of the 6 high-CAPE events occurred during the summer, while the other occurred during the spring. The small number of events represented by Figs. 3b-d precludes any statistically significant conclusions from being drawn by the data; however, the DCAPE distribution (Fig. 3b) indicates that the low-CAPE major events were mostly associated with larger DCAPE than the high-CAPE major events (with one exception). The 0-6 km wind speed also appeared to discriminate between the low-CAPE and high-CAPE major events, with low-CAPE major events always associated with larger wind speeds (Fig. 3c). Likewise, 0-6 km bulk shear was larger for the low-CAPE major events (not shown). Finally, the storm speeds associated with low-CAPE major events were also

Fig. 3(a).

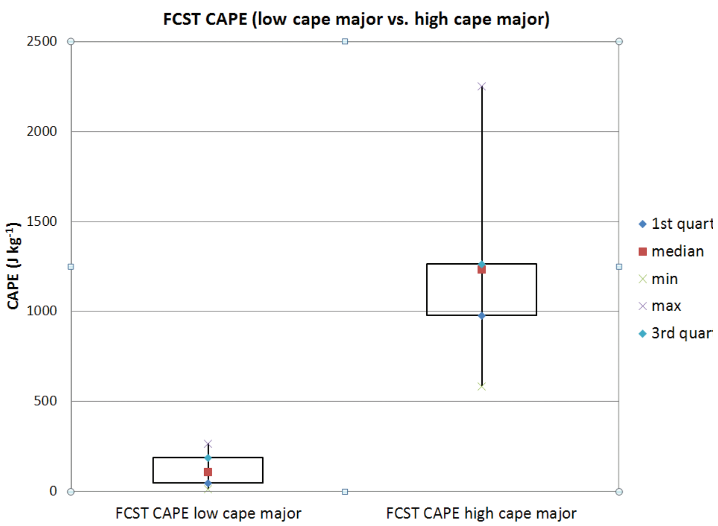

Fig. 3(c).

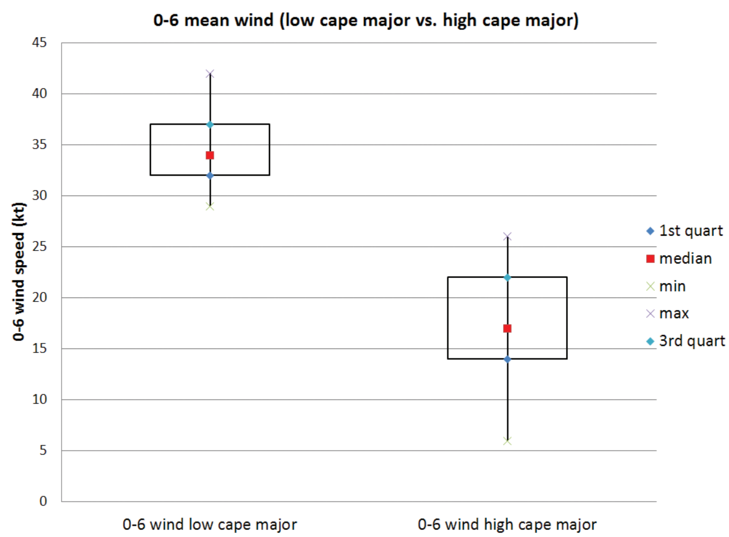

Fig. 3(b).

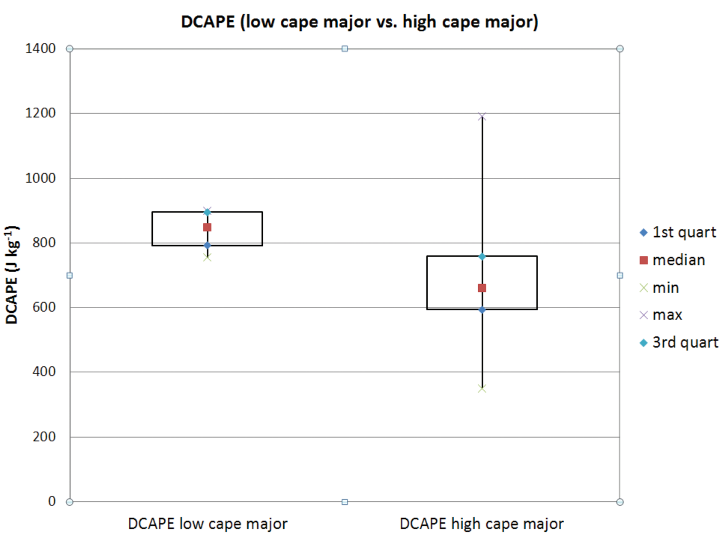

Fig. 3(d).

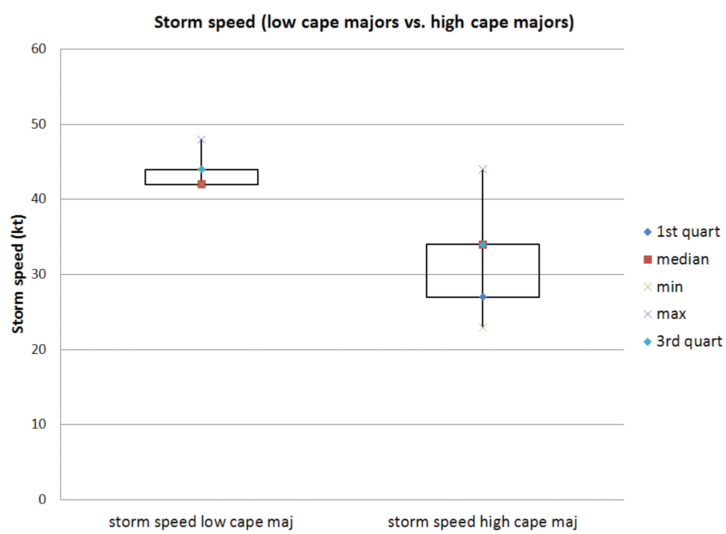

Fig. 3. Box and whisker plots showing upstream observed sounding parameters for low-CAPE major vs. high-CAPE major events for (a) FCST CAPE (J kg^{-1}), (b) DCAPE (J kg^{-1}), (c) 0-6 km mean wind (kt), and (d) storm speed (kt). The red dot is the median value, the boxes encompass the first and third quartiles of the data. The Xs mark the extremes.

generally higher than for the high-CAPE major events (Fig. 3d).

A comparison of composite mean fields and anomalies between the low-CAPE and high-CAPE major events (Fig. 4) indicate some differences between the two categories, although once again the small number of cases in the comparison precludes any statistically significant findings. At 500 hPa, the low-CAPE major events were associated with an anomalously strong trough over the northern Great Lakes (Fig. 4a) and an anomalously strong ridge over the mid-Atlantic region. In the high-CAPE major events, the anomalously high geopotential heights were centered over Quebec, and the anomalously low heights were far to the west over the northern Plains (Fig. 4b). At the surface, both event types were characterized by a trough over the Great Lakes, with the low-CAPE event composite trough much farther south, closer to New York and Pennsylvania (Figs. 4c and 4d). Finally, both types were associated with anomalously warm surface temperatures over the northern mid-Atlantic region, however the positive anomaly was more pronounced in the low-CAPE major events, and was centered directly over Pennsylvania (not shown).

4. Case Studies

In this section, two cases are shown to compare an event with an upstream inverted-V sounding and many severe weather reports (a major event), to an event with

Fig. 4(a).

