P9.140 Identifying Key Features to Predict Significant Severe Weather Outbreaks in the Northeastern United States.

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1. Introduction

On 1 June 2011, a significant severe weather event occurred in the northeastern United States (U.S.), with multiple reports of hail greater than 3 inches in New York and New England, and an EF3 tornado in Massachusetts. This significant severe weather event had similar atmospheric characteristics to other historical significant severe weather events. A significant severe weather event is defined by the Storm Prediction Center as hail greater than 2 inches, straight-line winds of ≥ 32 ms^{-1} (65 kt) and/or tornadoes of EF2 magnitude or greater (http://www.spc.noaa.gov/climo/online/rda/).

A previous study comparing significant severe weather events with severe weather forecast busts (non-events) in the Carolinas through the mid-Atlantic states, identified atmospheric features that contributed to the occurrence of significant severe weather outbreaks in that region (Stuart 2004). A forecast bust for this study is defined as no tornadoes reported within the majority of a tornado watch or within a forecasted moderate risk region.

That study researched 14 significant severe weather events from 1984 to 2002, identifying atmospheric characteristics that contributed to the development of the significant severe weather outbreak.

In the present study, 20 significant severe weather events in the northeastern U.S. from 1953 to 2011 that produced tornadoes of F2/EF2 or greater intensity (Table 1) were researched to determine if the atmospheric features in the Carolinas and mid-Atlantic events had similarities to the northeastern U.S. events. It was determined after researching these northeastern U.S. events, as well as selected forecast busts between 2003 and 2012 (Table 2), that the key atmospheric features supportive of significant severe weather in the Carolinas and mid-Atlantic were also valid for the northeastern U.S.

Atmospheric parameters that were analyzed include 850 hPa and 250 hPa winds, 850 hPa equivalent potential temperatures (Θ_e), 4-layer best lifted index and 850 hPa and 500 hPa heights and temperatures. The 4-layer best lifted index is determined by finding the most unstable parcel between the surface and 180 hPa above ground (about 1600 m) and could also be labeled as the most unstable lifted index.

2. Synoptic-scale features

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In all the severe events, the primary upper-level vorticity center originated in the U.S. northern plains or southern Canada, and tracked toward the Great Lakes. The movement/placement of the upper-level vorticity with respect to the eastern periphery of the Great Lakes and spine of the Appalachian Mountains is what distinguished the events versus the non-events.

In significant severe events, such as 1 June 2011, the primary upper-level vorticity tracked definitively east of the Great Lakes and spine of the Appalachian Mountains within 24 hours (Fig. 1), similar to the conclusions of LaCorte and Grumm (2002) about Pennsylvania severe weather events. In events such as 1 June 2011, NWP guidance correctly predicted the primary upper-level vorticity center to track east of the Great Lakes within 24 hours. This prediction increased the confidence and probability that this component of the "ingredients" for a significant severe weather outbreak existed.

Conversely, in the non-events, such as 5 June 2010, a slow moving upper-level vorticity center did not reach the spine of the Appalachian Mountains within 24 hours (Fig. 2). The slow movement of the upper vorticity center over the western Great Lakes implied upper dynamics and forcing that were too far to the northwest of the Mid-Atlantic region to increase low-level forcing and lift in the mid-Atlantic. On 5 June 2010, a tornado watch was issued over a large portion of the northeastern U.S., and only a few minor severe weather reports occurred within the watch area including one weak EF1 tornado in the very northeast corner of the watch area near Craftsbury, VT (Fig. 3).

Analysis of archived Numerical Weather Prediction (NWP) forecast guidance for the events and forecast busts between 2001-2012 illustrated the reliability of the NWP model guidance in predicting the movement of the upper level vorticity centers (not shown). The NWP guidance was viewed in real-time for some events, while archived NWP guidance from the Iowa State Environmental Mesonet website (http://mesonet.agron.iastate.edu/) was viewed in the remaining cases. The NWP guidance helped to effectively distinguish the potential significant severe weather events from the potential forecast busts.

One other synoptic parameter that supported significant severe weather was the position of the 250 hPa wind maximum, in relation to the region that exhibited the favorable thermodynamic and instability and boundary layer parameters. In every significant severe weather event, the region that experienced the severe weather was in the right-entrance region, left exit region or in between dual jet segments of the 250 hPa jet. One example of a significant severe weather event in the right entrance region was the 1 June 2011 F3 tornado event near Springfield, MA (Fig. 4). The magnitude of the wind maxima varied among the events but the jet positions were consistent and were well predicted by NWP guidance.

3. Thermodynamic and instability parameters

There were general patterns in the thermodynamic properties of the atmosphere with certain thresholds determined for parameters such as instability and midlevel lapse rates (700 hPa to 500 hPa). Careful investigation of historical soundings proximate to the significant severe weather events revealed 4-layer lifted indices (LI) ≤ -2° C (such as the Mechanicville, NY F3 tornado event on 31 May 1998; Fig. 5) and midlevel lapse rates ≤ -7°C km^{-1}, similar to how Banacos and Ekster (2010) define an elevated mixed layer in their study of significant severe weather in the northeastern U.S.

It should be noted that significant weather can occur when midlevel lapse rates are less steep and 4-layer lifted indices are between 0 and -2. These are considered outlier events, defined as a significant weather event occurring in the absence of one or more favorable parameters defined in this study. In one outlier event (Windsor Locks, CT F4 tornado event on 3 October 1979; listed as an outlier in table 3), relatively stable conditions existed but the boundary layer forcing mechanisms (described in section 4) contributed to the isolated significant severe weather.

4. Boundary layer processes

The difference in the evolution of synoptic scale features has a profound effect on the evolution of mesoscale features. Mesoscale features are the key to sustaining convection as it crosses the mountains, and when an upper-level vorticity center is not progressive, mesoscale features are often not maintained as they move east of the mountains.

For this study, the 850 hPa front (850 hPa is considered the upper limit of the friction zone and vertical extent of the Appalachian Mountains) will be defined as the region where the tightest gradient of equivalent potential temperature (θ_e) exists. In the severe weather events, the 850 hPa cold front was characterized as a θ_e gradient of 25 K or more in the region of the tightest gradient (such as during the Mechanicville, NY F3 tornado event on 31 May 1998; Fig. 6), typically in a distance of ≤ 400 km. Regions east of the Appalachian Mountains that do not experience the passage of this 850 hPa θ_e gradient, even with sufficient instability and shear present for severe weather, have greatly reduced chances of observing severe weather, sometimes even thunderstorms. During the non-events, the θ_e gradient did not meet the 25° K gradient threshold.

