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High Wind Events in Western New York: An Expanded Study and Development of Potential Impact Tables

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Abstract

*High Wind Events are a common occurrence in the Great Lakes region of the United States from the late Fall through early Spring. Specifically, this study focuses on non-convective high winds brought in on westerly cold air advection by strong extratropical cyclones tracking across the region. High wind events frequently cause widespread infrastructure and property damage, with monetary values ranging from thousands to millions of dollars, along with several fatalities as documented within the Storm Events Database (*National Centers for Environmental Information*).*

This study expands upon a previous local high wind study completed by Niziol and Paone (2000) *with new information and findings in several areas. In addition to using a more recent dataset of 2004-2014 cold-season events, the new study partitioned these events into three new categories to cover the full range of hazardous wind scenarios: Widespread, Limited and Advisory-only wind events. The need for the study came about through analysis of performance statistics for many of these more recent events. This study also expanded the coverage area beyond Buffalo, NY to the entire National Weather Service (NWS) Buffalo County Warning Area (CWA) along with developing new North American Regional Reanalysis (NARR) model composites of 500 hPa heights, Mean Sea Level Pressure (MSLP) and 850 hPa wind speed for each wind event category. Several high wind parameters were compared to identify distinct predictors of these categories with two standing out above the rest. The first being the strength of a surface low tracking northwest of Buffalo, NY which was also identified as a key requirement for a high wind event in the previous study and the second being strength of a strong and persistent 850 hPa jet tracking across the NWS Buffalo CWA. MSLP and 850 hPa wind data from these 2004-2014 cases were used to develop a set of High Wind Potential Impact Tables. The NARR composites and potential impact tables were created to both improve forecaster pattern recognition and increase forecaster confidence for impact extent of high wind events which should lead to improved performance statistics.*

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1. Introduction

The frequency of high wind events is especially high across western New York. A tally of 2004-2014 (Fig. 1) cold season non-convective high wind events shows the NWS Buffalo CWA experienced the most events of all Great Lakes NWS CWAs during the period. Previous local research by Niziol and Paone (2000) included a climatology for non-convective high wind events for western New York using 52 cases from 1977 to 1997 (Table 1). Events during that study were chosen using observed wind gusts of 50 kt (26 m/s) or more measured at a single point which was the Buffalo-Niagara International Airport. Findings from their study set the foundation for the understanding of high wind events impacting western New York and are still widely used by forecasters today.

In addition to the Niziol and Paone (2000) study there have been many other studies on the subject of non-convective high winds. Many of these studies include a climatology for specific forecast areas like Lacke et al. (2007), Zhong (2008), Layer and Colle (2015) while others such as Ashley and Black (2008) looked at fatalities associated with high wind events. Only one study, Kapela et al. (1995) included an operational forecast checklist but this was designed for the Northern Plains region. Motivation for the presented study came about from a personal desire to develop an operational tool to assist with forecasting of these frequent events along with an interest to update the previous study with new cases and datasets.

In an effort to update the Niziol and Paone (2000) study with new data, a new set of cold season non-convective high wind events was collected from the period between November 2004 and April 2014. While sifting through this new data, a notable difference in coverage of event impacts was found. Some of the events produced impacts across the majority of the NWS Buffalo CWA while other events only impacted a few isolated counties or forecast zones. Therefore, the events were sorted into three separate categories based on span of impact: Widespread events, Limited events, and Advisory-only events. Widespread and Limited events are defined in this study as having met NWS High Wind Warning threshold which for the NWS Buffalo CWA is sustained winds of 35 kt (18 m/s) or greater or wind gusts 50 kt (26 m/s) or greater while also being separated by the number of forecast zones impacted. Widespread events are defined in this study as impacting 12 or more of the 17 public forecast zones or 70% of the NWS Buffalo CWA and Limited events impacting less than 12 forecast zones. An example of the impact areas of a Widespread and Limited event is shown in Fig. 2. Advisory-only events can cover any number of forecast zones within the NWS Buffalo CWA but observed wind speeds and gusts are below High Wind Warning threshold.

Developing a pattern recognition can help improve forecaster confidence in the threat level of an oncoming wind storm and result in more precise and accurate forecasts and increased warning lead time. In order to improve pattern recognition for each category of wind event, NARR data was used to create new composite charts of 500 hPa heights, Mean Sea Level Pressure (MSLP), and 850 hPa wind speed using the 2004-2014 events. The composites highlighted notable differences between each wind event category.

In addition to the creation of the composite charts, a new forecast tool was developed after sorting through various high wind parameters to find clear predictors of the three event categories. This forecast tool consists of a set of tables which can help forecasters distinguish the potential impact level of a forecasted wind event using two key predictors discovered in this study as significant to the differentiating of event categories. These predictors are: 1) MSLP of a deepening mid-latitude cyclone with a favorable track within 500 miles northwest of Buffalo and 2) the strength in knots of the 850 hPa low level jet forecasted over the NWS Buffalo CWA during the expected onset time of surface mixing which usually coincides with a cold front passage and rise in pressure tendency. The tables provide forecast warning decision guidance using data collected from the 2004-2014 wind events. Along with background knowledge of high wind pattern recognition, these tables can be used for years to come to assist forecasters in cold-season high wind forecasting.

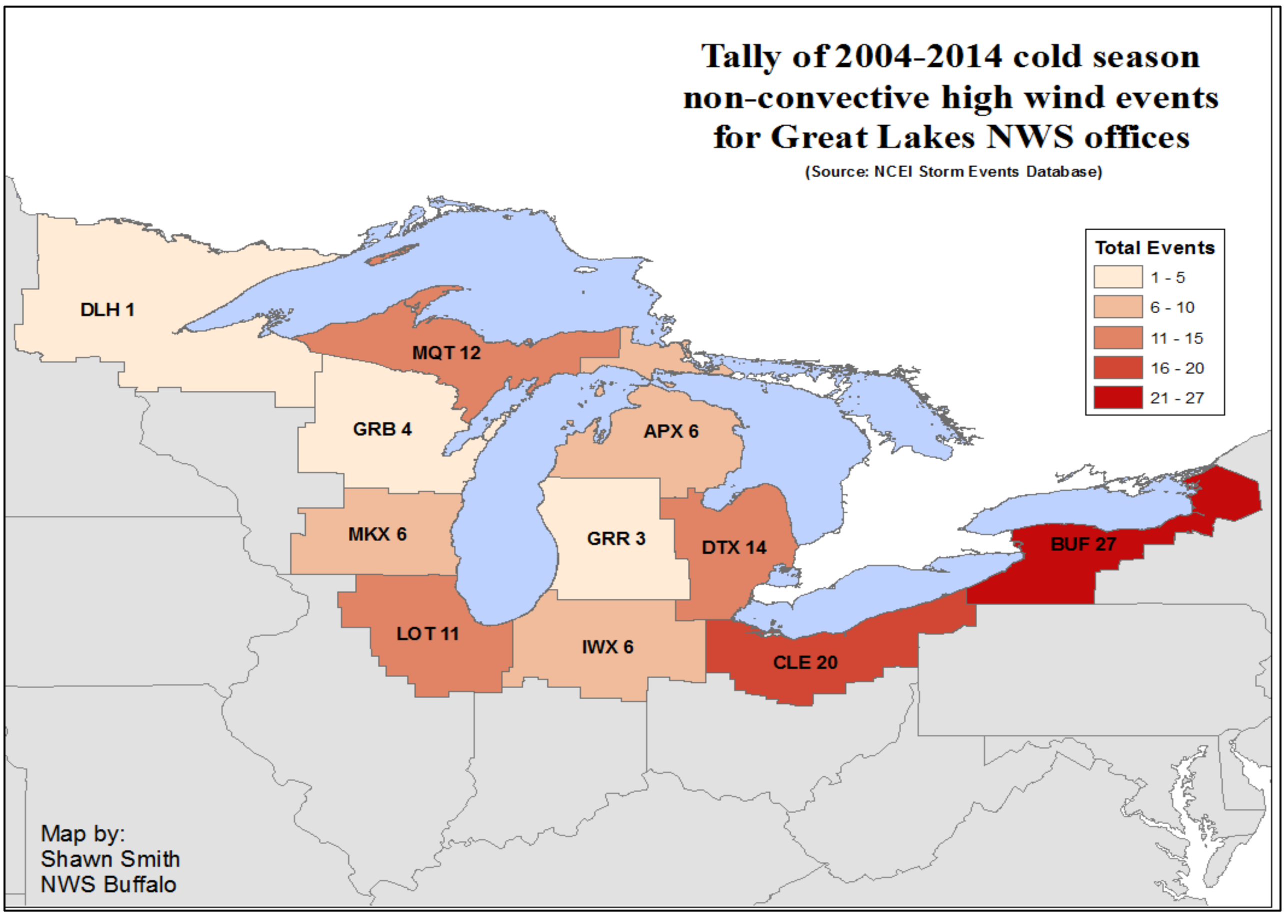


Figure 1. A map showing the tally of 2004-2014 cold season (Nov-Apr) non-convective high wind events for Great Lakes NWS offices.