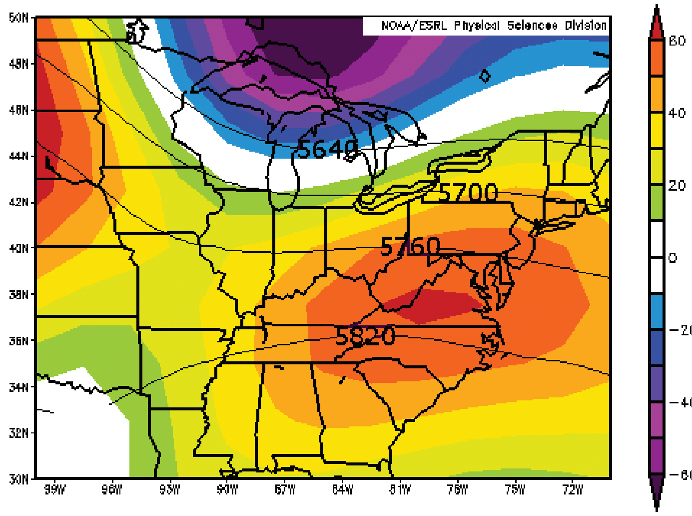

Fig. 4(c).

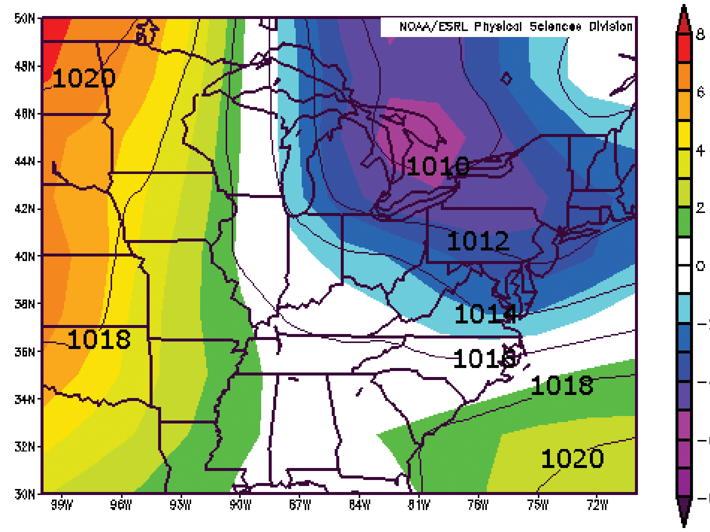

Fig. 4(b).

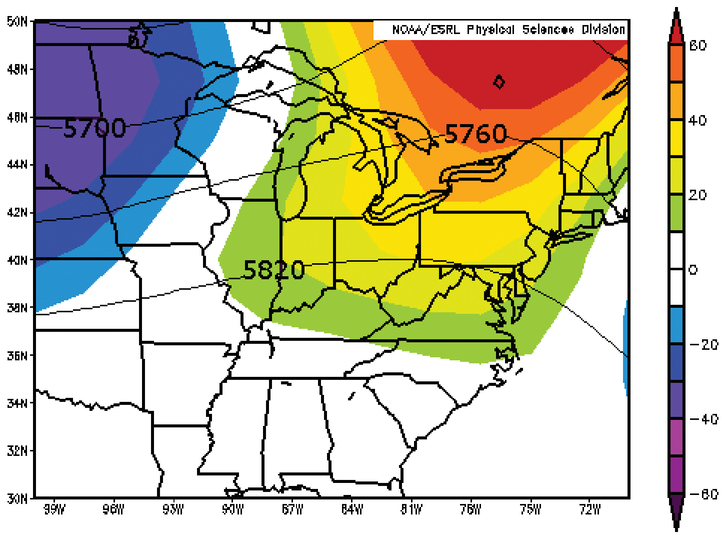

Fig. 4(d).

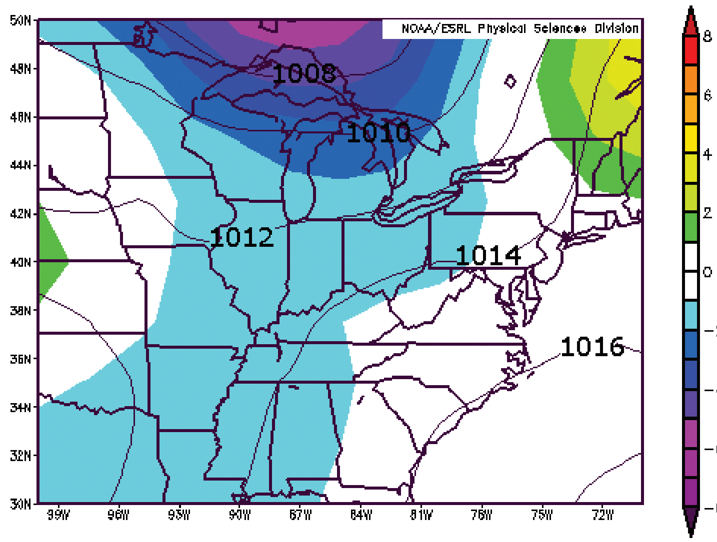

Fig. 4. Composites for (a) low-CAPE major event 500 hPa geopotential heights (m) and anomalies (m), (b) high-CAPE major event 500 hPa geopotential heights (m) and anomalies (m), (c) low-CAPE major sea-level pressure (hPa) and anomalies (hPa), and (d) high-CAPE major sea-level pressure (hPa) and anomalies (hPa).

an upstream inverted-V sounding and few severe weather reports (a null event). Similarities and differences between the two events are briefly discussed.

a. 16-17 April 2010

A major severe weather outbreak occurred over the Ohio Valley and Pennsylvania on 16-17 April 2010, with 44 severe reports in Pennsylvania. The surface map at 2100 UTC on 16 April 2010 featured surface low pressure over western Quebec with a cold front extending southward across central New York and Pennsylvania, and a warm front farther to the east (Fig. 5). The air mass in the warm sector between the warm and cold fronts was unseasonably warm, indicating the potential for severe weather over Pennsylvania and New York as the front approached the region late in the day. The 1200 UTC 16 April 2010 KPIT sounding featured a shallow, surface-based stable layer capped by a dry, well-mixed unstable layer (Fig. 6). The 925 hPa to 800 hPa lapse rate was 9.4 °C km^{-1}, with a maximum dew point depression of 14 °C. The unstable mixed layer was capped by a moist layer from 750 hPa to 650 hPa, resulting in a classic "inverted-V" appearance to the temperature and moisture profile. Some stability-related parameters associated with this sounding included an SBCAPE of 0 J kg^{-1}, a DCAPE value of 805 J kg^{-1}, and a FCST CAPE value of 161 J kg^{-1} The dry low-levels associated with this sounding resulted in very little CAPE, but a large potential for enhanced downdrafts. Mean 0-3 km winds were from 280° at 34 kts, indicating that moderately strong but sub-severe (50 kt) winds were available for downward mixing within the

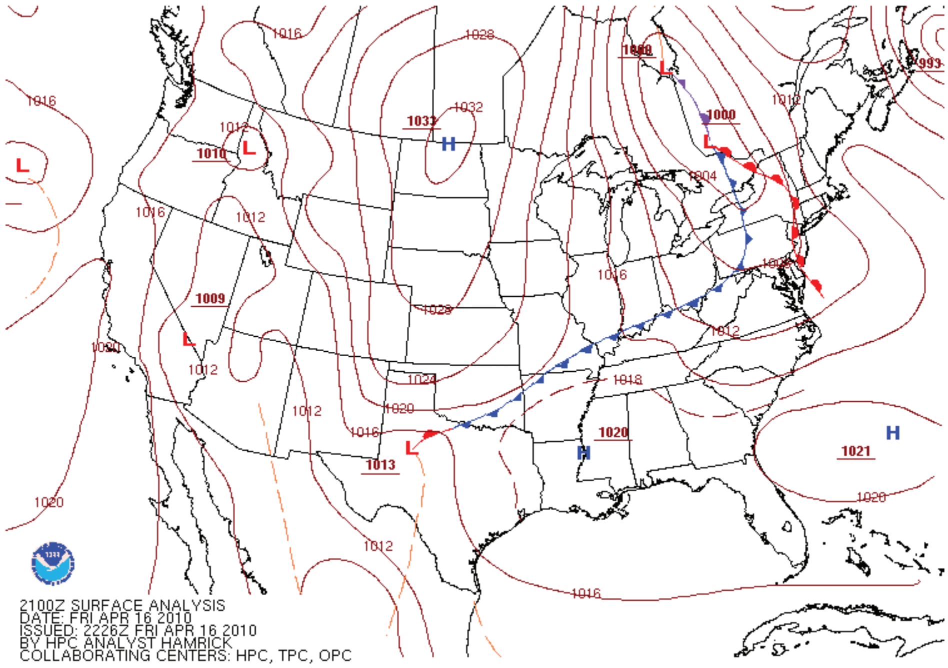

Fig. 5. NCEP/HPC surface analysis at 2100 UTC on 16 April 2010.

lower-tropospheric mixed layer. Forward trajectories from the KPIT sounding location at 1200 UTC on 16 April 2010, based on the GDAS (not shown), indicated that the lower-to-mid tropospheric air mass over KPIT at 1200 UTC would sweep eastward across southern Pennsylvania during the next several hours. This suggests that the 1200 UTC sounding at KPIT could be representative of the air mass over central and eastern Pennsylvania later that afternoon.