The presence of a low-level jet, wind shear and the associated low-level forcing were evaluated through analysis of 850 hPa winds from the North American Regional Reanalysis (NARR) project (Mesinger et al. 2006). The characteristics of the low-level jet, such as orientation, speed and forward propagation of the jet core, can be important when determining the presence of down slope wind flow in lee of the mountains, especially in the mid-Atlantic region. Sinking motion on the lee side of the mountains can disrupt the low-level forcing mechanisms that initiate or sustain convection. Hence, if the low-level jet segment over the eastern U.S. is nearly orthogonal to the mountains, then either strong low-level forcing or strong upper dynamics must overcome lee side down slope processes. Otherwise, the convection will weaken or dissipate in the process of crossing the mountains. Within southerly low-level jet cores along and east of the Appalachian Mountains, downslope processes were not an issue.

The magnitude of the low-level jet segments in the significant severe weather events were ≥ 18 ms^{-1} (35 kt) such as during the Great Barrington, MA F4 tornado event on 29 May 1995 event (Fig. 7). The severe weather occurred within all regions of the low-level jet cores, whether in the divergent or convergent regions. Analysis of the low-level jet evolution determined that the magnitude and the steady eastward component of the progression of the low-level jet segment associated with the upper vorticity center were the important factors in supporting convection that could produce significant severe weather, not the region of the low-level jet.

5. Outliers - Anomalous significant severe weather events

During the study period of 1953-2012, there were 4 prominent outlier events in which tornadoes of F2/EF2 magnitude or greater were observed under conditions when not all the severe weather parameters were present coincidentally. It should be noted, however, that the outlier events were very isolated events and occurred when at least one favorable parameter existed, even in the absence of some other favorable parameters.

An F4 tornado occurred in Stockbridge, MA on 28 August 1973 in conditions of extreme instability but there was very weak low-level jet forcing/shear in the vicinity of the associated warm front and the θ_e gradient did not meet the 25 K threshold. On 4 October 1979, an F4 tornado occurred in Windsor Locks, CT in conditions of very weak instability, relatively strong low-level jet forcing/shear but a very weak θ_e gradient. On 6 August 1993, an F4 tornado occurred in Petersburg, VA during conditions of considerable instability but in on the cyclonic shear zone of weak low-level jet forcing/shear and along a weak θ_e gradient. Finally, on 21 July 2003, a very strong mesoscale convective vortex with unusually strong upper level vorticity tracked through New York and the mid-Atlantic states with weak low-level jet forcing/shear and relatively weak θ_e gradient. Multiple F2 tornadoes were observed in NY and PA.

6. Conclusion

It was determined that a progressive 850 hPa and 500 hPa vorticity center and 850 hPa equivalent potential temperature change of ≥25K in 24 hours over the region identified the strong low-level forcing that supported significant severe weather events. Other important features were surface based instability characterized as a 4-layer lifted index ≤ -2° C, an 850 hPa wind maximum ≥ 18 m/sec (35 Kt) and being in the left-exit or right-entrance regions of the upper-level jet segment.

Based on a relatively small sample size of 3 null events, no statistical conclusions can be made about parameters contributing to null events. However, the signals in terms of the lack of significant instability and lack of eastward progression of upper vorticity centers and 850 hPa wind cores were consistent. No significant severe weather was observed in the null events and in fact, few if any severe weather events of any type were observed.

No forecast technique is foolproof as long as the atmosphere cannot be perfectly resolved in data networks and NWP guidance and outlier events can occur in rare cases. So, even though observing all the parameters defined in this study coincidentally greatly maximizes the chances for significant severe weather, significant severe weather can occur in rare instances when only one or some of the parameters are present, as is evidenced by the outlier events.

7. Future work

Preliminary analyses of historical NSHARP soundings and parcel trajectories at 500m (approximately 850 hPa), 1500m (approximately 700 hPa) and 3000m (approximately 500 hPa) has shown that regions of extreme instability, represented by elevated mixed layers, track into the northeastern U.S. during significant severe weather outbreaks. Tracking parcels allows analysis of temperature and moisture advection within the elevated mixed layer at different levels and may provide insight into areas with a high potential for severe convection.

For example, on 8 June 1953, an elevated mixed layer existed over the Great Lakes region, including Michigan, where F4-F5 tornadoes were observed. On 9 June 1953, the region of the elevated mixed layer tracked east into New England where the historic F4 Worcester, MA tornado was observed. The elevated mixed layer was apparent in historical NSHARP soundings from 1953 events in Mount Clemens, MI (MTC) and Hempstead, NY (NY9; Fig. 8), as well as in more recent events such as 31 May to 1 June 2011 in Detroit, MI (DTX) and Albany, NY (ALB; Fig. 9). Note the 700-500 hPa lapse rates exceeding 7°C km^{-1} in both events.

Parcel trajectories at 500m, 1500m and 3000m in both the 1953 and 2011 events showed how the elevated mixed layer advected east into the northeastern U.S. (Fig 10). These 12-24 hour parcel trajectory analyses show promise and all the events listed in tables 1-3 will be analyzed as will NWP model data in future events to see if this technique is viable for increasing lead times in predicting significant severe weather events.

Finally, the utility of analyzing θ_e at the surface and 925 hPa will be evaluated, as forcing at these levels may affect the mode of severe weather independent of the 850 θ_e gradients. It will also be important to evaluate the ability of NWP model guidance to resolve and predict these θ_e gradients.

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References

Banacos, P., and M. Ekster, 2010: The association of the elevated mixed layer with significant severe weather events in the northeastern United States. *Wea. Forecasting*, **25,** 1082–1102

Lacorte, J. J. and R. H. Grumm 2002: The climatology and character of Pennsylvania severe weather. *Preprints* 21st Conference on Severe Local Storms. San Antonio, TX, P8.3.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.*, **87**, 343–360.

Stuart N. A. 2004: The anatomy of the big event that never happened – The Grand

Finale of the May 2003 Tornado Outbreak. *Preprints* 22nd Conference on Severe Local Storms. Hyannis, MA, 12.8.

Table 1. List of significant severe weather events in the northeastern U.S. from 1953 through 2011 used for this study.

Northeastern U.S. Events	**Observed Severe Weather**
3 June 1953	Worcester, MA F4 tornado
2 May 1983	Multiple F2+ tornadoes
31 May 1985	Multiple F2+ tornadoes
10 July 1989	Multiple F2+ tornadoes
29 May 1995	Great Barrington, MA F4 tornado
3 July 1997	Multiple F2 tornadoes
31 May 1998	Mechanicville, NY F3 tornado
1 June 2011	Springfield, MA EF3 tornado

Table 2. List of forecast busts between 1953 and 2011 used for this study.