Table 1. High Wind Cases from Niziol and Paone (2000) Study

11 Jan 1977 00z	29 Jan 1977 00z	31 Jan 1977 12z	05 Mar 1977 00z	02 Dec 1977 00z
09 Jan 1978 12z	26 Jan 1978 12z	06 Apr 1979 12z	27 Nov 1979 00z	08 Dec 1979 00z
07 Jan 1980 12z	12 Jan 1980 00z	05 Jan 1982 00z	24 Jan 1982 00z	01 Feb 1982 00z
01 Apr 1982 00z	13 Nov 1982 00z	29 Dec 1982 00z	14 Oct 1983 12z	28 Oct 1983 12z
01 May 1984 00z	16 Nov 1984 12z	02 Jan 1985 00z	12 Mar 1985 12z	06 Apr 1985 12z
20 Nov 1985 12z	02 Dec 1985 12z	28 Dec 1985 00z	11 Mar 1986 00z	19 Mar 1986 12z
16 Dec 1987 00z	13 Jan 1988 12z	11 Nov 1988 00z	08 Jan 1989 12z	15 Mar 1989 12z
12 Nov 1989 00z	20 Nov 1989 12z	11 May 1990 00z	18 May 1990 00z	04 Jun 1990 00z
06 Nov 1990 12z	28 Mar 1991 12z	16 Apr 1991 00z	15 Dec 1991 00z	24 Jan 1992 12z
12 Nov 1992 12z	26 Dec 1992 00z	16 Apr 1993 12z	21 Oct 1993 12z	29 Jan 1994 00z
16 Apr 1994 12z	28 Nov 1994 12z			

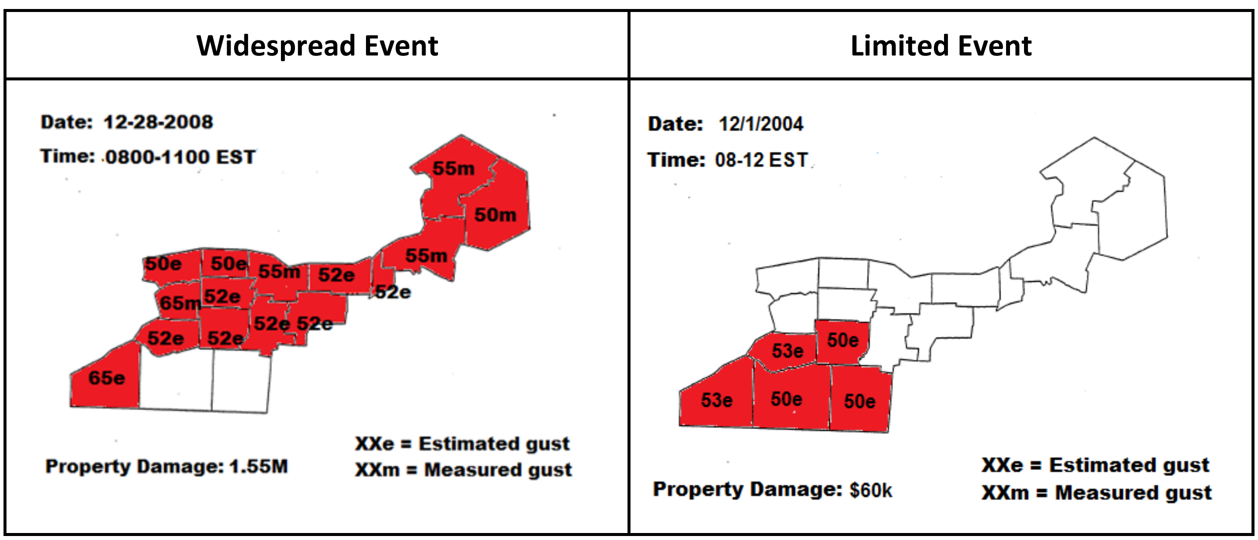


Figure 2. Comparison of a Widespread high wind event impact and Limited high wind event impact. Widespread events are defined as impacting 12 or more forecast zones and Limited events as impacting less than 12 forecast zones. Red-filled zones are those impacted by high winds with magnitude of winds included for each zone in knots. A gust with an appended "m" is a measured gust and an "e" is an estimated gust in knots. Total property damage estimates are included for each type of event in the lower left.

2. Data and Methodology

a. Case Selection

High wind cases for this study were collected from an 11-season period using verified non-thunderstorm wind damage and non-thunderstorm wind gust reports from NWS Storm Data. Cases were only included if they occurred during the climatological maximum frequency cold season months of November through April (Angel and Isard 1998) between November 2004 and April 2014. NWS Storm Data includes events with measured winds meeting or exceeding locally defined criteria or those events with reported damage that would have been caused by winds meeting or exceeding locally defined criteria which for NWS Buffalo is sustained winds of 35 kt (18 m/s) or greater or wind gusts 50 kt (26 m/s) or greater. During the study period, 24 high wind events were collected with a combined total property damage estimate of 18.2 million dollars. Property damage estimates within Storm Data are gathered from disaster declarations, insurance claims and input from emergency management, cooperative extensions and utility companies.

The following data was then collected for each high wind event (Table 2a-b): Initial event onset time of high winds within the NWS Buffalo CWA, Number of Storm Data verified forecast zones, Maximum event wind gust (measured or estimated), estimated total Property Damage and MSLP rise/fall difference between 12 hours before and 12 hours after onset. The high wind events were then split into two groups based on extent of spatial impact or number of Storm Data verified forecast zones across the NWS Buffalo CWA, Widespread events impacting 12 or more forecast zones and Limited events impacting less than 12 forecast zones. These groups also correlated well with maximum event wind gust, estimated property damage and MSLP rise/fall differences where means for each were higher in Widespread events than Limited events. For the 24 high wind events, 11 were categorized as Widespread, while 13 were categorized as Limited.

In addition to the high wind events, a total of 34 Advisory-only events were collected during the study period in order to include lower end wind events. (Table 3) An Advisory-only event is defined in this study as an event where only Wind Advisories were issued in the NWS Buffalo CWA without any High Wind Warnings. Since Wind Advisory events are not included in NWS Storm Data, event dates were identified by filtering the local product archive for issued Advisories without any High Wind Warnings issued. Advisory level winds are locally defined as sustained winds of 27 to 34 kt (14 to 18 m/s) or gusts of 40 to 49 kt (21 to 25 m/s). For purposes of this study, in order to independently verify an Advisory, measured winds from METARs reaching into the range of advisory criteria were used since few damage reports exist for Wind Advisory events (Iowa State University NWS Watch/Warning/Advisory + ASOS/AWOS Observations App). While damage to small branches and trees and even unsecured light-weight yard items can occur in advisory level winds, these events go unreported and thus can't be used to track Advisory events as they are not considered as significant as damage which occurs in high wind events.

Table 2a. Widespread High Wind Warning events 2004-2014 with onset time within NWS Buffalo CWA, Number of Storm Data verified forecast zones, Magnitude of event (Mag.) in knots Measured (m) or Estimated (e), Estimated Property Damage in thousands (K) of dollars, MSLP Rise/Fall difference from 12 hours before onset time to 12 hours after onset time, NWS Buffalo probability of detection (POD), false alarm ratio (FAR) and warning Lead Time in hours (LT) statistics. Verified forecast zones, Mag and Property Damage collected from Storm Events Database. Performance statistics not available before October 2007 from NWS Performance Management website.

Widespread Events	# of Verified Forecast Zones	Mag of event (kt)	Est Property Damage ($K)	MSLP Press Rise/Fall (mb) 12h before onset to 12h post onset	NWS Buffalo (POD/FAR/LT)
17 Feb 2006 09z	17	70m	3000	-13	N/A
01 Dec 2006 18z	17	58m	455	-4	N/A
09 Jan 2008 12z	12	64e	3750	-23	0.91/0.08/1.2
30 Jan 2008 09z	17	61m	2175	-11	1.00/0.00/20.8
28 Dec 2008 12z	15	65m	1550	-18	1.00/0.00/8.7
12 Feb 2009 09z	12	60m	340	-11	1.00/0.20/17.5
18 Jan 2012 00z	17	63m	765	-14	1.00/0.00/11.0
20 Jan 2013 09z	16	67m	265	-10	1.00/0.06/17.8
31 Jan 2013 06z	13	55m	150	-29	1.00/0.00/19.4
1 Nov 2013 09z	15	50m	305	-23	1.00/0.00/27.6
18 Nov 2013 06z	12	59m	245	-21	1.00/0.00/28.4
Widespread Avg.	14.8	61.1	1182	-16	0.99/0.04/16.9

Table 2b. Limited High Wind Warning events 2004-2014 with onset time within NWS Buffalo CWA, Number of Storm Data verified forecast zones, Magnitude of event (Mag.) in knots Measured (m) or Estimated (e), Estimated Property Damage in thousands (K) of dollars, MSLP Rise/Fall difference from 12 hours before onset time to 12 hours after onset time, NWS Buffalo probability of detection (POD), false alarm ratio (FAR) and warning Lead Time in hours (LT) statistics. Verified forecast zones, Mag and Property Damage collected from Storm Events Database. Performance statistics not available before October 2007 from NWS Performance Management website. Note high level of FAR (0.50 or greater in several Limited events and the Limited events average.

Limited Events	# of Verified Forecast Zones	Mag. of event (kt)	Est Property Damage ($K)	MSLP Press Rise/Fall (mb) 12h before onset to 12h post onset	(POD/FAR)
01 Dec 2004 12z	5	53e	60	-22	N/A
08 Dec 2004 00z	8	54e	235	2	N/A
03 Nov 2005 15z	1	50e	4	3	N/A
06 Nov 2005 18z	6	56m	750	-7	N/A
24 Dec 2007 00z	2	53m	100	5	1.00/0.91/28.9
25 Dec 2008 00z	10	54m	275	-22	1.00/0.09/10.1
09 Dec 2009 21z	8	59m	1850	-1	1.00/0.53/19.8
30 Nov 2010 15z	1	50m	25	-6	1.00/0.50/19.0
28 Apr 2011 12z	8	72m	1070	-9	0.88/0.22/4.7
01 Jan 2012 21z	3	53m	70	-13	1.00/0.70/12.9
24 Feb 2012 21z	9	58m	425	-11	1.00/0.40/8.2
03 Mar 2012 09z	9	60m	240	-7	1.00/0.47/27.8
06 Jan 2014 09z	7	52m	100	-25	1.00/0.59/17.7
Limited Avg.	5.9	55.7	400	-9	0.99/**0.49/16.6**

Table 3. Wind Advisory-only events 2004-2014 with onset time within the NWS Buffalo CWA. Performance statistics and Storm Data not available for advisory events. *Average pressure rise/fall for Advisory events was -2mb.

05 Nov 2004 15z	04 Dec 2004 21z	06 Jan 2005 21z	16 Nov 2005 12z	29 Nov 2005 06z
18 Jan 2006 06z	05 Feb 2006 12z	10 Mar 2006 15z	14 Mar 2006 12z	10 Feb 2008 15z
17 Feb 2008 21z	01 Apr 2008 18z	30 Dec 2008 06z	11 Mar 2009 12z	03 Apr 2009 21z
04 Apr 2010 00z	17 Nov 2010 15z	14 Feb 2011 09z	19 Feb 2011 15z	10 Mar 2011 00z
11 Apr 2011 18z	24 Jan 2012 06z	28 Jan 2012 21z	09 Apr 2012 15z	22 Dec 2012 12z
04 Jan 2013 15z	09 Jan 2013 18z	11 Feb 2013 18z	19 Feb 2013 18z	07 Apr 2013 15z
19 Apr 2013 15z	19 Jan 2014 21z	22 Feb 2014 15z	05 Apr 2014 03z	

b. NWS Buffalo Performance for Widespread and Limited Events

Each NWS office calculates performance statistics for high wind warnings which are published to the NWS Performance Branch. Probability of Detection (POD), False Alarm Ratio (FAR) and warning Lead Time (LT) were available for each of the Widespread and Limited events after October 2007. (Tables 2a-b) These scores show that NWS Buffalo has an excellent 99% POD with less than 1% FAR and 16.9 hour LT for Widespread events. Scores for Limited events also showed a high POD of 99% and similar LT of 16.6 hours however the FAR is quite high with a 49% average for the 9 events with scores. Five of nine events scored an FAR of 50% or more. A high FAR indicates that significantly more forecast zones were warned than those that were impacted. The high FAR results for Limited events led to further motivation by the author to develop a forecast tool which could assist forecasters with assessing impact extent to reduce the number of over warned areas.

c. Composite Charts

Seasoned forecasters have often stated that pattern recognition plays a huge role in putting together a successful weather forecast. Pattern recognition can be aided by creating composite charts from a group of cases. For example, Colle et al. (2012) developed a tornado climatology using composites created with the NARR model. Construction of composites was also done by Niziol and Paone (2000) using an older National Center for Atmospheric Research (NCAR) data set. These composites were created using their 52 cases with a temporal resolution of 12 hours, spanning the entire calendar year including a case during the month of June. The composites included 500 hPa geopotential height and vorticity, 850 hPa geopotential height and temperature advection and MSLP.