Composite fields and anomalies of heights, winds, temperatures, and relative humidity on 16 April 2010 indicated that the large-scale pattern associated with this event was similar to the composites indicated for major events and low-CAPE major events (Fig. 7). Specifically, the 500 hPa height pattern indicated an anomalously strong ridge centered over the central Ohio Valley, with a trough over the northern Great Lakes (Fig. 7a). The 700 hPa zonal wind speed indicated an anomalously strong westerly wind maximum centered over the central Great Lakes (Fig. 7b). At the surface, a pronounced maximum of anomalously high temperatures was centered over the eastern Ohio Valley (Fig. 7c), while at 925 hPa, anomalously low relative humidity covered much of the southeastern United States and mid-Atlantic region (Fig. 7d).

Select fields that imply forcing for synoptic-scale ascent are shown on Fig. 8. At 300 hPa, a deep trough was moving east across the Great Lakes area, with a pronounced jet streak along the southern edge of the trough, placing Pennsylvania

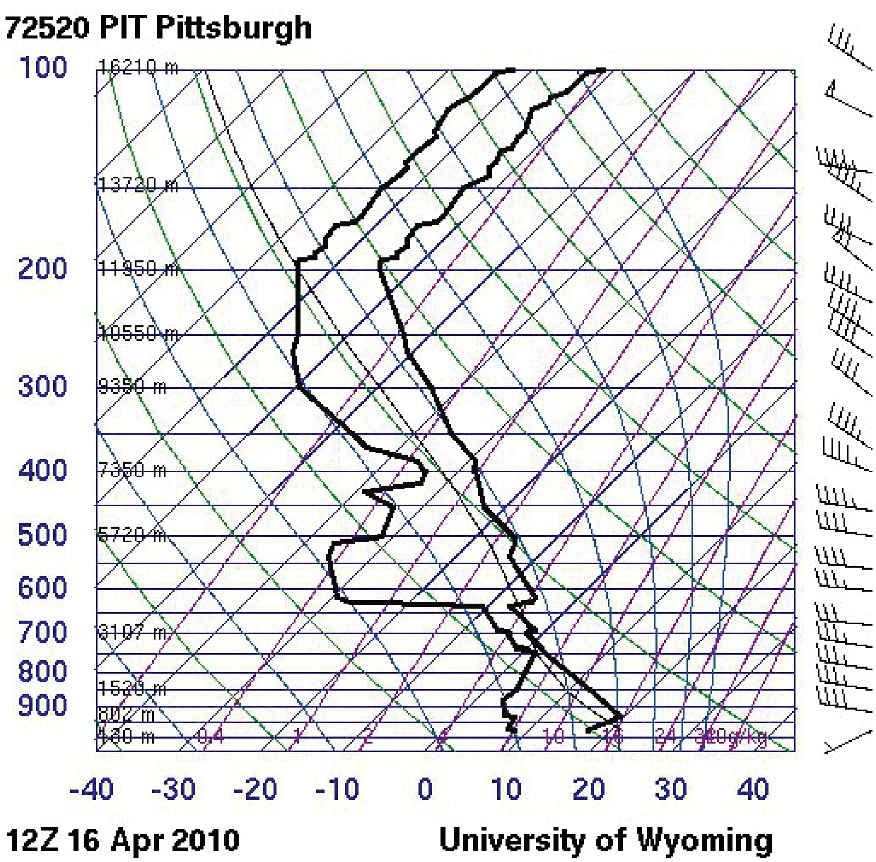

Fig. 6. Observed 1200 UTC 16 April 2010 KPIT skew-T diagram.

Fig. 7(a).

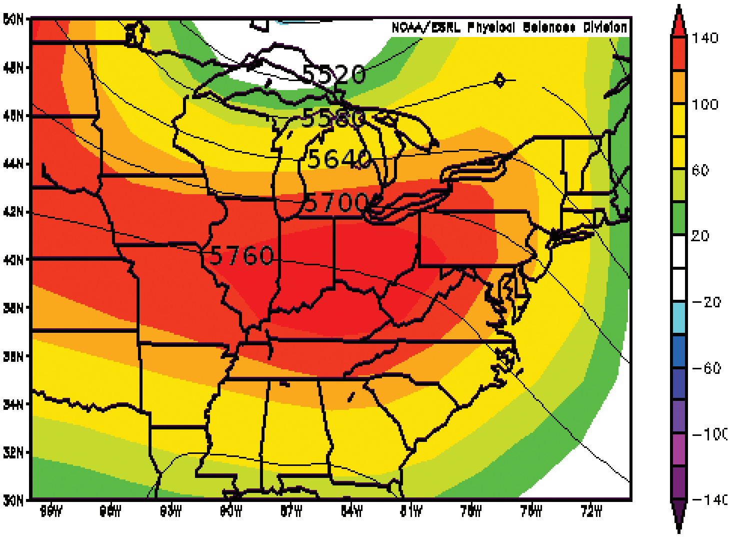

Fig. 7(c).

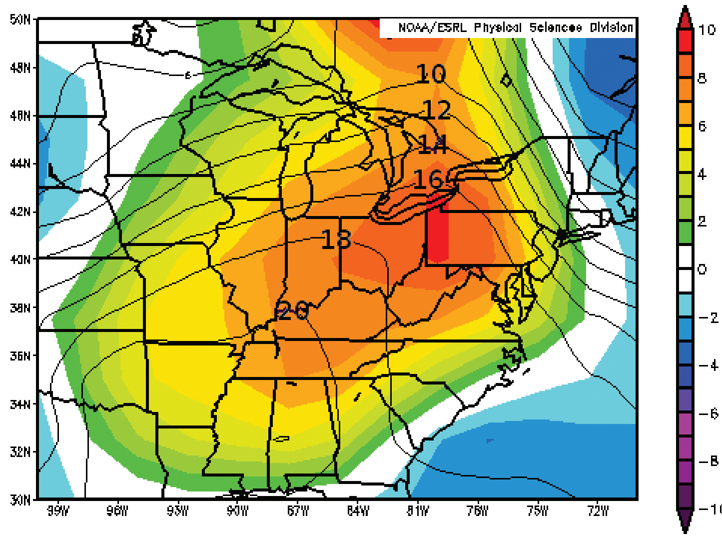

Fig. 7(b).

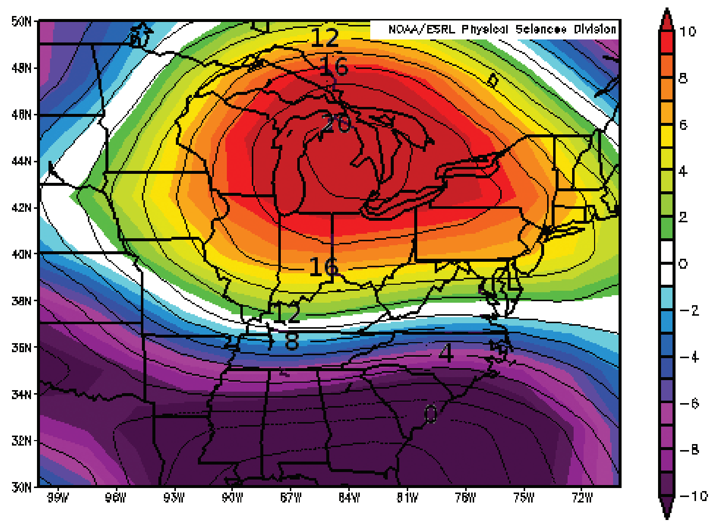

Fig. 7(d).