Forecast Busts	No Observed Severe Weather
11 May 2003	Moderate Risk and Tornado Watch
31 May 2004	Slight Risk and Tornado Watch
5 June 2010*	Slight Risk and Tornado Watch

*1 brief EF1 tornado in the northeast corner of a Tornado Watch

Table 3. List of outlier events between 1953 and 2011.

Outlier Events	Weak Low-Level Forcing and/or 850 hPa Wind
29 August 1973	West Stockbridge, MA F4 tornado
3 October 1979	Windsor Locks, CT F4 tornado
6 August 1993	Petersburg, VA F4 tornado
21 July 2003*	Multiple F2+ tornadoes

*Unusually strong midlevel vortex with high instability and shear

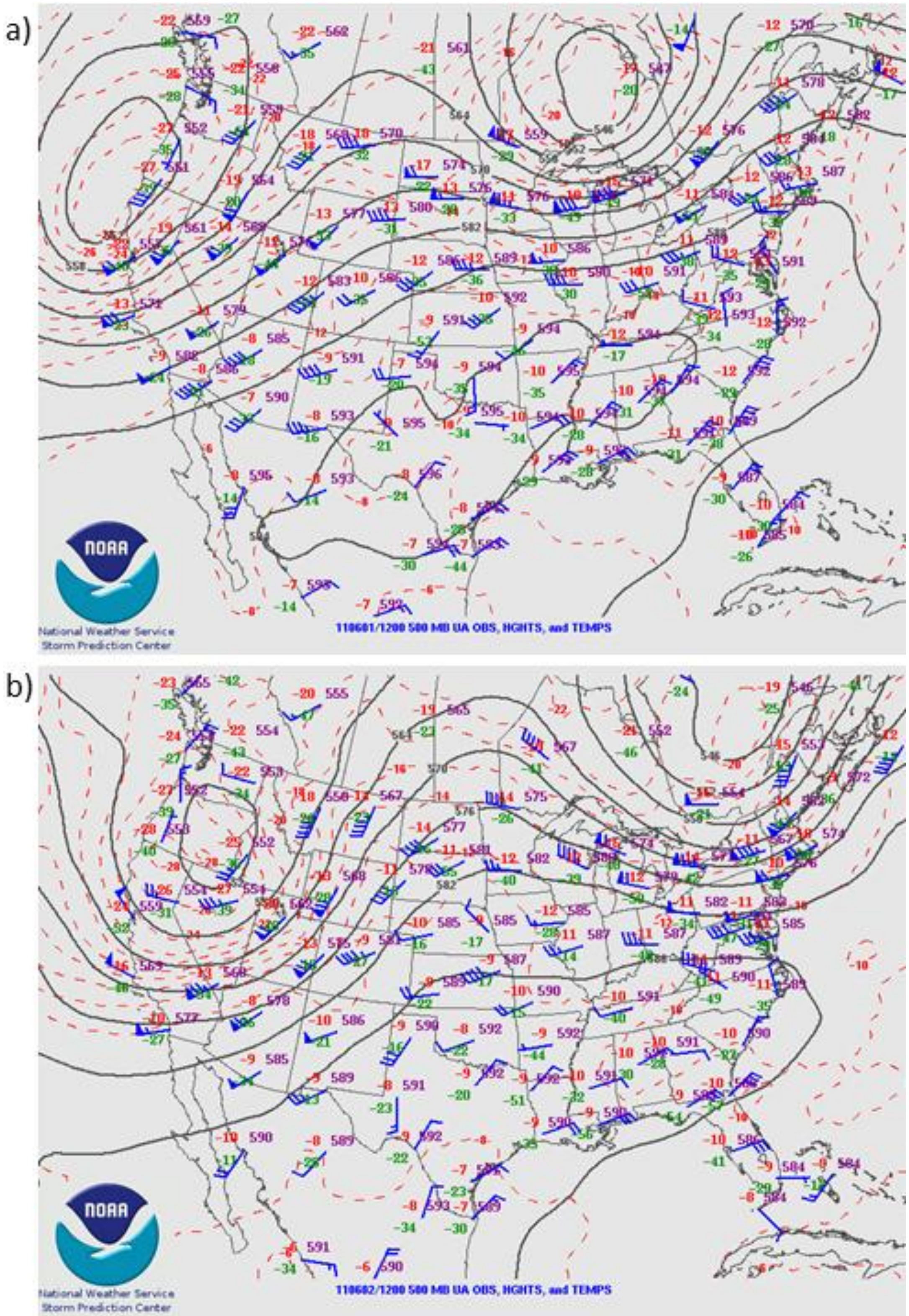


Figure 1. Upper air 500 hPa analysis from the Storm Prediction Center depicting heights, winds and temperatures at a) 1200 UTC 1 June 2011 and b) 1200 UTC 1 June 2011. Note the 500 hPa upper trough axis was along or just east of the Appalachian mountains by 1200 UTC 2 June.

a)
b)