The current study includes a new set of higher temporal and spatial resolution composite charts using more recent cases while also adding a new composite for 850 hPa wind speed. Composite plots of 500 hPa geopotential height, MSLP and 850 hPa wind speed were constructed for each category (Widespread, Limited, and Advisory-only) using the high resolution (32km/45 layer) NARR model (Mesinger et al. 2006) provided by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory Physical Sciences Division in Boulder, Colorado. For each event, the closest 3-hourly time to when the onset of high winds was observed within the NWS Buffalo CWA was used. Composites were also created for time periods 12 hours before and 12 hours after the corresponding onset time to show how the magnitudes of the parameters changed leading up to and beyond onset time. The new composites highlighted significant differences in the synoptic pattern between the Widespread, Limited, and Advisory-only categories summarized in the results section.

d. Potential Impact Tables

Perhaps the most significant outcome of the study was the creation of new operational Potential Impact Tables (Table 4). These tables were designed to be used by forecasters as additional guidance for deciding whether to issue a High Wind Warning and the associated extent of the warning or only issue a Wind Advisory with winds/damage expected to remain below warning criteria. In order to determine which parameters would serve as the best predictors of event category, several were compared looking for the largest deviation values of the means between event categories. The parameters measured and maximum values for each event separated by event category are included in Tables 5a-c. The parameters include: Mean Sea Level Pressure (hPa) at onset time of high winds in the NWS Buffalo CWA, Maximum 850 hPa wind speed (kt) over the NWS Buffalo CWA at surface gust onset time, 0-3 km Lapse Rate (C/km) maximum within 3 hours of onset time, 2 hour pressure rise (hPa) within 3 hours of onset time and NARR 850 hPa U-component wind anomaly within 12 hours post onset time. MSLP values were collected from Weather Prediction Center (WPC) surface analysis charts, 850 hPa wind speeds and U wind anomalies were taken from the NARR model via the Saint Louis University Cooperative Institute for Precipitation Systems (CIPS) and 0-3km lapse rates and 2 hour pressure rises were collected from the Storm Prediction Center Mesoanalysis archive (SPC). Values of 850 hPa wind speed, 0-3 km Lapse Rate, and 2 hour pressure rise were measured as the maximum value contours within the bounds of the NWS Buffalo CWA. Table 5d shows the means of each of these parameters for the three event types and the standard deviation (SD) of these means. Looking at these deviations, MSLP and 850 hPa wind speeds show the largest deviations between the event categories 2.9 mb and 5.3 kt respectively and were therefore used as the two main predictors for the Potential Impact Tables. This method allowed minimal cross-mixing of parameter values across the event types this minimizing the area of the “May Fit Any Wind Event” category on the Potential Impact Tables. The deviations of the other three parameters were found to be too narrow to use as predictors for differentiating wind categories.

Statistical values of Mean, Minimum, Maximum and one SD above and below the mean for MSLP and 850 hPa wind speed in each event type were then calculated and plotted as box and whisker charts (Table 6a-b). The significance of one SD from the mean was chosen because it encompasses 68.2% of events in a normal distribution. Notable trends in wind speed versus event type and MSLP verses event type were observed in the box and whisker charts which led to the creation of the Potential

Impact Tables. An effort was made attempting to capture all events within two SD of the mean but there was too much cross-mixing of values between event types.

Detail of the need for two predictors is revealed in Table 6c. The XY scatterplot shows results revealing low R-squared values or poor correlation between the two predictors for each event type. Therefore you cannot linearly use MSLP to predict 850 hPa wind speed and vice versa. Thus two predictors are needed to determine an event impact. Strong 850 hPa jets can occur with weak lows and strong lows can have weak 850 hPa jets (as measured over the NWS Buffalo CWA) as indicated mainly by Advisory cases toward the upper right and lower left corners of the plot.

The values from the two plots were then used to create a range of MSLP and 850 hPa wind speed for each event type within one SD of the mean. This data was then merged into a combined range scale with clear indicators of possible event type on the extremes and combinations of possible event types toward the middle (Table 7). The three event types were broken into the following six possible outcomes and associated colors on the Potential Impact Tables.

- **Widespread (Red):** Values match the range observed during previous Widespread high wind events.
- **Widespread or Limited (Orange):** Values match observed values of both Widespread and Limited events.
- **May Fit Any Wind Event (Black):** This range of values was found to occur in any of the three event types but typically on the low end range of a Widespread, mid-range of a Limited and high end range of an Advisory-only event.
- **Limited or Advisory (Green):** Values match observed values of both Limited and Advisory-only events.
- **Advisory Events (Blue):** Values match observed values of wind advisory-only events.
- **Unlikely Event (White):** Values in this range very rarely produced winds meeting Advisory or Warning criteria within NWS Buffalo CWA.

These charts were then recreated in both web format and as a program that forecasters can use on operational Linux systems. The web format (Fig. 3), created with JavaScript HTML, only requires a forecaster to enter a forecast MSLP from within 500 mi northwest of Buffalo and an 850 hPa wind speed from over the NWS Buffalo CWA at the expected onset time of high winds within the forecast area. The JavaScript then displays the matching event category for each parameter. The Linux display was written as a TCL TK program (Fig. 4) where the forecast values are input with slider bars.

Table 4. Potential Impact Tables. Colors correspond to categories created with data in Table 7.

Mean Sea Level Pressure High Wind Potential Impact Table	
<= 980 hPa	Widespread Event
981-983 hPa	Widespread or Limited Event
984-989 hPa	May Fit Any Wind Event (See 850hPa wind result)
990-994 hPa	Limited or Advisory Event
995-997 hPa	Advisory Event
>= 998 hPa	Unlikely Event

850 hPa Wind Speed High Wind Potential Impact Table	
>=64 kts	Widespread Event
61-63 kts	Widespread or Limited Event
57-60 kts	May Fit Any Wind Event (See MSLP result)
51-56 kts	Limited or Advisory Event
41-50 kts	Advisory Event
<= 40 kts	Unlikely Event

Table 5 a-d. Data for cases separated by event type. Columns include several parameters which were looked at to determine predictors used for Potential Impact Tables. Table 5d includes parameter means and a standard deviation of the means. MSLP and 850 hPa winds had the largest desired separation of means in order to minimize the "May Fit Any Wind Event" table category.

a. Widespread Events

Widespread Events (Date/onset time)	MSLP (hPa)	Max 850 hPa Wind Speed (kt)	0-3km Laspe Rate Max w/n 3hr onset time C/km	2 hr pressure rise (hPa) Max w/n 3hr onset time (hPa)	NARR 850 U(west) Anomaly w/n 12h post onset
17-Feb-2006 09z	993	68	6	2.1	2
01-Dec-2006 18z	991	56	5.5	4	3
09-Jan-2008 12z	984	71	6.5	5	3
30-Jan-2008 09z	971	58	5	7	2
28-Dec-2008 12z	985	68	5.5	6	3
12-Feb-2009 09z	982	68	6	3	3
18-Jan-2012 00z	987	68	5.5	4	3
20-Jan-2013 09z	987	60	7	4	2
31-Jan-2013 06z	979	50	5.5	2	2
01-Nov-2013 06z	978	71	6	2	3
18-Nov-2013 06z	971	58	6	2	3
Mean	**983**	**63**	**5.9**	**3.7**	**2.6**

b. Limited Events

Limited Events (Date/onset time)	MSLP (hPa)	Max 850 hPa Wind Speed (kt)	0-3km Laspe Rate Max w/n 3hr onset time C/km	2 hr pressure rise (hPa) Max w/n 3hr onset time (hPa)	NARR 850 U(west) Anomaly w/n 12h post onset
01-Dec-2004 12z	992	52	n/a	n/a	1
08-Dec-2004 00z	988	54	n/a	n/a	2
03-Nov-2005 15z	1000	56	6.5	0.7	2
06-Nov-2005 18z	988	56	7	2.8	2
24-Dec-2007 00z	989	44	7.5	5	1
25-Dec-2008 00z	993	56	5.5	3	2
09-Dec-2009 21z	974	54	6.5	3	2
30-Nov-2010 15z	994	64	4.5	0	1
28-Apr-2011 12z	985	56	7	3	3
01-Jan-2012 21z	990	56	6.5	3	1
24-Feb-2012 21z	985	56	7	3	2
03-Mar-2012 09z	978	64	5.5	2	3
06-Jan-2014 09z	986	68	5	3	1
Mean	**988**	**57**	**6.2**	**2.6**	**1.8**