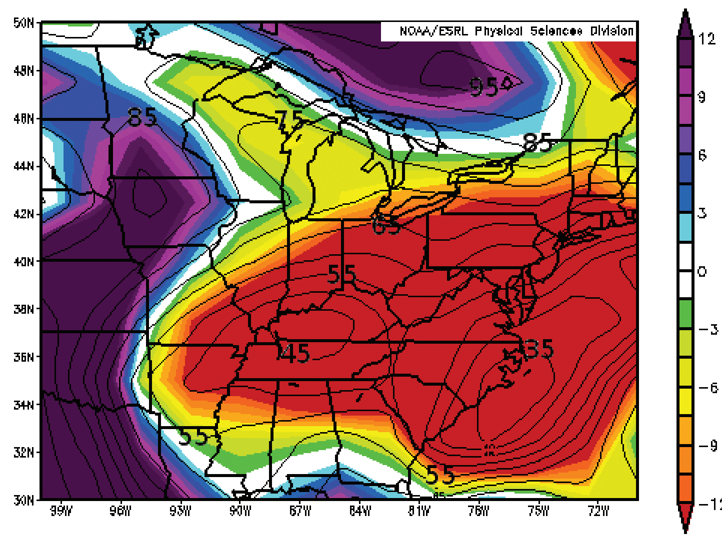

Fig. 7. Composites of 00, 06, 12 and 18 UTC reanalysis data from 16 April 2010 of: (a) 500 hPa geopotential heights (m, contoured) and anomalies (m, shaded). (b) 700 hPa zonal wind (m s^{-1}, contoured) and anomalies (m s^{-1}, shaded). (c) Surface temperature (°C, contoured) and anomalies (°C, shaded). (d) 925 hPa relative humidity (percent, contoured), and anomalies (percent, shaded).

in a favorable region for upward vertical motion forcing within the exit region of the jet (Moore and VanKnowe 1992). Figure 8b shows an NCEP North American Model (NAM) 6-h forecast of 12-h 500 hPa height change and surface-850 hPa frontogenesis, valid at 0000 UTC on t17 April 2010. Strong forcing for upward vertical motion is implied across central Pennsylvania by the data on this figure, as a progressive upper trough overrides a significant lower-tropospheric frontal boundary. A line of showers and low-topped thunderstorms developed over eastern Ohio during the afternoon on 16 April 2010 and moved quickly across the southern half of Pennsylvania through early evening. The 0-6 km wind speed on the 1200 UTC KPIT sounding was 35 kt for this event, while storms were observed moving east at approximately 40 to 45 kt. Damaging wind occurred at many locations in a swath from southeast Ohio across southern Pennsylvania. No large hail or tornadoes were reported. Reflectivity data from the State College (KCCX) Weather Surveillance 88 Doppler Radar (WSR-88D; Fig. 9), indicated low-topped cells with 50 dBz cores generally below 15,000 feet and echo tops around 30,000 feet as the storms tracked across central Pennsylvania. Note that some of the damage associated with these storms in the southern portion of the state occurred at locations where the radar was overshooting the 50-dbz portion of the storms, indicating the frequent difficulty in diagnosing the severity of these types of low-topped storms.

Fig. 8(a).

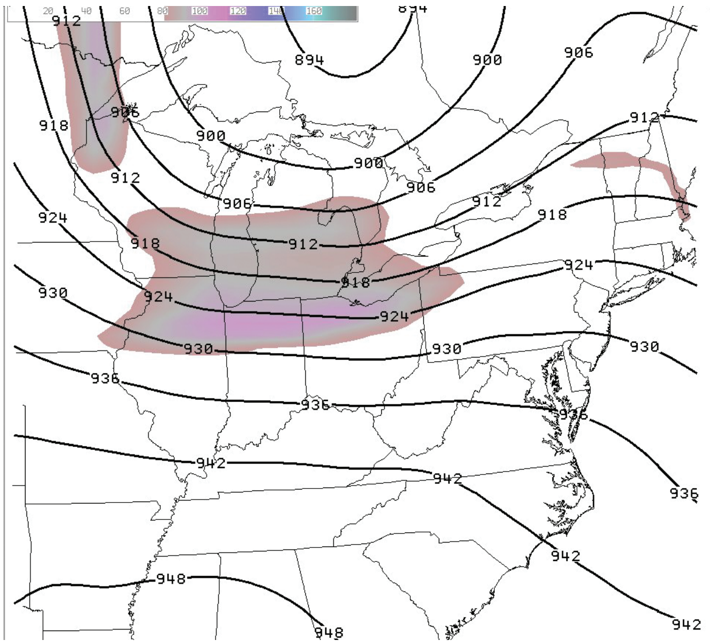

Fig. 8(c).

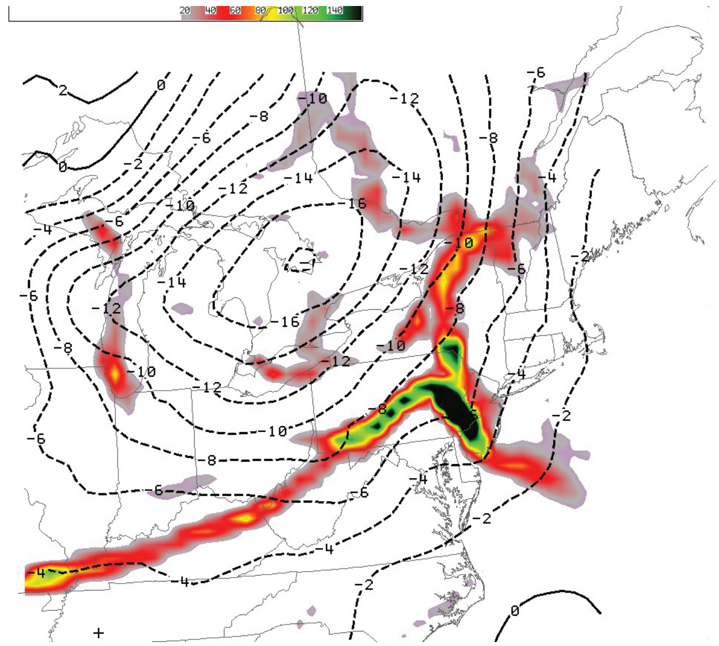

Fig. 8. Six-hour NCEP operational NAM forecasts, interpolated to a 40 km grid, valid at 0000 UTC on 17 April 2010 of (a) 300 hPa geopotential heights (dm) and wind speed (values greater than 80 kt, shaded), and (b) 12-h 500 hPa geopotential height change (dm) and 1000-850 hPa frontogenesis {[˚C m^{-1} (1x1010 s^{-1})], values greater than [20 ˚C m^{-1} (1x1010 s^{-1})] shaded}.