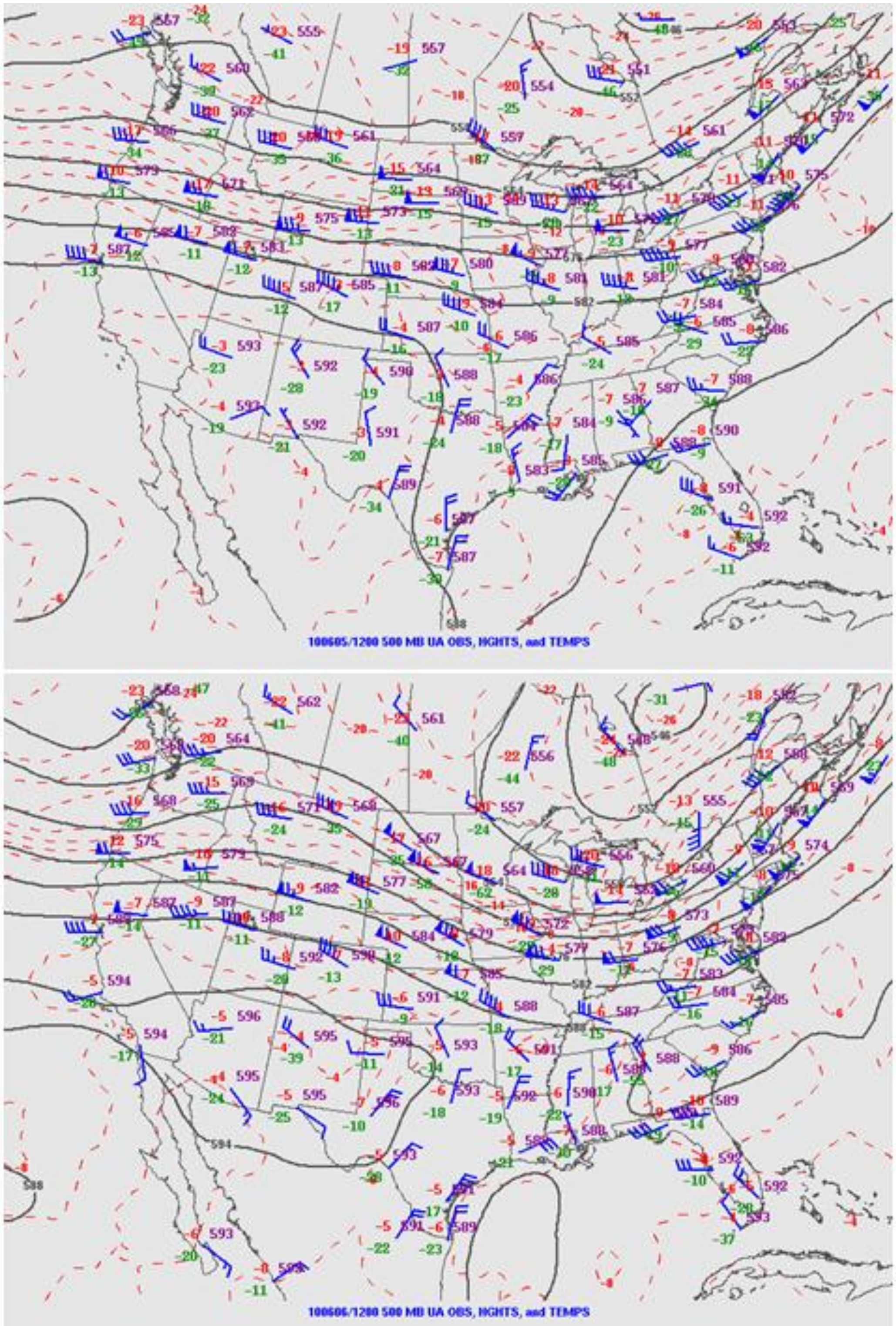


Figure 2. Upper air 500 hPa analysis from the Storm Prediction Center depicting heights, winds and temperatures at a) 1200 UTC 5 June 2010 and b) 1200 UTC 6 June 2010. Note that the 500 hPa upper trough axis remained west of the Appalachian mountains by 1200 UTC 6 June 2010.

a)

b)

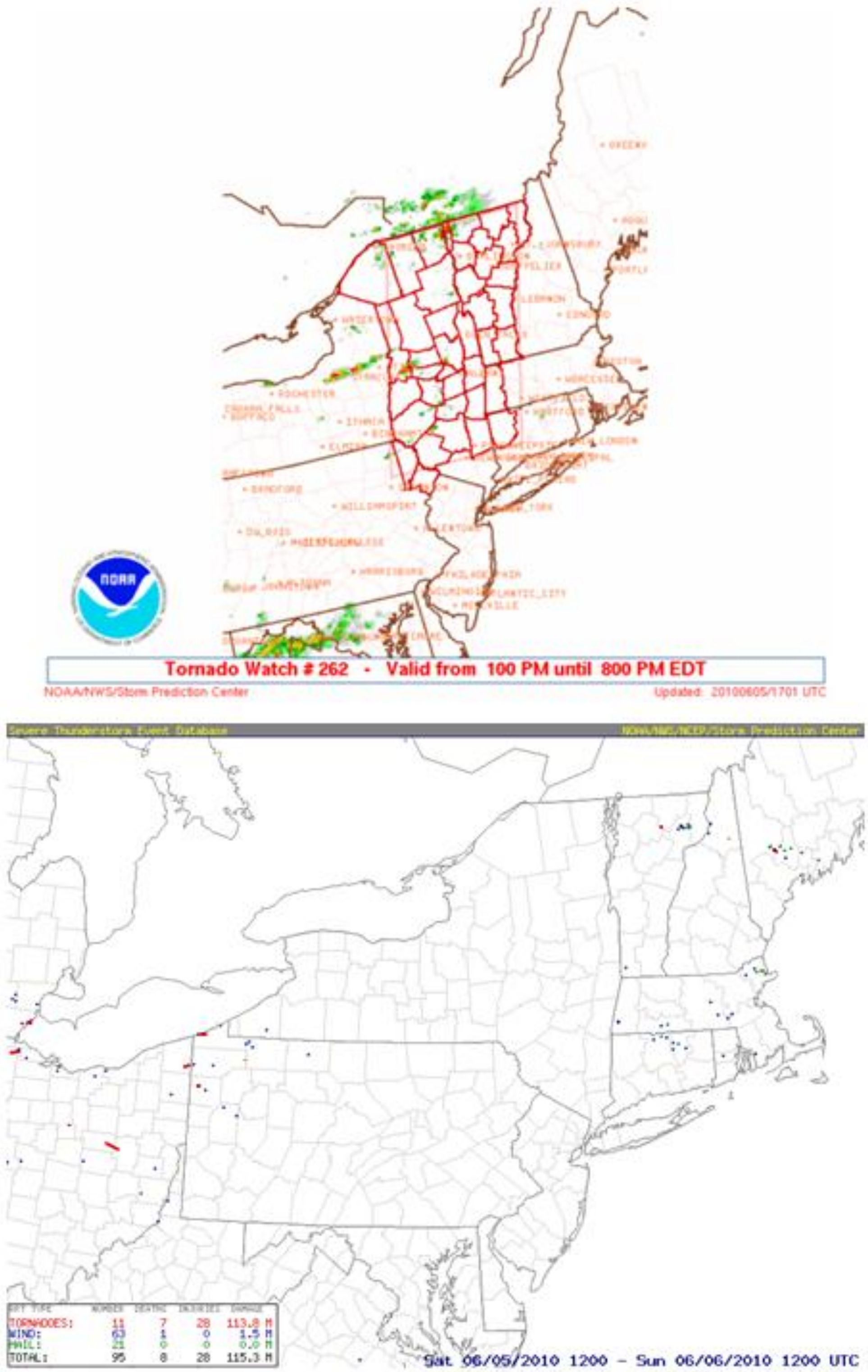


Figure 3. Plot of a) Tornado watch #262 issued by the Storm Prediction Center on 5 June 2011 and b) all severe weather reports from 1200 UTC 5 June 2010 through 1200 UTC 6 June 2010. Note the 1 tornado report in northern Vermont.