c. Advisory-only Events

Advisory-only (Date/onset time)	MSLP (hPa)	Max 850 hPa Wind Speed (kt)	0-3km Laspe Rate Max w/n 3hr onset time C/km	2 hr pressure rise (hPa) Max w/n 3hr onset time (hPa)	NARR 850 U(west) Anomaly w/n 12h post onset
05-Nov-2004 15z	980	45	n/a	n/a	2
04-Dec-2004 21z	988	49	n/a	n/a	2
06-Jan-2005 21z	1004	47	n/a	n/a	1
16-Nov-2005 12z	983	62	6	2.8	2
29-Nov-2005 06z	990	62	6	0	1
18-Jan-2006 06z	993	70	4.5	0	2
05-Feb-2006 12z	983	54	6.5	1.4	1
10-Mar-2006 15z	989	58	6.5	5.4	2
14-Mar-2006 12z	982	50	6	1.4	2
10-Feb-2008 15z	992	41	8	3	1
17-Feb-2008 21z	988	60	4.5	-3	2
01-Apr-2008 18z	995	54	7.5	2	2
30-Dec-2008 06z	996	47	7	2	1
11-Mar-2009 12z	986	54	4.5	3	2
03-Apr-2009 21z	985	45	6	3	2
04-Apr-2010 00z	989	33	8	3	1
17-Nov-2010 15z	993	49	6	5	2
14-Feb-2011 09z	988	66	5.5	0	3
19-Feb-2011 15z	981	41	6.5	2	1
10-Mar-2011 00z	1009	66	4.5	0	1
11-Apr-2011 18z	982	41	7.5	1	2
24-Jan-2012 06z	995	45	4.5	2	1
28-Jan-2012 21z	998	49	n/a	n/a	2
09-Apr-2012 15z	995	35	8	0	1
22-Dec-2012 12z	987	52	5.5	2	1
04-Jan-2013 15z	993	31	4.5	0	1
09-Jan-2013 18z	997	50	6.5	2	2
11-Feb-2013 18z	992	43	6	1	2
19-Feb-2013 18z	992	35	6.5	1	1
07-Apr-2013 15z	999	58	8	0	2
19-Apr-2013 15z	987	56	7	2	2
19-Jan-2014 21z	985	56	5	n/a	2
22-Feb-2014 15z	980	54	7.5	n/a	2
05-Apr-2014 03z	995	49	4.5	1	2
Mean	**990**	**50**	**6.2**	**1.5**	**1.6**

d. Standard Deviation of Predictor Means

	MSLP (hPa)	Max 850 hPa Wind Speed (kt)	0-3km Laspe Rate Max w/n 3hr onset time C/km	2 hr pressure rise (hPa) Max w/n 3hr onset time (hPa)	NARR 850 U(west) Anomaly w/n 12h post onset
Widespread means	983	63	5.9	3.7	2.6
Limited means	988	57	6.2	2.6	1.8
Advisory-only means	990	50	6.2	1.5	1.6
SD of means	**2.9**	**5.3**	0.1	*0.9*	0.4

Table 6a. Statistical data with box and whisker plots used to create the MSLP Potential Impact Table.

Mean Sea Level Pressure (hPa)	Widespread	Limited	Advisory
Minimum	971	974	980
-1 Standard Deviation	976	981	984
Mean	983	988	990
+1 Standard Deviation	989	994	997
Maximum	993	1000	1009

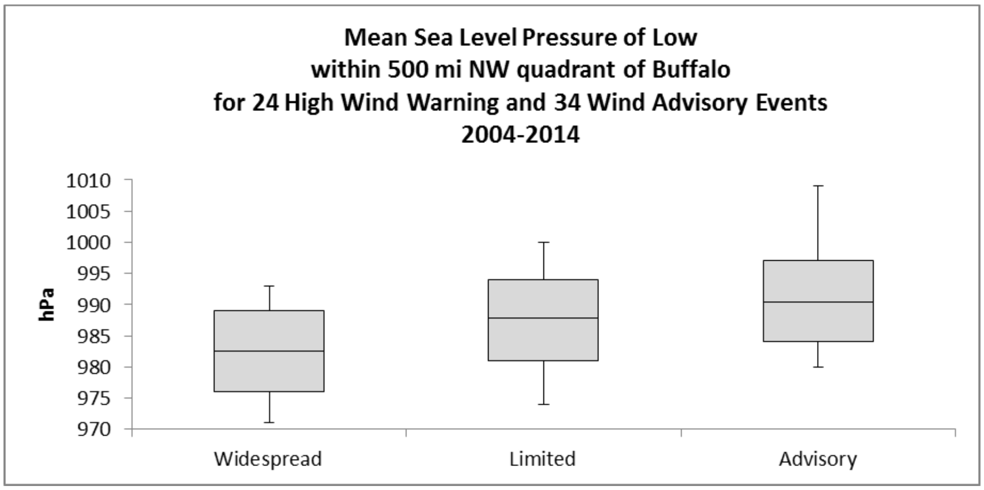


Table 6b. Statistical data with box and whisker plots used to create the 850 hPa Potential Impact Table.

850 hPa wind speed (kts)	Widespread	Limited	Advisory
Minimum	51	45	31
-1 Standard Deviation	57	51	41
Mean	64	57	50
+1 Standard Deviation	70	63	60
Maximum	72	68	70

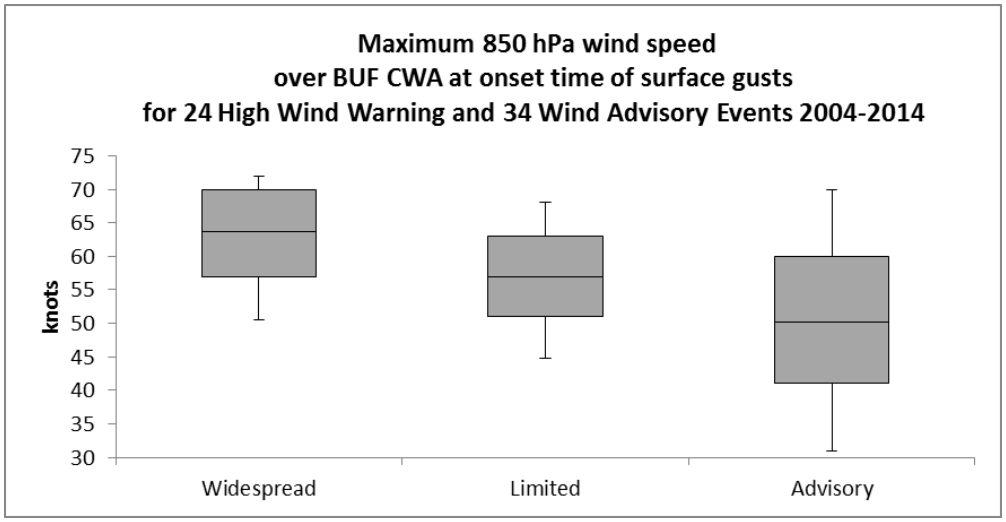


Table 6c. An XY Scatter plot of MSLP verses 850 hPa winds speed at onset time for each of Widespread (Blue), Limited (Red) and Advisory-Only (Green) wind events. Liner regression trend lines and R-squared values are included for each event type. This scatterplot shows the two predictors are not well correlated for each event with R-squared values less than 7%. Thus it is not recommended to use only one predictor to determine a potential impact result.

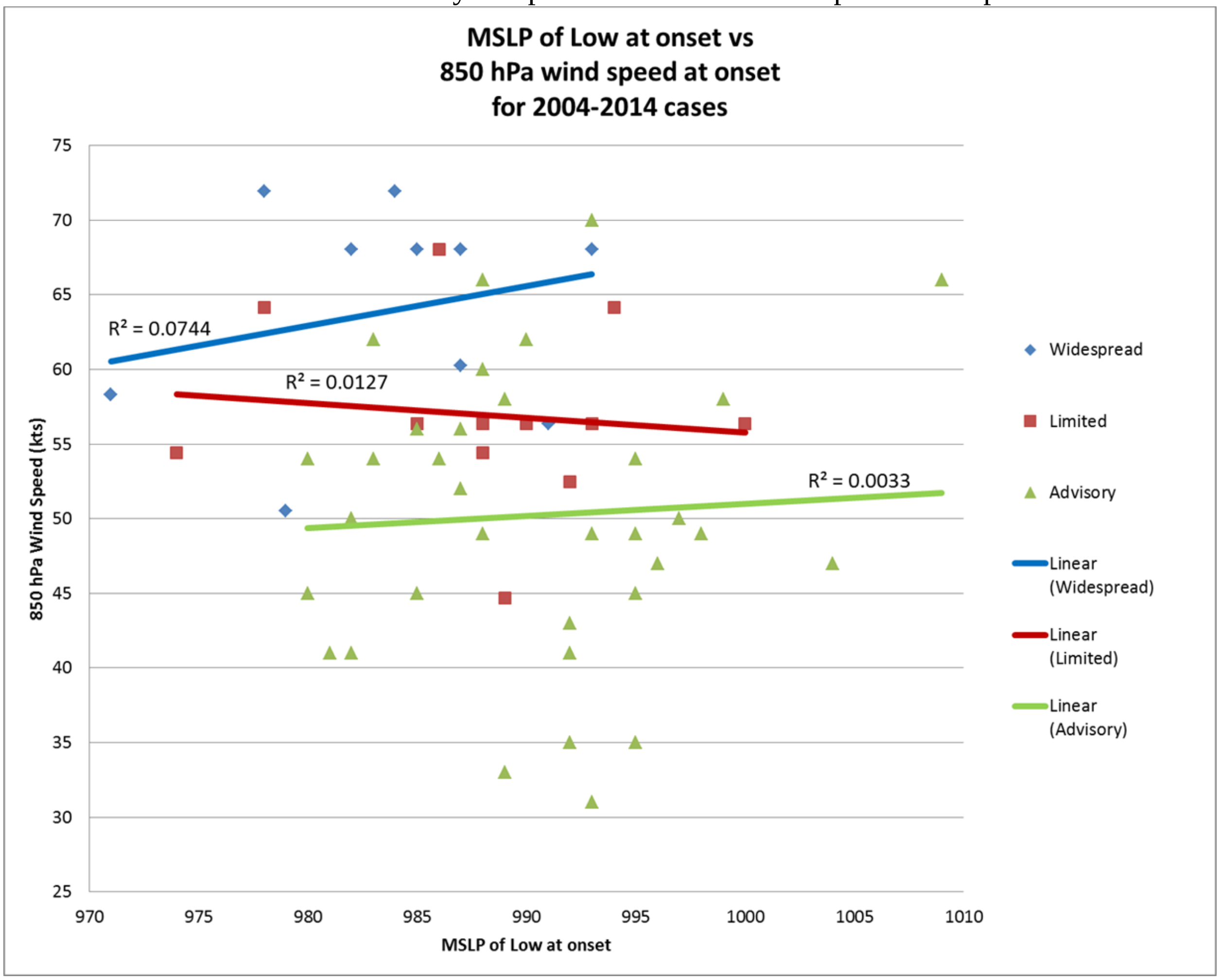


Table 7. Expanded data from box and whisker charts used to create Potential Impact Tables. Collected values from the three event types were merged into a combined scale. Results that match two categories were filled with secondary colors of orange and green. The colored cells indicate the values which match each impact type within one SD of the mean. Red for Widespread, Yellow for Limited events and Blue for Advisory events. Orange indicates combined values matching Widespread and Limited events, Green matching Limited and Advisory and Black for values which were observed in all event types.