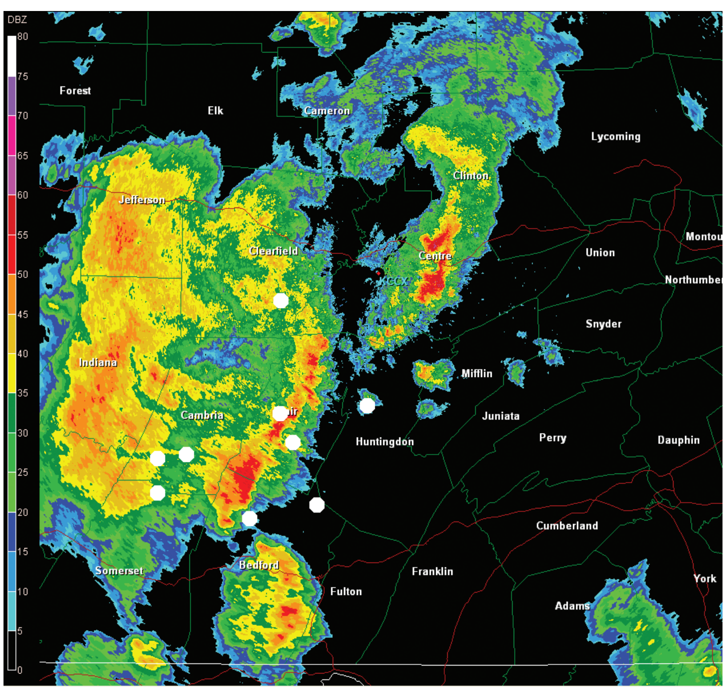

Fig. 9. 0.5˚ reflectivity from the KCCX WSR-88D at 2101 UTC on 16 April 2010. Locations where severe wind gusts were reported between 2030 UTC and 2130 UTC are labeled with a white dot.

b. 17-18 May 2008

In this section, a null event featuring only 3 severe reports is described in order to provide a contrast with the major event shown in section 4a. The surface weather map at 0000 UTC 18 May 2008 featured low pressure over western Quebec with a cold front extending southward across central New York and Pennsylvania (Fig. 10). The 1200 UTC KPIT sounding indicated a 925-800 hPa lapse rate of 7.5 °C km^{-1}, with a maximum dew point depression of 9 ° C. The unstable mixed layer was capped by a moist layer at 800 hPa, resulting in a classic inverted-V appearance to the profile (Fig. 11). Unlike the sounding from 16 April 2010, a stable layer can be seen from 600 hPa to 500 hPa. Stability-related parameters associated with this sounding included an SBCAPE of 0 J kg^{-1}, a DCAPE of 185 J kg^{-1}, and a FCST CAPE of 57 J kg^{-1}. Mean 0-3 km winds were from the west at 33 kt. Forward trajectories from the KPIT sounding location at 1200 UTC on 17 May 2010 from the GDAS (not shown) indicated that the lower-to-mid tropospheric air mass over KPIT would sweep east across Pennsylvania and southern New York during the next several hours. This case was similar to 16 April 2010 in that both cases featured a cold front progressing east across the Great Lakes, and both cases included an inverted-V profile evident on the KPIT sounding, with similar wind velocity magnitudes. However, the mixed layer was not as deep in this case, and the mid-troposphere was more stable.

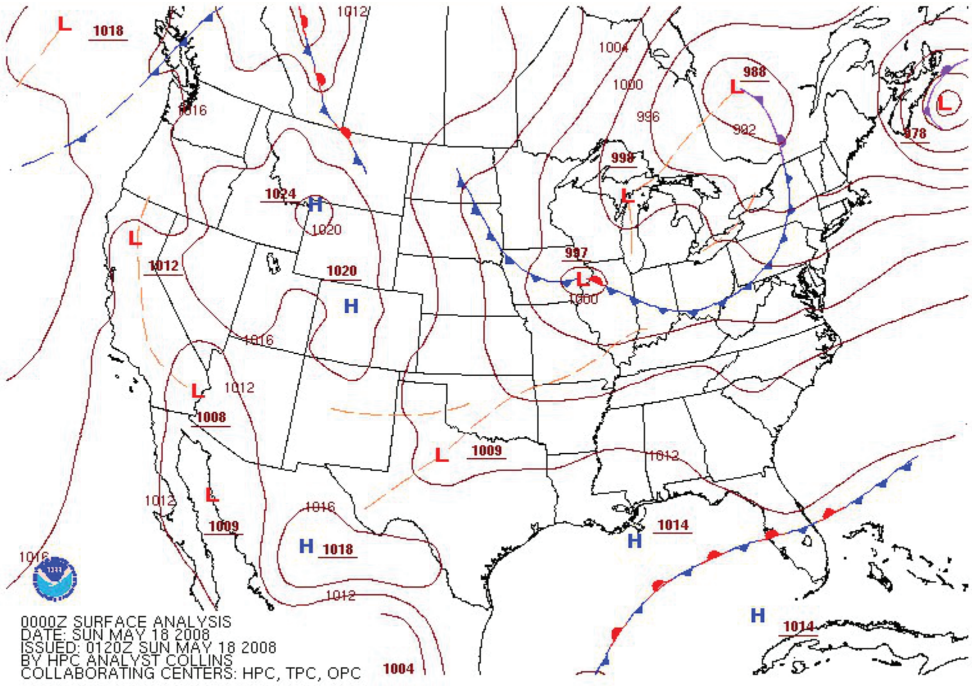

Fig. 10. NCEP/HPC surface analysis at 0000 UTC on 18 May 2008.

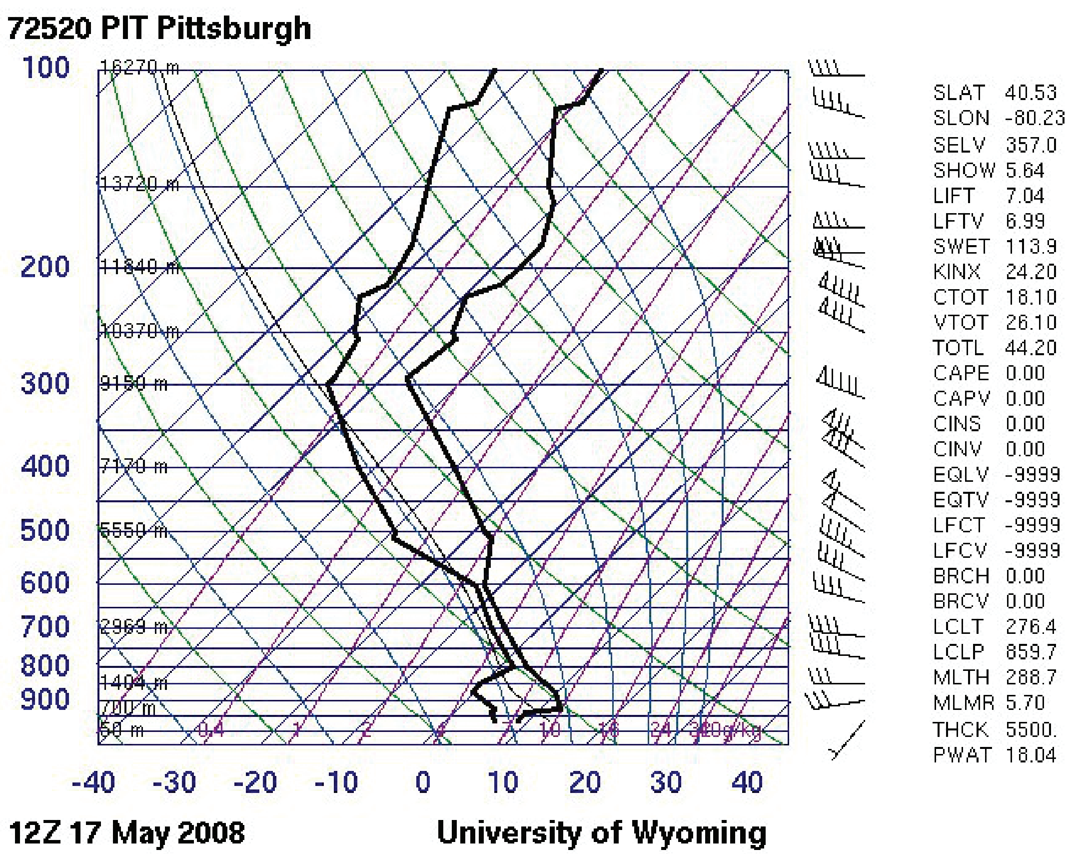

Fig. 11. Observed 1200 UTC 17 May 2008 KPIT skew-T diagram.