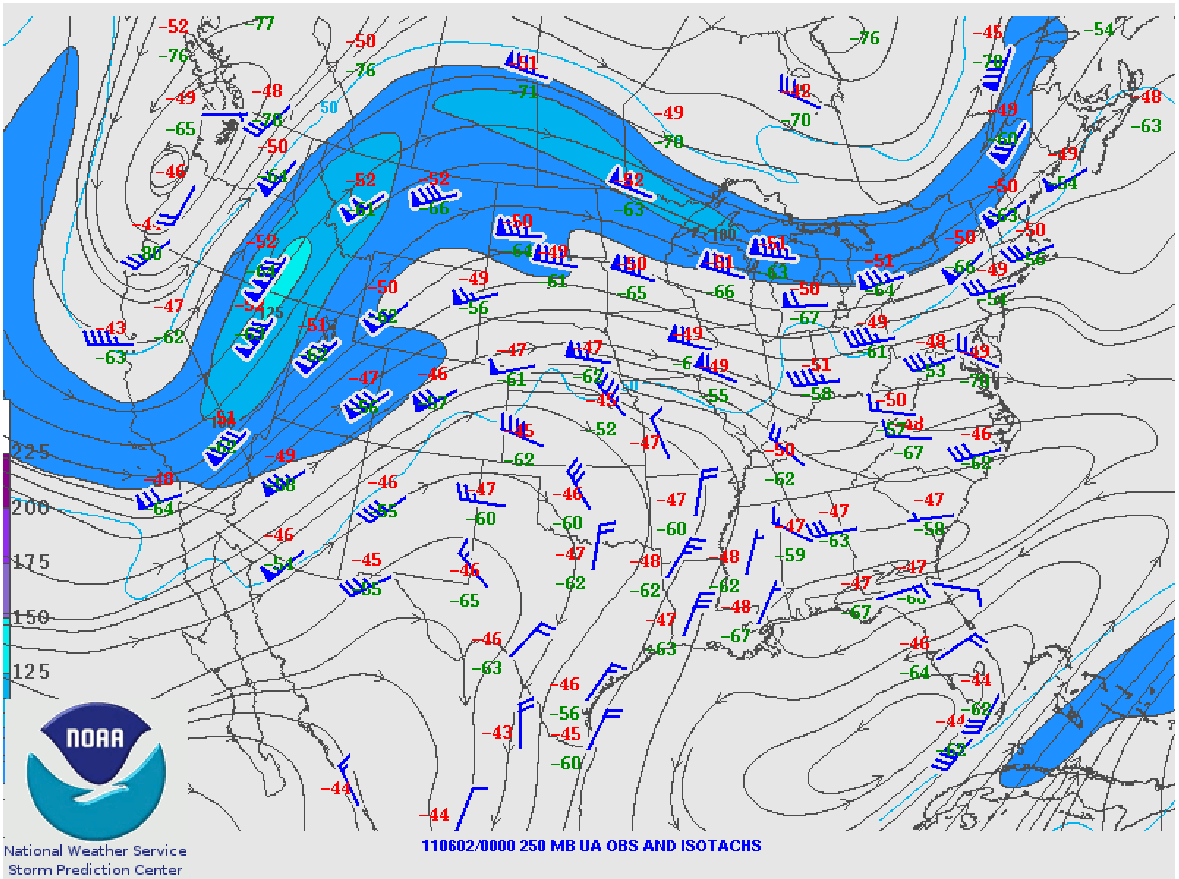


Figure 4. Upper air analysis of 250 hPa from the Storm Prediction Center valid 0000 UTC 2 June 2011 depicting winds, temperatures and streamlines. Note that the northeastern U.S. is in the diffluent and divergent, right entrance region of an upper jet segment.

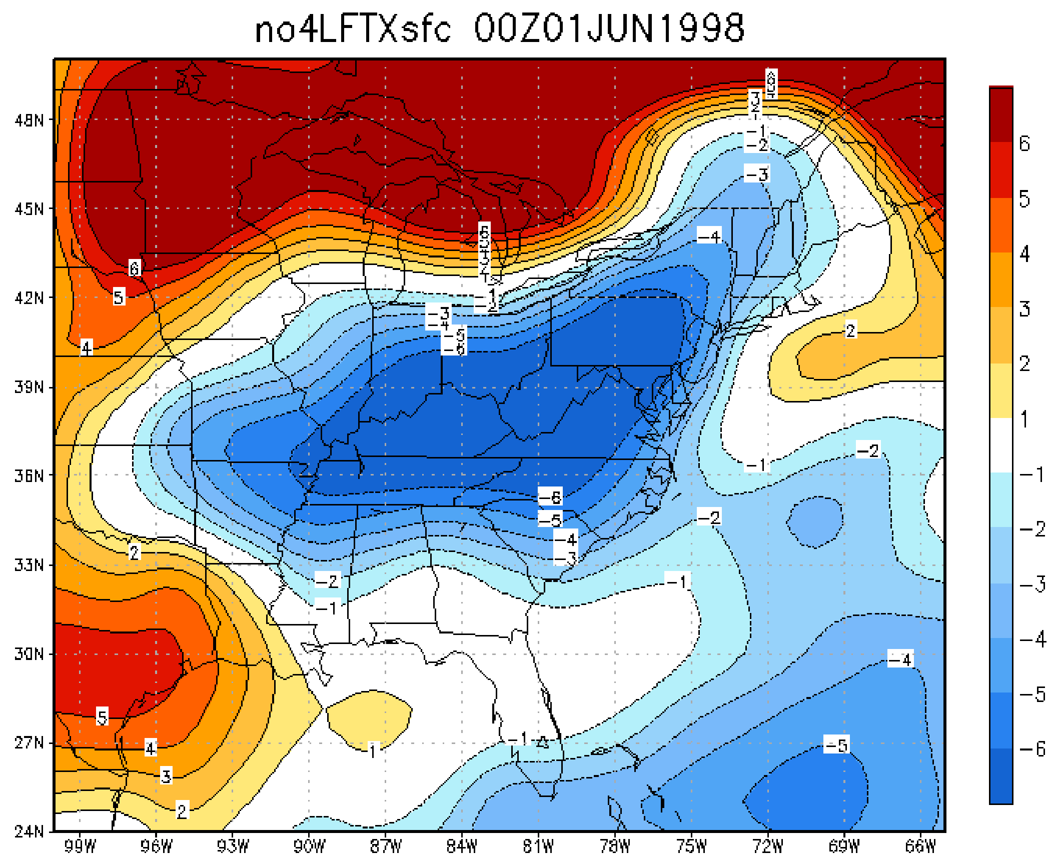


Figure 5. NARR analysis of 4-layer lifted index (K) valid 0000 UTC 1 June 1998. Note the 4-layer lifted indices ≤ -4° C over much if the interior northeastern U.S.