MSLP (hPa) to 1SD

Widespread	<=980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	>=998
Limited	<=980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	>=998
Advisory	<=980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	>=998
Unlikely	<=980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	>=998
Combined	<=980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	>=998

850 hPa Wind Speed (kts) to 1SD

Widespread	<=40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	>=64
Limited	<=40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	>=64
Advisory	<=40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	>=64
Unlikely Event	<=40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	>=64
Combined	<=40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	>=64

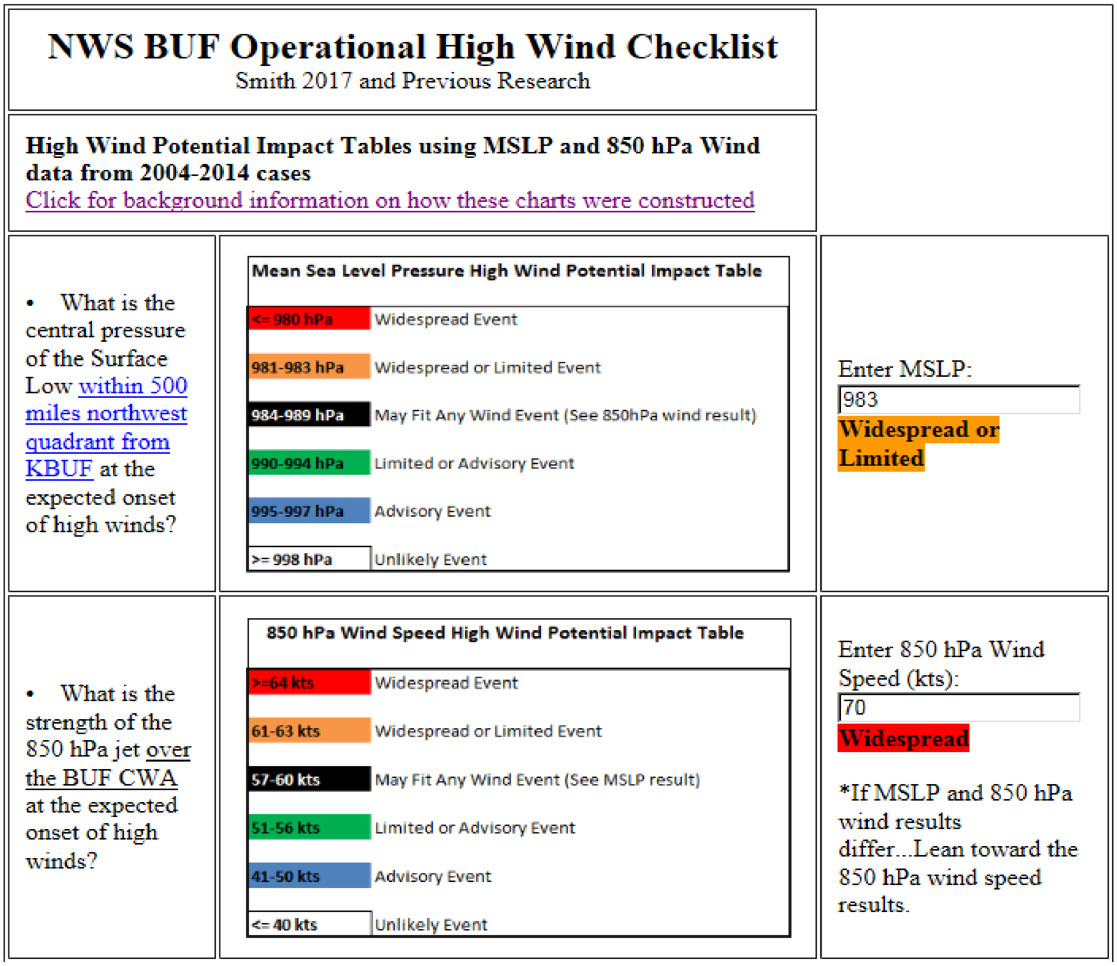


Figure 3. Screen capture of the HTML web version of the Potential Impact Tables.

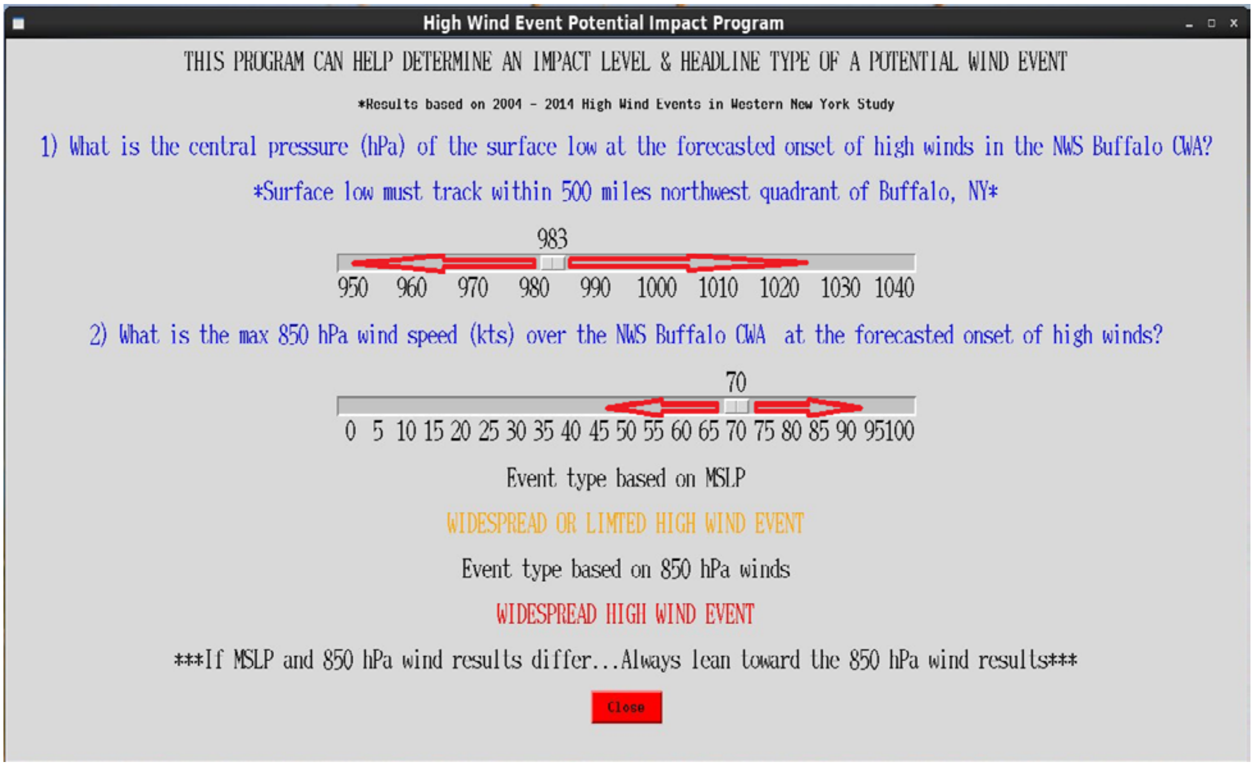


Figure 4. Screen capture of the TCL/TK AWIPS version of the Potential Impact Tables

3. Results

a. 500 hPa Composite Charts

The composite charts using the NARR model were designed to improve forecaster pattern recognition of high wind events. The 500 hPa composites (Fig. 5) showed only slight differences between Widespread and Limited events. Widespread events typically exhibited a deeper negatively tilted 500 hPa trough crossing the Great Lakes, while shallow troughs were observed for both Limited and Advisory-only events. More definitive differences were found with the composites of MSLP and especially 850 hPa wind speed.

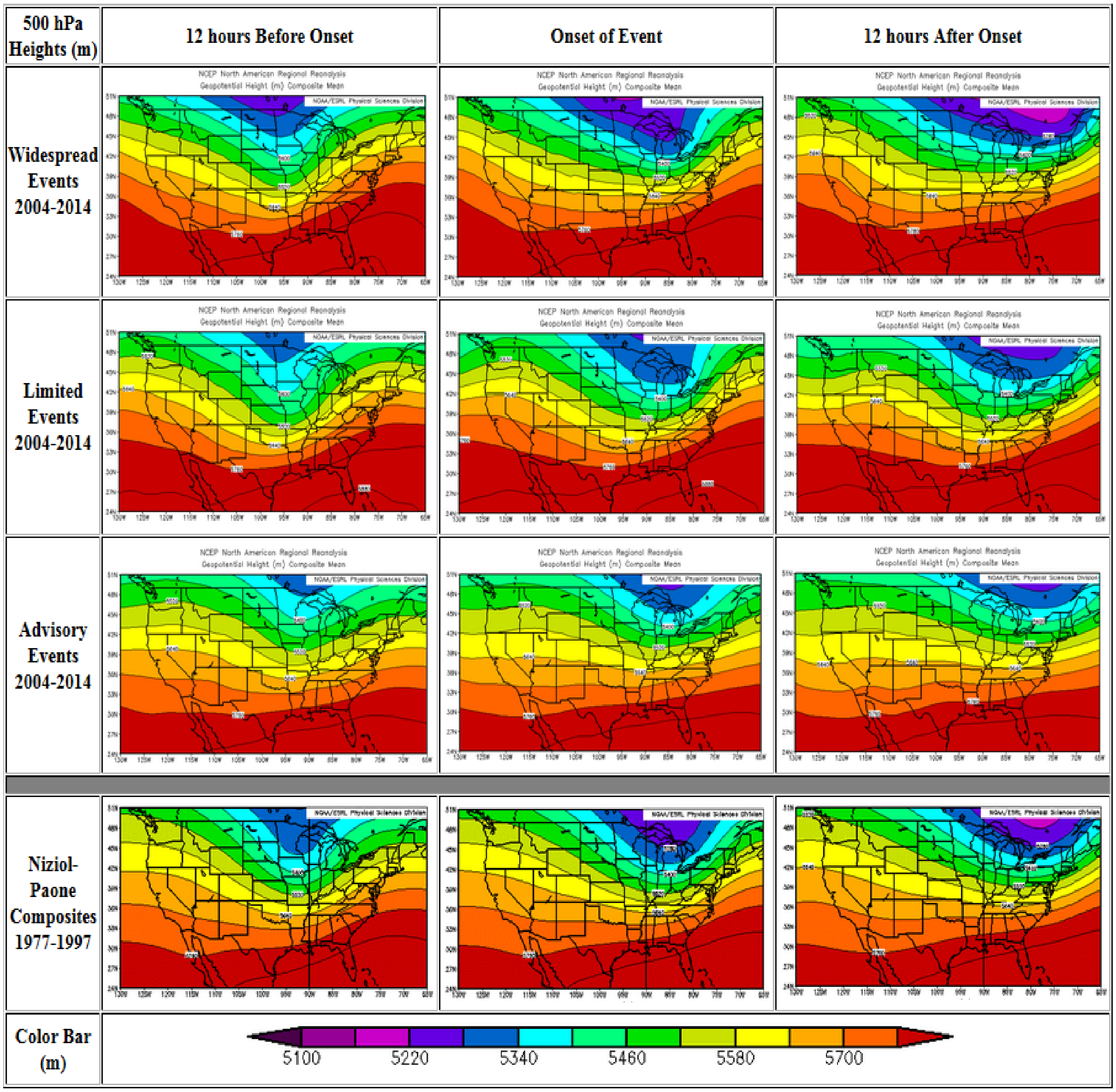


Figure 5. NARR Composite Charts of 500 hPa geopotential height (m) for 11 Widespread, 13 Limited, 34 Advisory-only high wind events from 2004-2014. Reconstructed composites for 52 high winds events from Niziol and Paone (2000) were also included for comparison. All NARR graphics from here forward were provided by the NOAA/ESRL Physical Science Division, Boulder Colorado from their Web site at http://www.esrl.noaa.gov/psd/". Color bars for composites are located at the bottom of each figure.