Composite fields and anomalies of heights, winds, temperatures, and relative humidity on 17 May 2008 (Fig. 12) indicate some similarities and differences compared to 16 April 2010. Both cases featured significant 500 hPa-troughs moving across the Great Lakes area, however the 500 hPa heights on 17 May 2008 were anomalously low well downstream of the trough, with negative anomalies extending across the mid-Atlantic area (Fig. 12a). The 700 hPa zonal wind pattern was rather similar in both cases, with a strong, positive anomaly indicated over the Great Lakes in each event (Fig. 12b). Unlike on 16 April 2010, no warm anomaly was indicated at the surface on the 17 May 2008; instead, a cool anomaly extended from the Gulf coast states northeast to the northern mid-Atlantic region (Fig. 12c). Finally, both events were associated with anomalously low relative humidity at 925 hPa over the northern mid-Atlantic region, with similar relative humidity values over the severe weather area ranging approximately between 50 and 70 percent (Fig. 12d).

Some fields that imply forcing for synoptic-scale ascent are shown in Fig. 13. At 300 hPa, a strong upper level wind speed maximum embedded within westerly flow was moving east across the southern Great Lakes, similar to what was shown for 16 April 2010(Fig. 13a). Figure 13b shows a NAM 3-h forecast of 12-h 500 hPa height change and 1000-850 hPa frontogenesis valid at 2100 UTC on 17 May 2008. In contrast to the first case, the 500 hPa height falls are much smaller across New York and Pennsylvania,

Fig. 12(a).

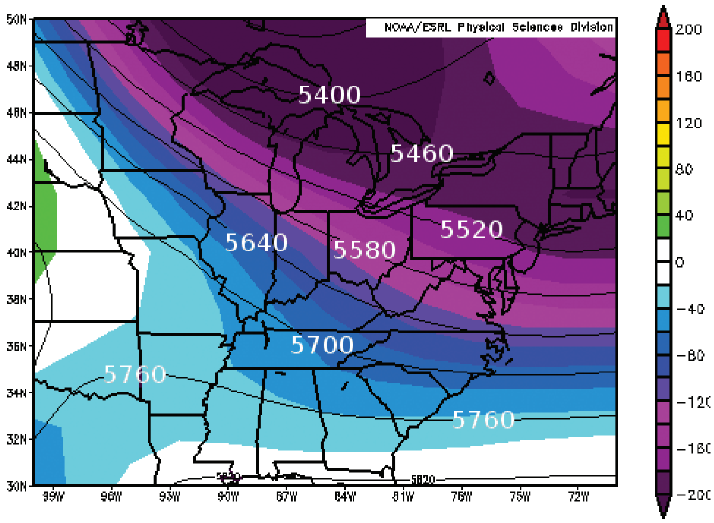

Fig. 12(c).

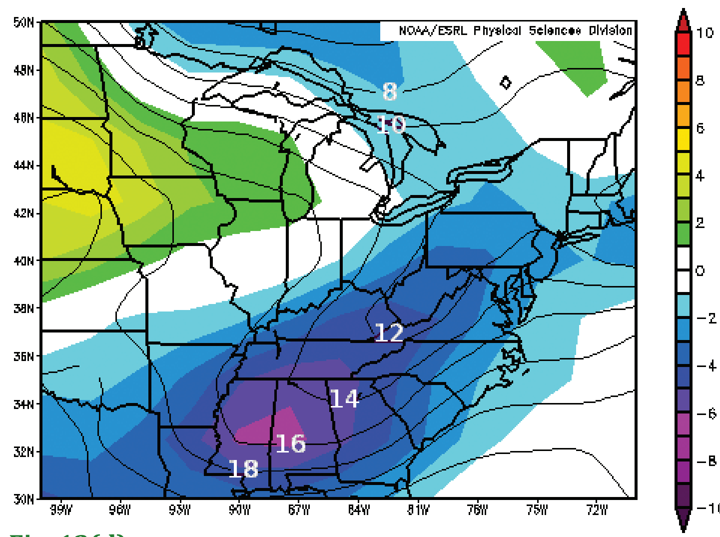

Fig. 12(b).

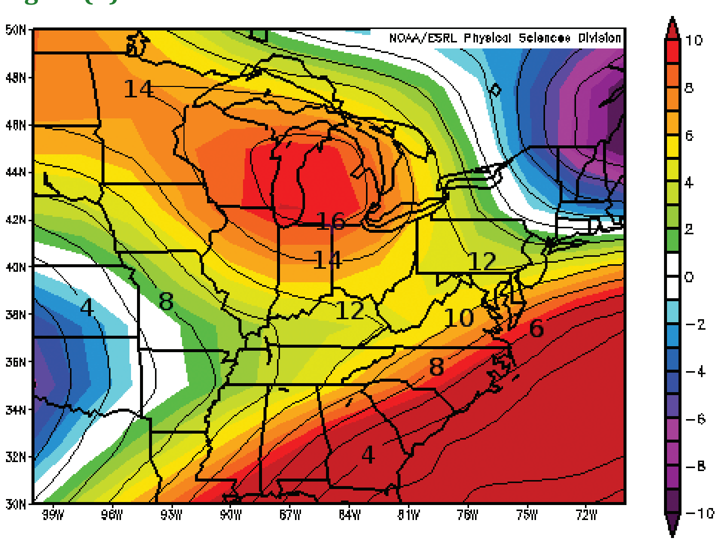

Fig. 12(d).

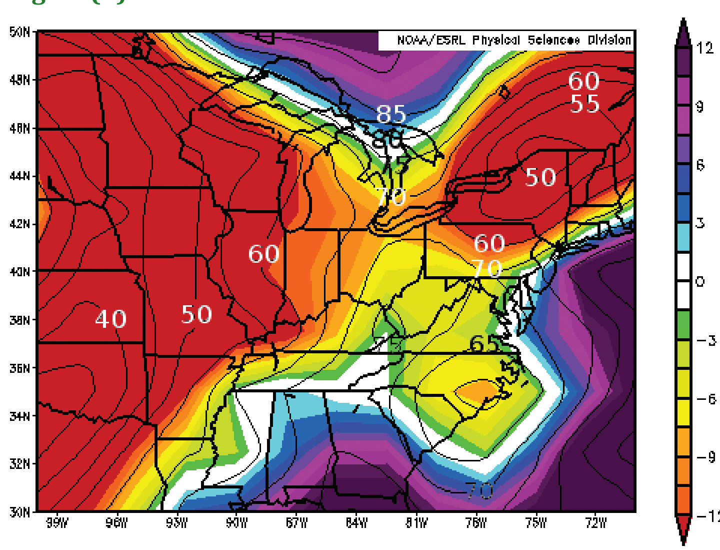

Fig. 12. Composites of 00, 06, 12 and 18 UTC reanalysis data from 17 May 2008 of: (a) 500 hPa geopotential heights (m, contoured) and anomalies (°C, shaded). (b) 700 hPa zonal wind (m s^{-1}, contoured) and anomalies (m s^{-1}, shaded). (c) Surface temperature (°C, contoured) and anomalies (°C, shaded). (d) 925 hPa relative humidity (percent, contoured) and anomalies (percent, shaded).

Fig. 13(a).

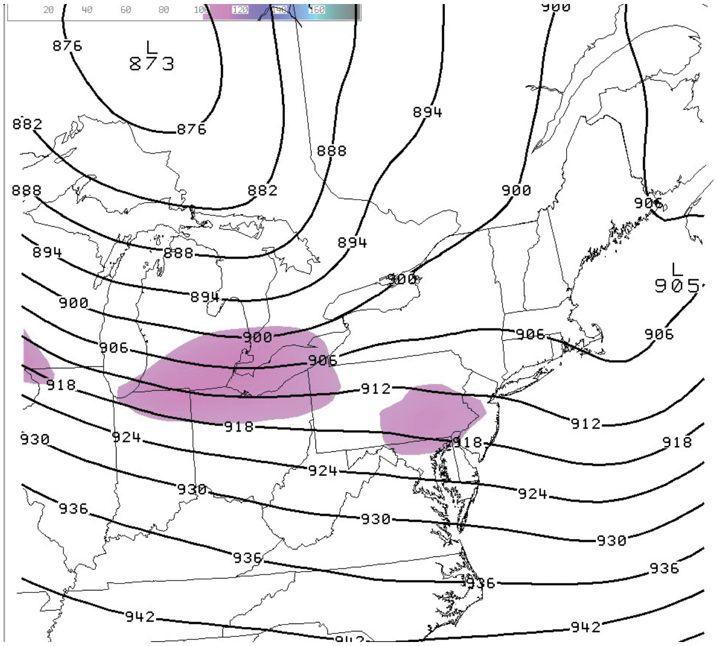

Fig. 13(b).