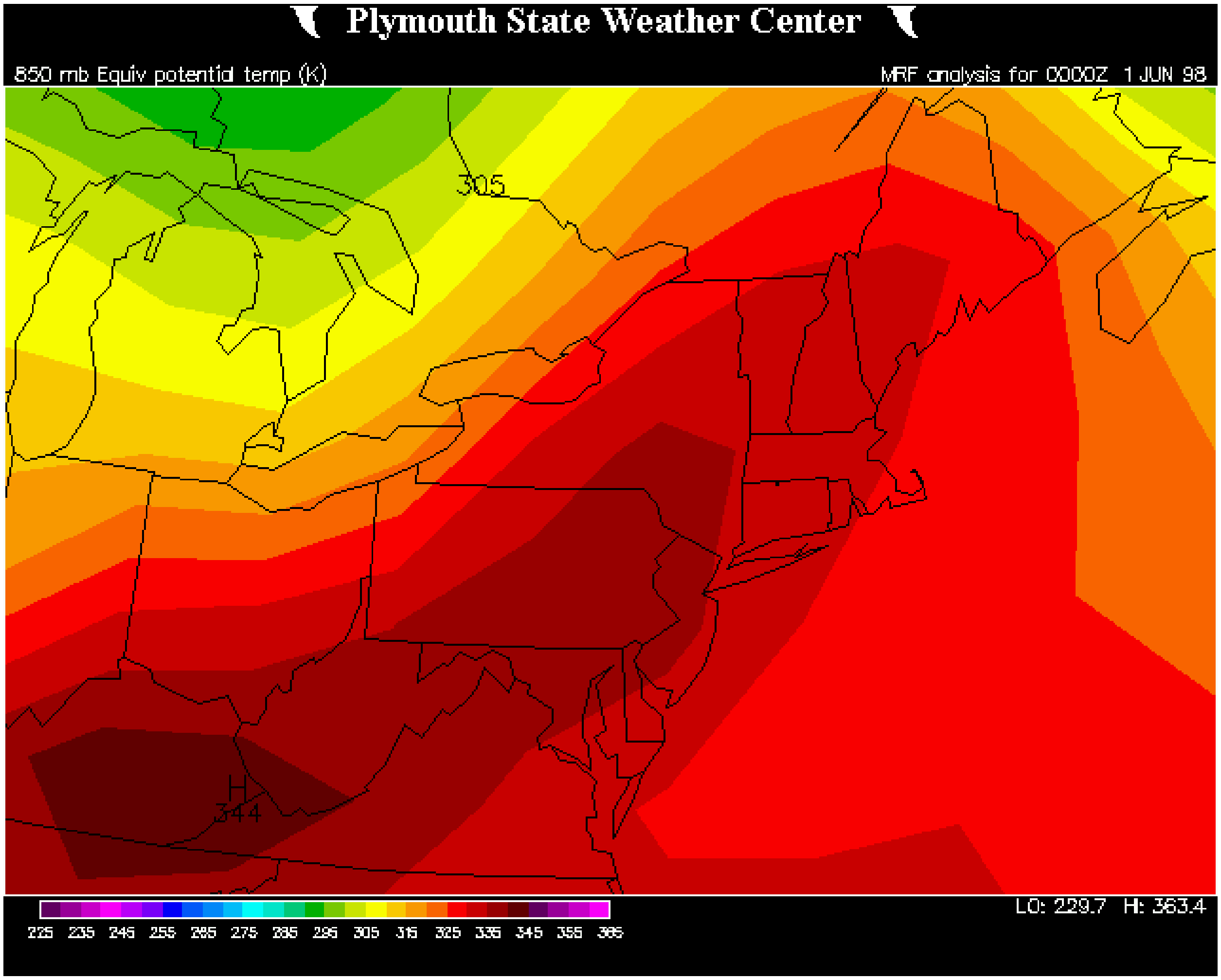


Figure 6. NARR analysis of 850 hPa θ_e (K) valid 0000 UTC 1 June 1998 (courtesy of Plymouth State University). Note the 850 hPa θ_e values ranged from 335K to 310K from the eastern Great Lakes to the interior northeastern U.S

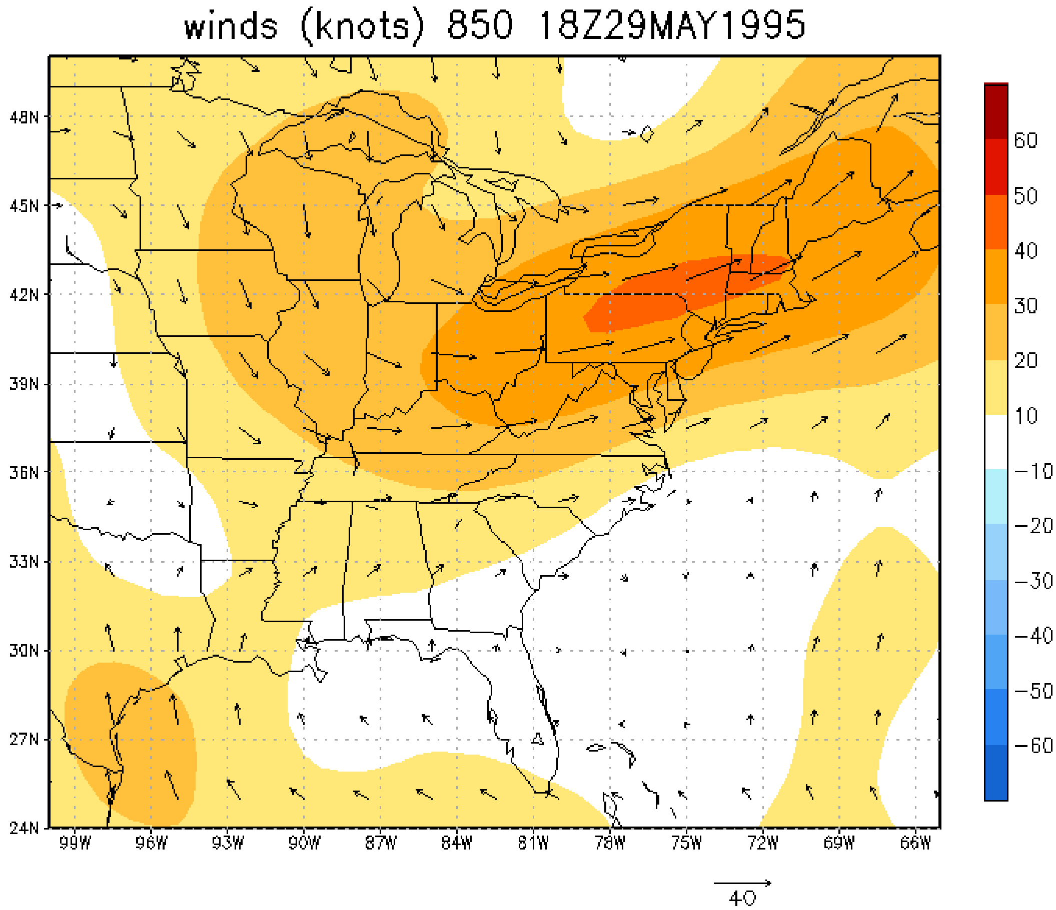


Figure 7. NARR analysis of 850 hPa winds (Kt) valid 18Z 29 May 1995. Note the 850 hPa low level jet core of 40-50 kt (20-25 m s^{-1}) over the interior northeastern U.S.