b. MSLP Composite Charts

MSLP composites (Fig. 6) showed clear differences between each event category. In Widespread high wind events, there will nearly always be a *continually* deepening area of low pressure passing along a favorable track northwest of the NWS Buffalo CWA. For widespread events, the continually deepening characteristic is supported by case data from Tables 2a-b which show the MSLP rise/fall from 12 hours before onset to 12 hours after onset were all negative. On the composites, at 12 hours before the onset of high winds within the NWS Buffalo CWA, the center of the composite low is near the southern tip of Lake Michigan, shifting to just east of Georgian Bay by onset time then just northeast of Quebec City at 12 hours after onset. Composite charts for the Limited events show a similar track but with a weaker low center deepening until the onset time then filling post onset. Advisory-only events have the weakest low center that remains north of the Widespread and Limited composite tracks. These composites clearly show (as they also did in Niziol and Paone (2000)) that high wind events require a closed low to be continually deepening while passing along a favorable track just northwest of Buffalo.

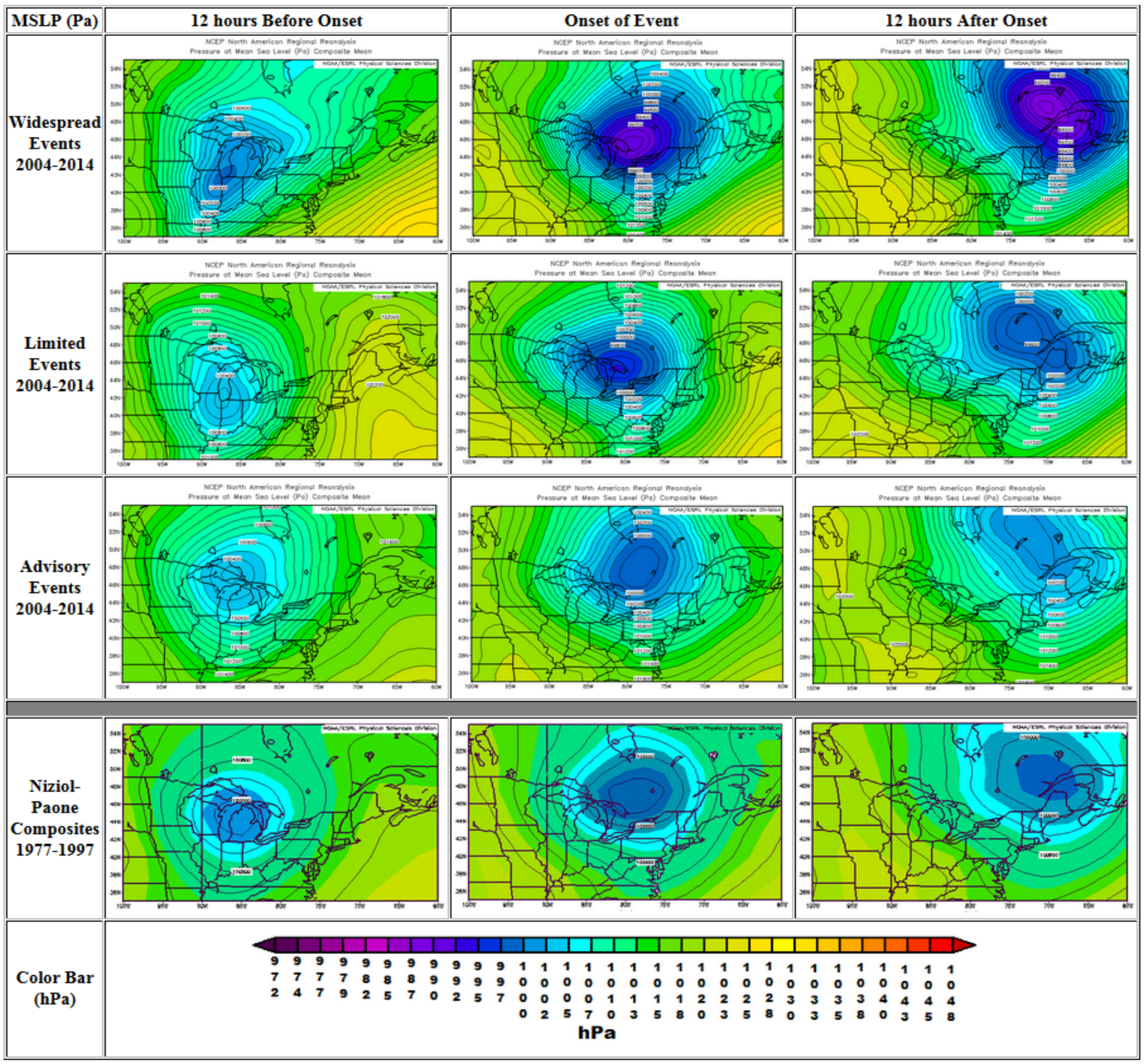


Figure 6. NARR Composite charts of Mean Sea Level Pressure (Pa) for 11 Widespread, 13 Limited, 34 Advisory-only high wind events from 2004-2014. Reconstructed composites for 52 high winds events from Niziol and Paone (2000) were also included for comparison. Color bars for composites are located at the bottom of each figure.

c. 850 hPa Composite Charts

Composite charts of 850 hPa wind speed in units of m/s (Fig. 7) perhaps show the most pronounced signal between the three event types. Widespread events will exhibit a strong 850 hPa jet that maintains strength as it tracks just southeast of the surface low from over the Ohio Valley 12 hours before onset, then across the NWS Buffalo CWA at onset, before shifting east of the Gulf of Maine 12 hours post onset. Defining a strong jet within these Widespread composites resulted in a jet of 29 m/s (56 kt) but what must be kept in mind is that this is a mean value of jets from all Widespread events. Contours were colored at one m/s (2kt) intervals from 21 to 40 m/s (41 to 78 kt) with the Widespread composite low level jet clearly present within these color bins throughout the 12 hours either side of the onset of high winds. Looking at Limited events, a much weaker 850 hPa jet of around 24 m/s (47 kt) 12 hours before onset over the lower Ohio River Valley strengthens to around 26 m/s (51 kts) over the NWS Buffalo CWA at onset time then weakens back to 24 m/s (47 kt) by 12 hours post onset. Advisory event composites showed 850 hPa winds were below 21 m/s (41 kt) 12 hours before onset only strengthening to 22 m/s (43 kt) at onset over the NWS Buffalo CWA then weakening again below 21 m/s (41 kt) through 12 hours post onset. These composites clearly show that a Widespread high wind event features a strong and persistent 850 hPa jet tracking across the NWS Buffalo CWA.