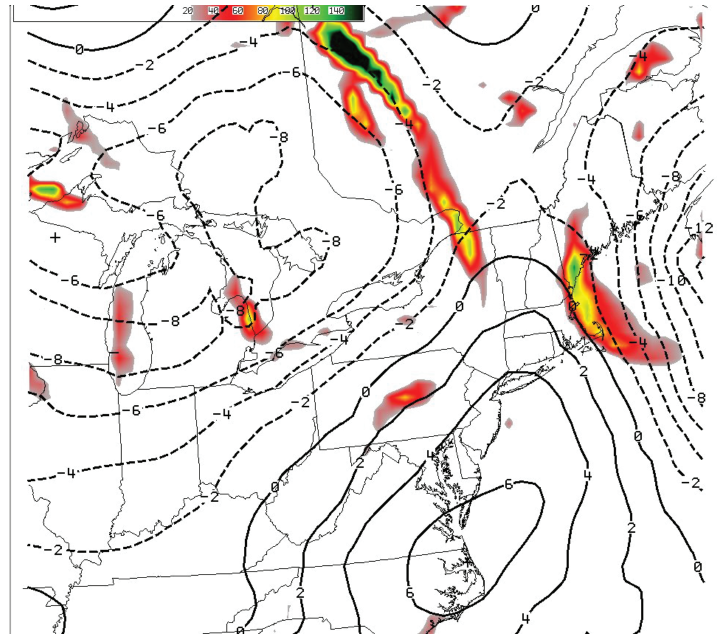

Fig. 13. (a) 0 h NCEP operational NAM forecasts, interpolated to a 40 km grid, of 300 hPa geopotential heights (dm) and wind speed (values greater than 100 kt shaded) valid at 1800 UTC 17 May 2008 and (b) 3-h NAM forecast of 12-h 500 hPa geopotential height change (dm) and 1000-850 hPa frontogenesis {[˚C m^{-1} (1x1010 s^{-1})], values greater than [20 ˚C m-1 (1x1010 s^{-1}) shaded]} valid at 2100 UTC 17 May 2008.

and the surface to 850 hPa frontogenesis associated with the surface front is much weaker. This implies much less forcing for upward vertical motion than on 16 April 2010. The similarities between this event and the event on 16 April 2010 included a progressive cold front moving east from the Great Lakes area, an upstream inverted-V sounding associated with very small CAPE and FCST CAPE values, a deep mid-to-upper tropospheric trough over the Great Lakes, and anomalously strong 700 hPa westerly flow over the southern Great Lakes. Differences on 17 May 2008 included a shallower lower-tropospheric mixed layer with less DCAPE, and weaker forcing for large-scale upward vertical motion.

A line of showers with embedded low-topped thunderstorms developed over Pennsylvania and southern New York on 17 May 2008 and moved east (Fig. 14). In this case, the result was a very minor event. One damaging wind report (an EF0 tornado), and one small hail report occurred in central New York, and one small hail report was received from western Pennsylvania.

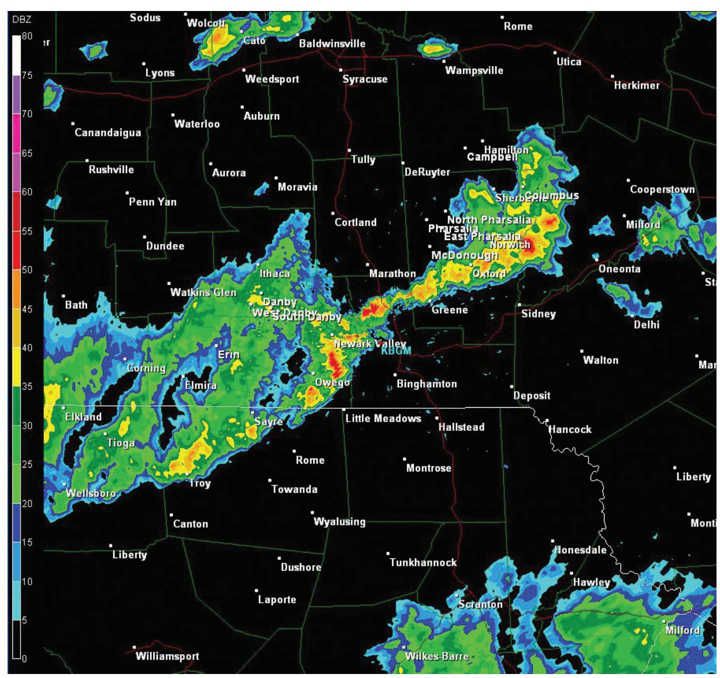

Fig. 14. 0.5° reflectivity from the KBGM WSR-88D at 2319 UTC 17 May 2008.

5. Discussion / Summary

A study of severe weather events occurring in New York and Pennsylvania from 2005 through 2010 identified 29 major severe weather events (defined as events associated with 20 or more severe reports) associated with upstream inverted-V profiles at KPIT and/or KBUF. This represented approximately 37 percent of all major events that occurred during this period. Meanwhile, 56 null events (defined as events associated with one to five severe reports) associated with upstream inverted-V profiles were identified, representing approximately 38 percent of all null events that occurred during this period.

These findings indicate that, while major inverted-V severe weather events are somewhat common, null events are more common.

The majority of major events occurred during the summer months (June through August), but fall, spring and even a winter event were also identified. A closer examination of 10 major events, determined by application of a strict, objective criteria for an upstream inverted-V sounding, indicated that 87 percent of the reports associated with these events were damaging wind reports. Six of the 10 major events were associated with lines of convection, with 96percent of severe reports in those cases being damaging wind reports. The lower-tropospheric mixed layer extended to an average pressure level of 704 hPa in these 10 events, indicating a more shallow mixed layer than what is often observed with inverted-V soundings over the western half of the U.S. For example, Beebe (1955) illustrated an inverted-V (or "Type IV") sounding by showing a profile with a surface-based mixed layer extending to around 550 hPa.

Atmospheric profiles associated with the major events in this study were approximated by utilizing data from observed 1200 UTC soundings taken at KPIT and KBUF, at the western edge of the study area. It should be noted that examination of soundings farther upstream is sometimes appropriate for anticipating conditions over New York and Pennsylvania, especially for the western portions of those states, however KPIT and KBUF were selected in order to simplify the study. The downstream severe weather in these cases occurred at times and locations up to 12-h after and 600 km downstream from the sounding observations. The methodology included examination of lower-tropospheric trajectories, to ensure that the severe weather occurred downstream from the observed soundings. However, no allowances were made to account for potential downstream changes in the vertical structure of the air mass due to vertical motion or temperature advection (Banacos and Ekster 2010). In addition, the effects of diabatic heating on the lower part of the sounding were only roughly approximated through calculation of parameters such as FCST CAPE (details given in section 2) and the estimated lower tropospheric lapse rate (details given in section 3). As such, the assumption that these observed profiles were representative of the downstream environment at the time of severe-weather occurrence should only be made with these limitations in mind, as the temporal and spatial criteria for these proximity soundings were more relaxed than in many recent convective studies (Potvin et al. 2010). However, Rasmussen and Blanchard (1998) employed similar criteria (a spatial distance of 400 km and a temporal distance of up to 6 h) when utilizing observed soundings to develop a climatology of sounding-derived supercell and tornado forecast parameters. Despite these limitations, one of the motivations for using observed soundings as proximity soundings in this study is that operational forecasters frequently use observed soundings to help anticipate downstream conditions at temporal and spatial distances comparable to the distances in this study. A detailed validation of the proximity soundings from this study is beyond the scope of this work; however, a cursory examination of Rapid Update Cycle (RUC; Benjamin et al. 2004) forecast soundings at locations in central New York and Pennsylvania indicated inverted-V profiles around the time of the onset of convection in all of these cases.