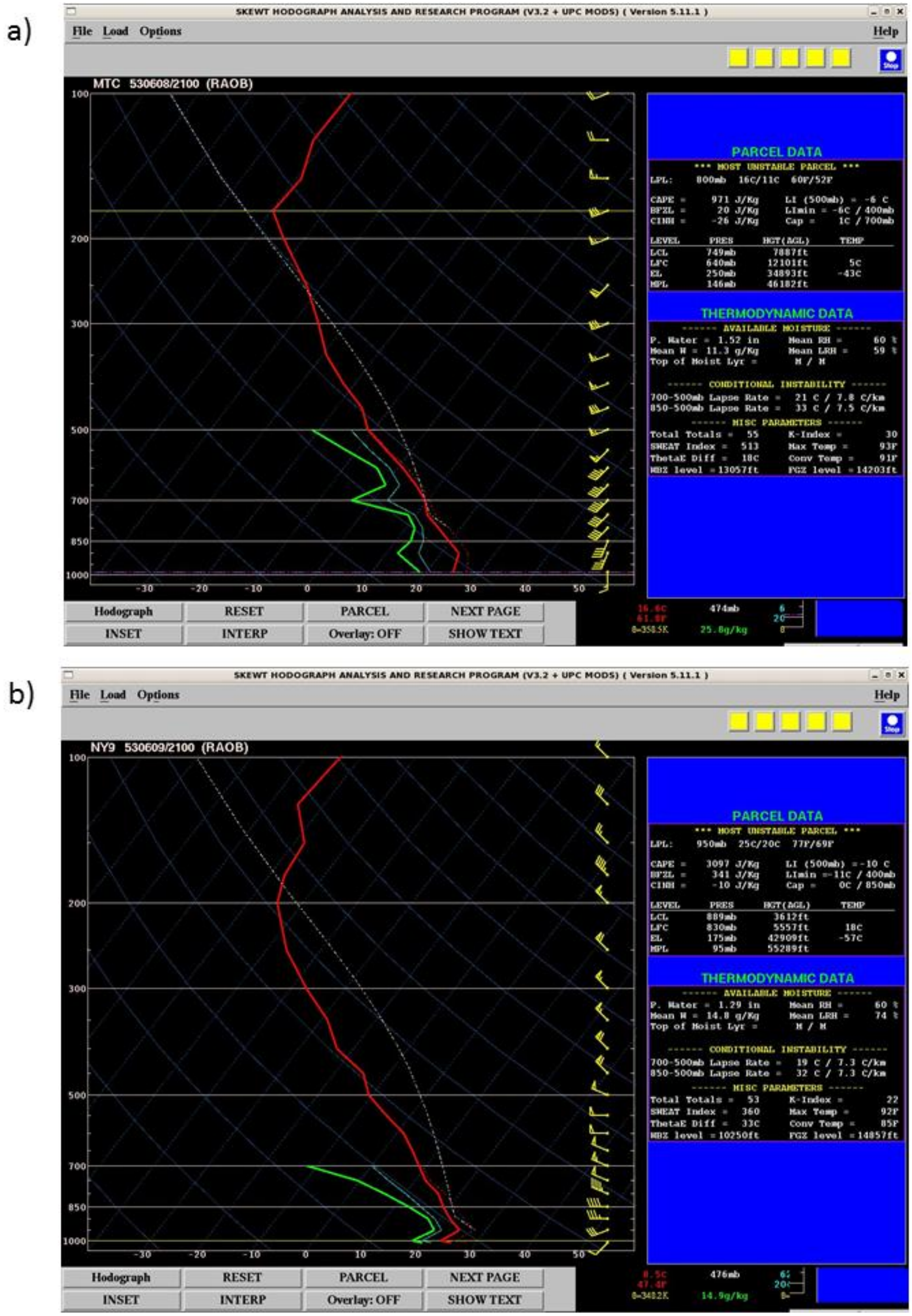
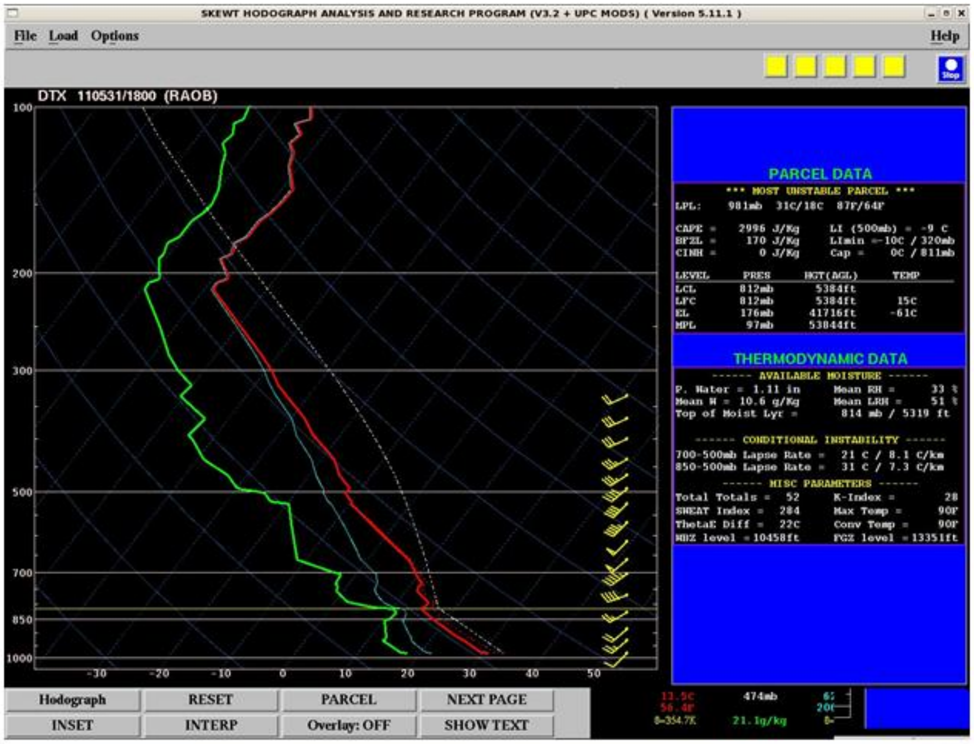