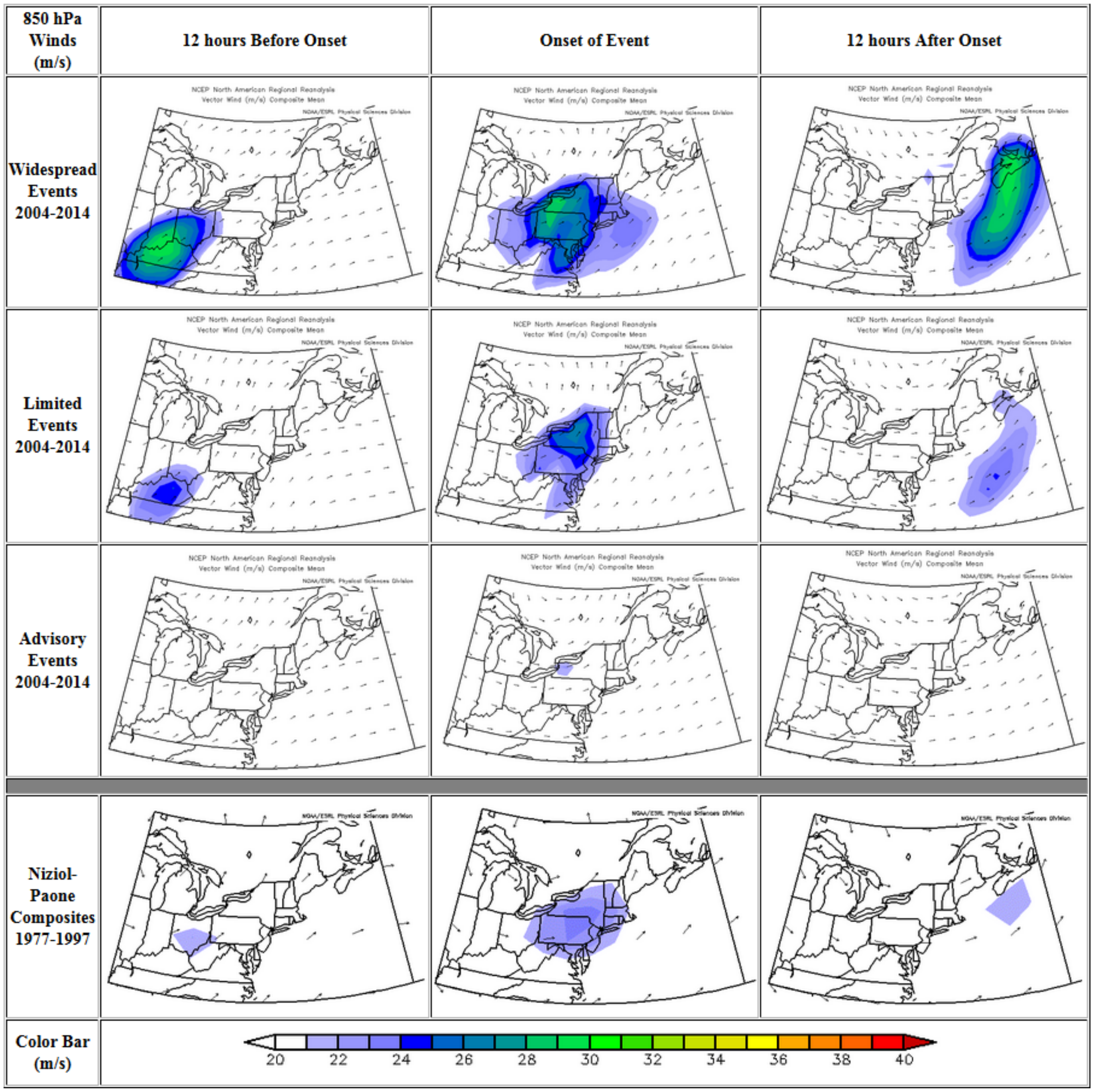


Figure 7. NARR Composite Charts for 850 hPa wind speed (m/s) for 11 Widespread, 13 Limited, 34 Advisory-only high wind events from 2004-2014. Reconstructed composites for 52 high winds events from Niziol and Paone (2000) were also included for comparison. Color bars for composites are located at the bottom of each figure.

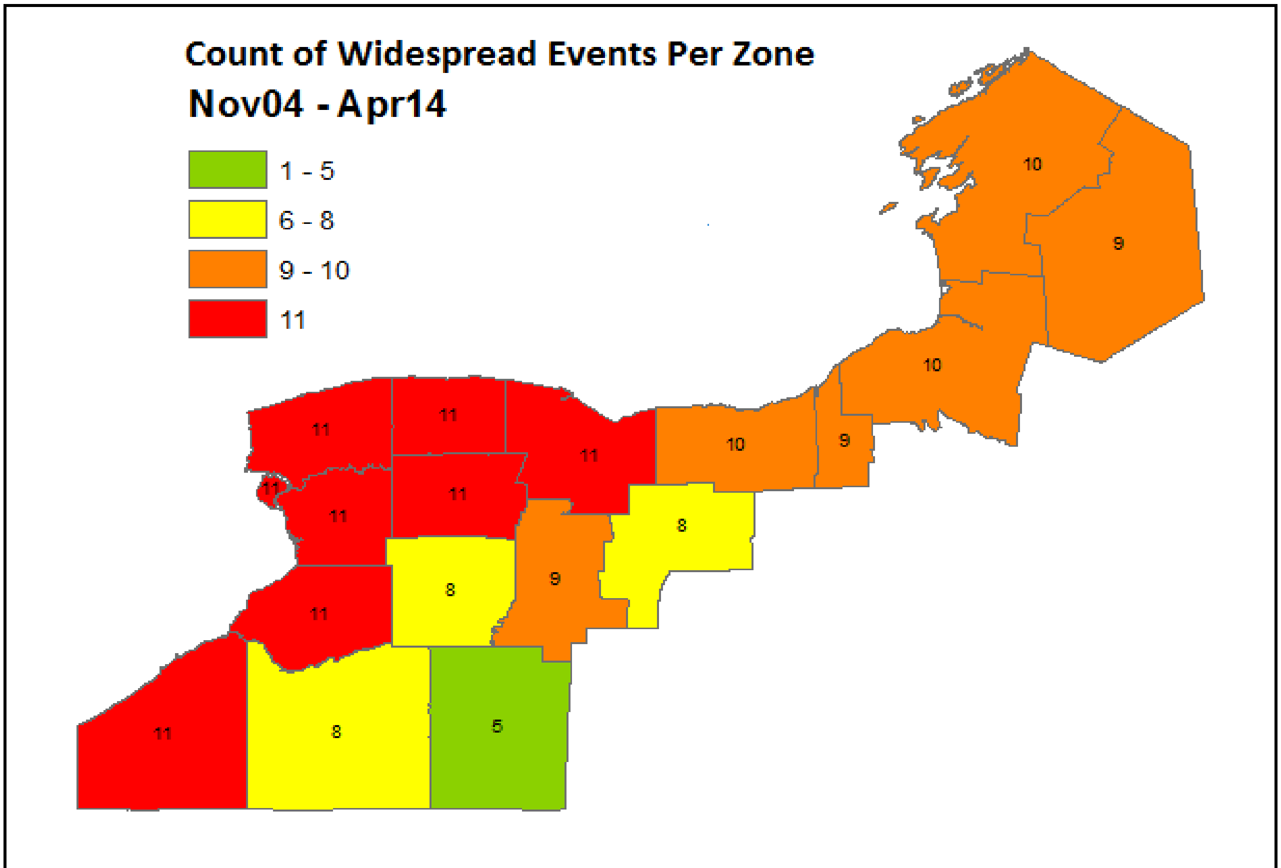
d. Comparison of new high wind composites to Nizol 2000 composites

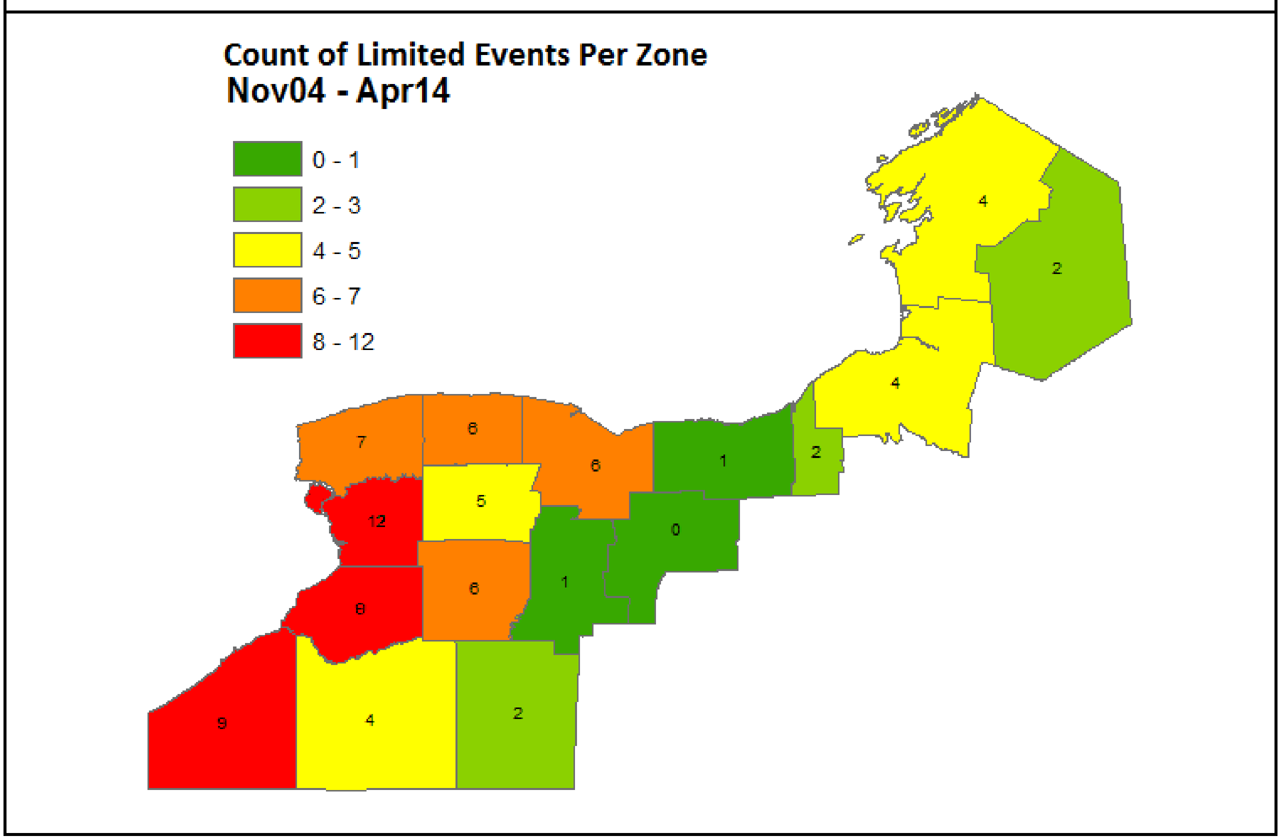
In addition to the creation of the composites from cases for this study, composites were re-created using the 52 cases from Niziol and Paone (2000) (Figs. 5-7). That study included composites of 500 hPa heights and MSLP but did not include 850 hPa winds, which makes that particular composite new information in this expanded study. Composites from the previous study matched closer to Limited event composites from this expanded study and were much weaker than Widespread composites while Advisory-only composites were weaker than the re-created Niziol composites. This is positive proof that the division of event types into the three different categories provides an additional level of pattern recognition to the forecaster.

e. High Wind Spatial Impact Maps, Seasonal/Monthly Frequency Graphs and Storm Track Climatology

Case data was also used to create new spatial impact maps with ESRI ArcMap software. (Fig. 8a) The maps show the number of counties impacted by Widespread, Limited and Combined (Widespread and Limited) high wind events, and can be used to help forecasters identify which forecast zones see a higher frequency of each event type. It is not surprising Lake Erie shoreline zones saw the highest frequency of high wind events due to the reduced friction and funneling effect of westerly winds down the length of Lake Erie for both Widespread and Limited events. The higher frequency of events in Lake Erie bordering zones could be hypothesized as being tied to a well-mixed boundary layer near the lake during the late Autumn however looking at all event dates shows that some of the strongest events occur in December and January when lake-land temperature differences are not as large. There is no clear correlation between high wind events and over-lake instability helping to mix down the wind in lakeshore bordering zones. At initial glance it may also appear that the higher frequency of high wind events is population related however much of Southern Erie and Chautauqua counties are rural except for some spotty small cities and villages along the lakeshore as shown a 2010 US Census population map in Fig. 8b.

Seasonal and monthly frequency graphs were plotted to yield a temporal frequency of high wind events (Fig. 9). Monthly graphs were very similar to those produced by Niziol and Paone (2000) showing the highest frequency of high wind events occurring in December and January. Finally, a collection of storm tracks were plotted using Google Earth software (Fig. 10). Points at 24 and 12 hours before onset time, at onset time and 12 hours after onset time were plotted for Widespread events. A clear consensus shows the climatological track of lows which produce high winds, passes from west to north of the NWS Buffalo CWA within a 500 mile northwest quadrant.