The sounding data indicated that most of the major cases occurred with low values of 1200 UTC SBCAPE; however, a wider range of FCST CAPE values was indicated. Assuming that the FCST CAPE was a reasonable approximation of CAPE values present during the afternoon and evening, when most of the severe weather occurred, this finding implies a wide range of instability associated with major events. The range of DCAPE values was relatively narrow, with values in most cases ranging from 600 J kg^{-1} to 900 J kg^{-1}. Wide ranges of 0-3 km and 0-6 km wind speeds were found for the cases; however, no events occurred with upstream observed mean 0-3 km or 0-6 km wind speed greater than 45 kt. This indicates that the severe (greater than 50 kt) wind gusts observed at the surface with most of these events were generated by other processes, in addition to convective mixing of strong winds to the surface. The observed storm speeds for these events were also substantially larger than the 0-3 km and 0-6 mean wind, indicating that propagation associated with storm-induced cold pools likely played a significant role in the motion of storms, increasing storm speeds above what would be expected from advection by the mean wind alone. This result matches the finding from Corfidi et al. (2006) for their collection of convective events occurring in dry lower-tropospheric environments.

The small surface-based FCST CAPE values associated with many of these events can make them difficult to anticipate operationally. However, the results of this study indicate that forecasters can improve their situational awareness for these events by looking for the conditions identified in this study, as well as by understanding the range of conditions under which these events can occur. The recent proliferation of the use of model-based forecast soundings makes it tempting for forecasters to focus primarily on model output to assess convective potential, especially in areas such as central New York and central Pennsylvania, where the nearest sounding site may be a few hundred km away. However, the results of this study indicate that there is still a very important place for analysis of observed soundings, especially when trajectory analysis indicates that conditions over the upstream sounding sites could potentially reach the area of interest within 12 h. Forecast trajectories from the HYSPLIT model are readily available to operational forecasters at http://ready.arl.noaa.gov/hysplit-bin/trajtype.pl. The results of this study imply that, while the upstream observed soundings in this study may not be perfect proximity soundings, they may often be appropriate for use to anticipate the potential for severe weather in dry, unstable lower-tropospheric environments, even when the temporal and spatial difference between the sounding and potential location of severe weather is as large as 12-h and/or 600 km.

Examination of composite synoptic-scale patterns and associated anomalies from climatological averages appeared to highlight several important environmental characteristics associated with major, inverted-V severe weather events in the northern mid-Atlantic region. The composites indicated passage of a surface-through-700 hPa short wave trough, and a 500 hPa trough located over the northern Great Lakes with an anomalously strong ridge downstream over the eastern U.S. Anomalously strong, zonal flow was indicated over the Great Lakes at 700 hPa. The lower tropospheric pattern for these cases was characterized by large positive surface temperature anomalies and strongly negative 925 hPa relative humidity anomalies. Similarities can be seen between the composite flow patterns shown for these cases, and the composites shown for significant-severe, elevated mixed layer events studied by Banacos and Ekster (2010). The similarities are most pronounced with regard to the 500 hPa flow pattern, which was characterized by a trough over the Great Lakes area, and enhanced zonal flow to the south. A cursory examination of backward trajectories from the cases in this study indicate that flow associated with four of the ten events originated over the central or northern Plains of the U.S., implying that a subset of these events may have been associated with elevated mixed layers upstream of the northern mid-Atlantic region.

A closer look at the major events in the study indicated that these events can be divided into "low-CAPE" major and "high-CAPE" major categories, based on the FCST CAPE indicated by the upstream soundings. In addition to the presence of little if any forecast CAPE on upstream soundings, the low-CAPE major events were associated with larger DCAPE, stronger deep-layer wind profiles, faster storm speeds and larger mid-tropospheric height falls than the high-CAPE major events. Composite analysis indicated that the low-CAPE major events were also associated with stronger mid-level troughs over the Great Lakes area, more pronounced surface troughs over the Great Lakes, and stronger positive anomalies of low-level temperature. These findings imply that many of the most prominent characteristics of features associated with major inverted-V severe weather events are particularly pronounced for the low-CAPE major events.

The first case study depicted an example of a low-CAPE major event. Many of the characteristics associated with low-CAPE major events were represented in this case, including storms moving faster than the mean wind, a pronounced 500-hPa southeast-northwest oriented ridge-trough couplet with anomalously high heights in the ridge over the Ohio valley, and a pronounced low-level warm temperature anomaly centered over Pennsylvania. Substantial forcing for upward vertical motion was implied for this case by large 500 hPa height falls juxtaposed with strong 1000-850 hPa frontogenesis. Evans (2010) found that cool-season convective events associated with numerous severe weather reports in LCHS environments over New York and Pennsylvania most often occur with strong, progressive synoptic-scale forcing as indicated by large 500-hPa height falls. He speculated that the strong, deep dynamical forcing associated with these progressive cases can help to maintain an atmosphere conducive for convective storms in a LCHS environment, at times when the cold pool-shear balance might otherwise be unfavorable for long-lived severe storms. In these cases, the mid-tropospheric ascent may be sufficiently strong to reduce capping sufficiently to allow for deep enough updrafts to produce long-lived severe convection. The first case example from 16-17 April 2010 appears to conform to this conceptual model, as substantial dynamical forcing for ascent was evident during the time of most active convection. The second case example from 17-18 May 2008 exhibited many of the same features as the first example including an upstream inverted-V sounding, a progressive cold front, and a substantial mid-tropospheric trough. However, the 500 hPa height falls were not juxtaposed with the lower-tropospheric front in this case, and the lower-tropospheric frontogenesis was much weaker than in the first case. A line of showers and thunderstorms developed, but severe reports were largely absent.

Finally, the radar data shown in Section 4 highlights some of the challenges associated with diagnosing severe weather using radar during a low-CAPE event. The low storm tops and small 50 dBz echo cores can mislead warning meteorologists into assuming that associated storms are not severe. In addition, strong velocity signatures may only be observed at the lowest elevation slices, as results from this study indicate that storm speeds and observed winds in these cases are often larger than the deep-layer wind speed. In cases where observed radar signatures are different than what meteorologists may consider typical for severe weather, high situational awareness is critical for the effective issuance of warnings with adequate lead time.

A summary of key points for operational meteorologists to consider regarding severe weather occurrence and upstream, observed inverted-V soundings over the northern mid-Atlantic is given below:

1) A substantial percentage of major severe weather events in New York and Pennsylvania occur with upstream, observed inverted-V soundings. Therefore, operational meteorologists would be well-advised to check for this feature on observed soundings. However, it should be noted that null inverted-V events are more common than major events.

2) The depth of the inverted-V layer over the northern mid-Atlantic area is typically lower than in previously documented cases farther to the west.

3) Major events with inverted-V soundings are often associated with linear convective structures and severe reports are often dominated by wind damage. Severe convective storms will often move faster than the mean wind, and these storms can often possess low echo tops and small 50 dbz cores in low-CAPE environments.

4) CAPE and shear profiles associated with these observed soundings can vary widely for major events, and there is considerable overlap in many of the sounding-based parameters between major and null events. Low CAPE and FCST CAPE does not mean that a case should be eliminated from consideration as a potentially major event. However, moderately large values of DCAPE may be a good indicator for a potentially major event.

5) Composite analysis of the mid-troposphere for major events associated with inverted-V soundings indicate a trough over the Great Lakes area along with anomalously large, westerly wind speeds, and anomalously high mid-tropospheric heights downstream over the mid-Atlantic area. Lower-tropospheric features include a surface trough over the eastern Great Lakes along with anomalously high temperatures and low relative humidity over the northern mid-Atlantic region. These features appear to be particularly pronounced in cases where the FCST CAPE is low.

6) Discrimination between major and null events can be difficult for these cases, however major events may be associated with a more amplified flow pattern and stronger large-scale forcing for upward vertical motion than null events.

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