Figure 8. RAOBS analyzed in NSHARP from a) Mount Clemens, MI (MTC) at 2100UTC 8 June 1953 and b) Hempstead, NY (NY9) at 2100 UTC 9 June 1953. Note the 700-500 hPa lapse rates exceeded 7°C km^{-1} in both RAOBS.

a)



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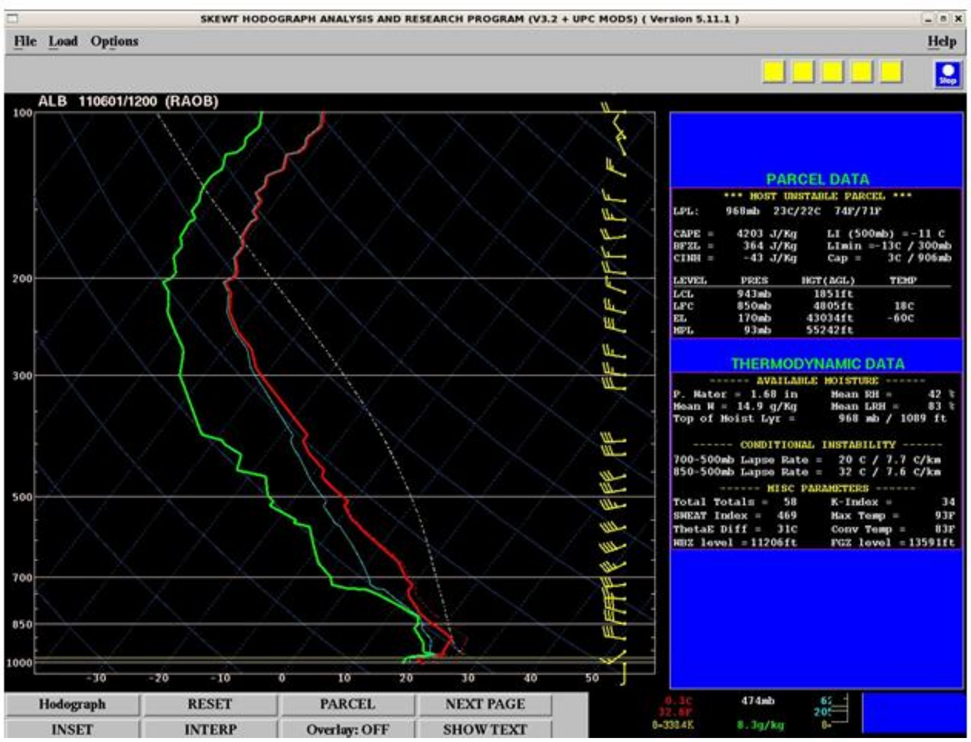

Figure 9. RAOBS analyzed in NSHARP from a) Detroit, MI (DTX) at 1800 UTC 31 May 2011 and b) Albany, NY (ALB) at 1200 UTC 1 June 2011. Note the 700-500 hPa lapse rates exceeded 7°C km^{-1} in both RAOBS.

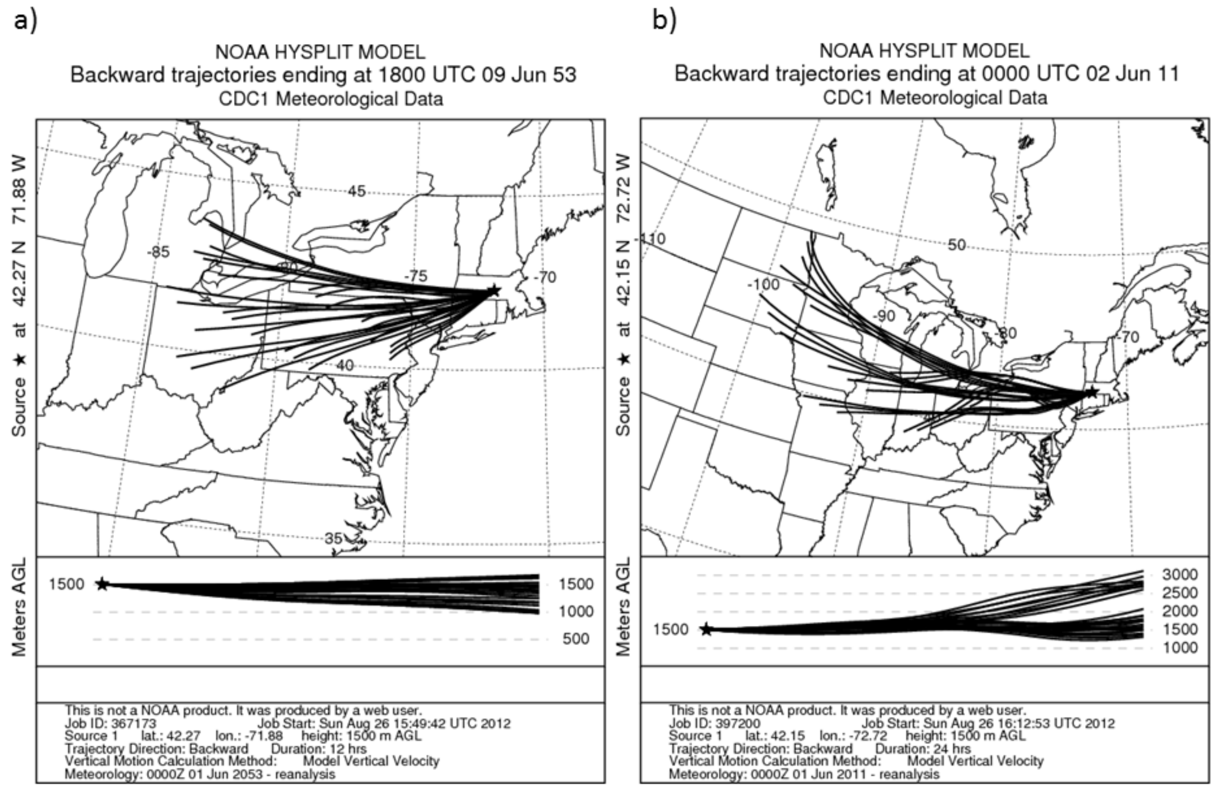

Figure. 10. HYSPLIT backward ensemble parcel trajectories for a) Worcester, MA 12 hours prior to 1800 UTC 9 June 1953 and b) 24 Westfield, MA 24 hours prior to 0000 UTC 2 June 2011. Note the 18-24 hour trajectories originated in regions where elevated mixed layers and tornadoes were observed.