Count of Widespread Events Per Zone
Nov04 - Apr14
1 - 5
6 - 8
9 - 10
11


Count of Limited Events Per Zone
Nov04 - Apr14
0 - 1
2 - 3
4 - 5
6 - 7
8 - 12

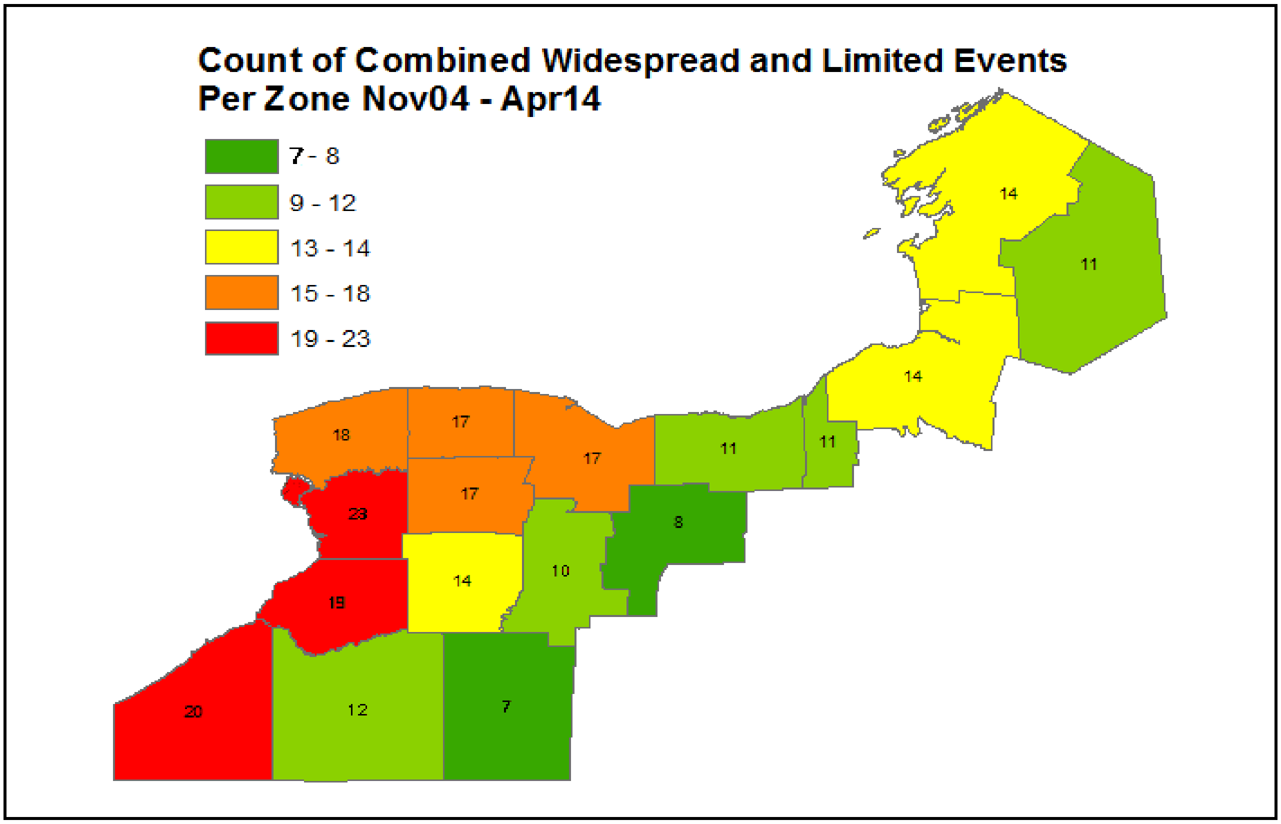


Figure 8a. Spatial impact maps for Widespread, Limited and Combined Widespread-Limited Events which occurred during the November to April cold seasons of 2004-2014. Numbers indicate the tally of events which impacted each zone during the study period.

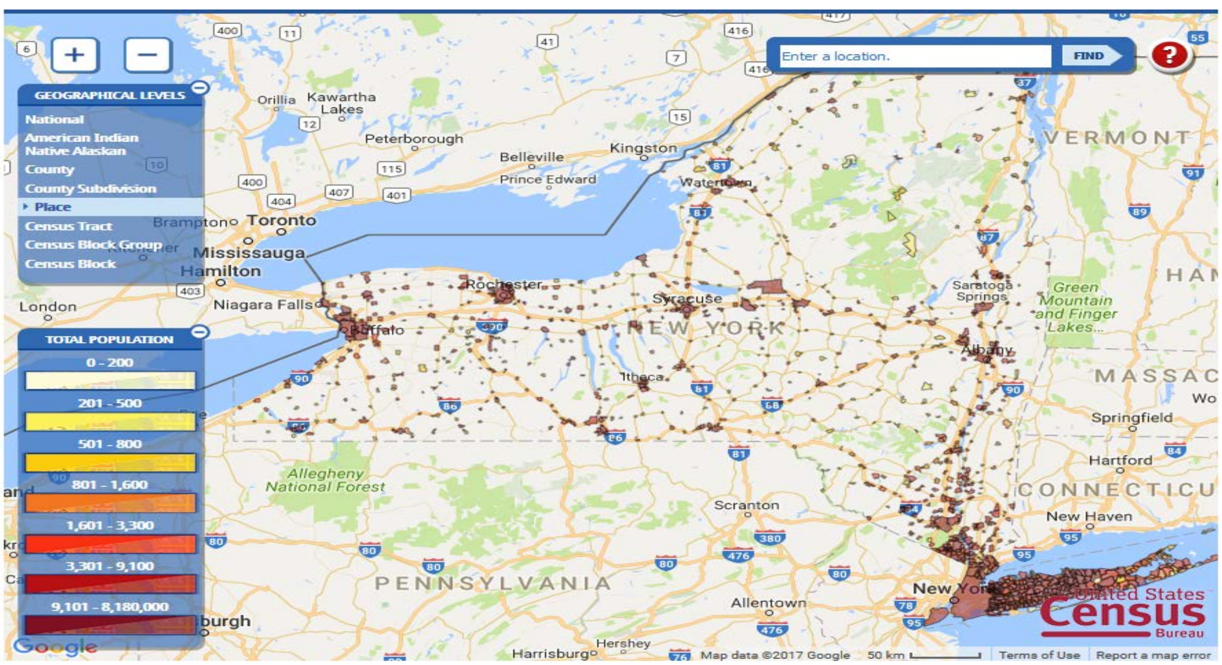
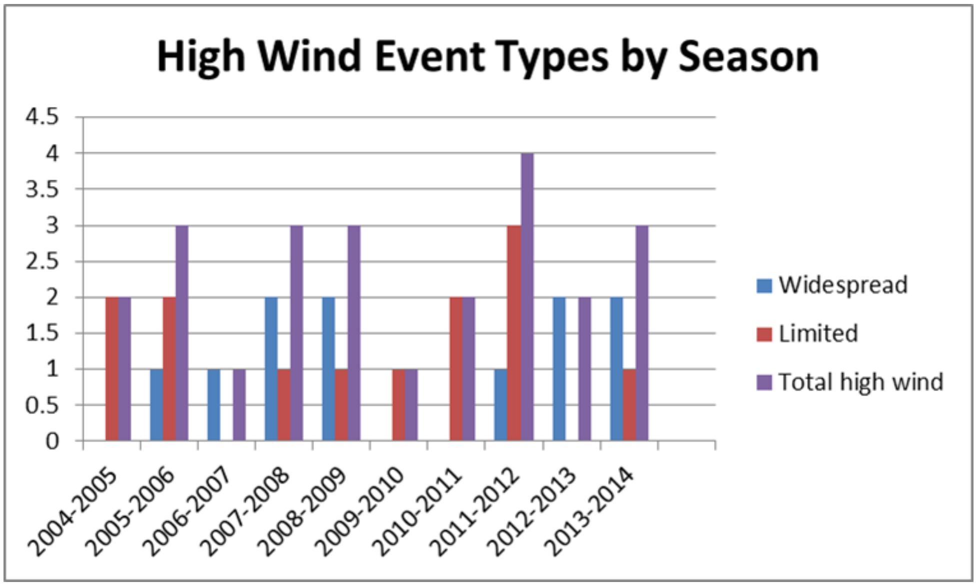


Figure 8b. 2010 US Census Map of NY population sorted by Place (Cites/towns). Obtained via the Census Data Mapper.



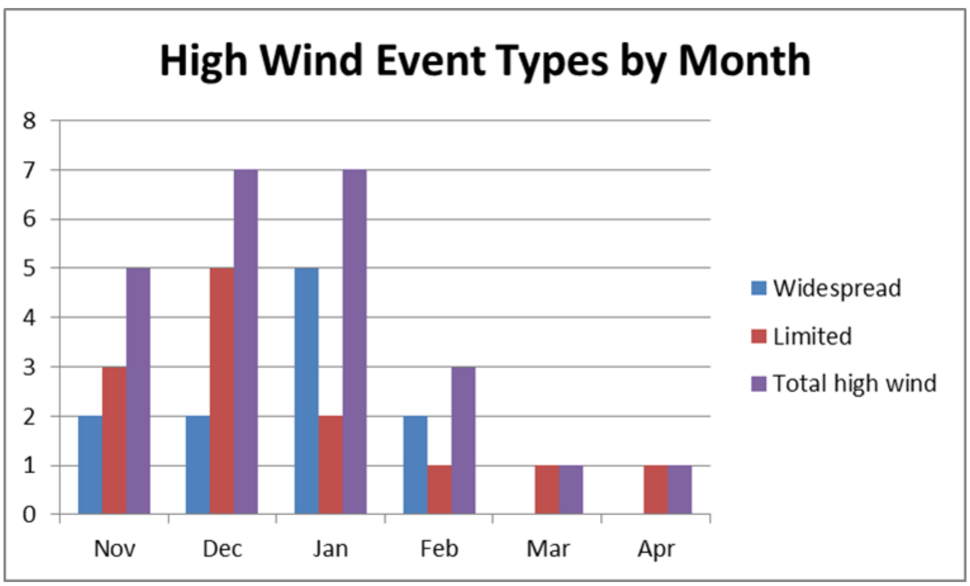


Figure 9. Seasonal and Monthly High Wind Frequency Graphs (2004-2014)

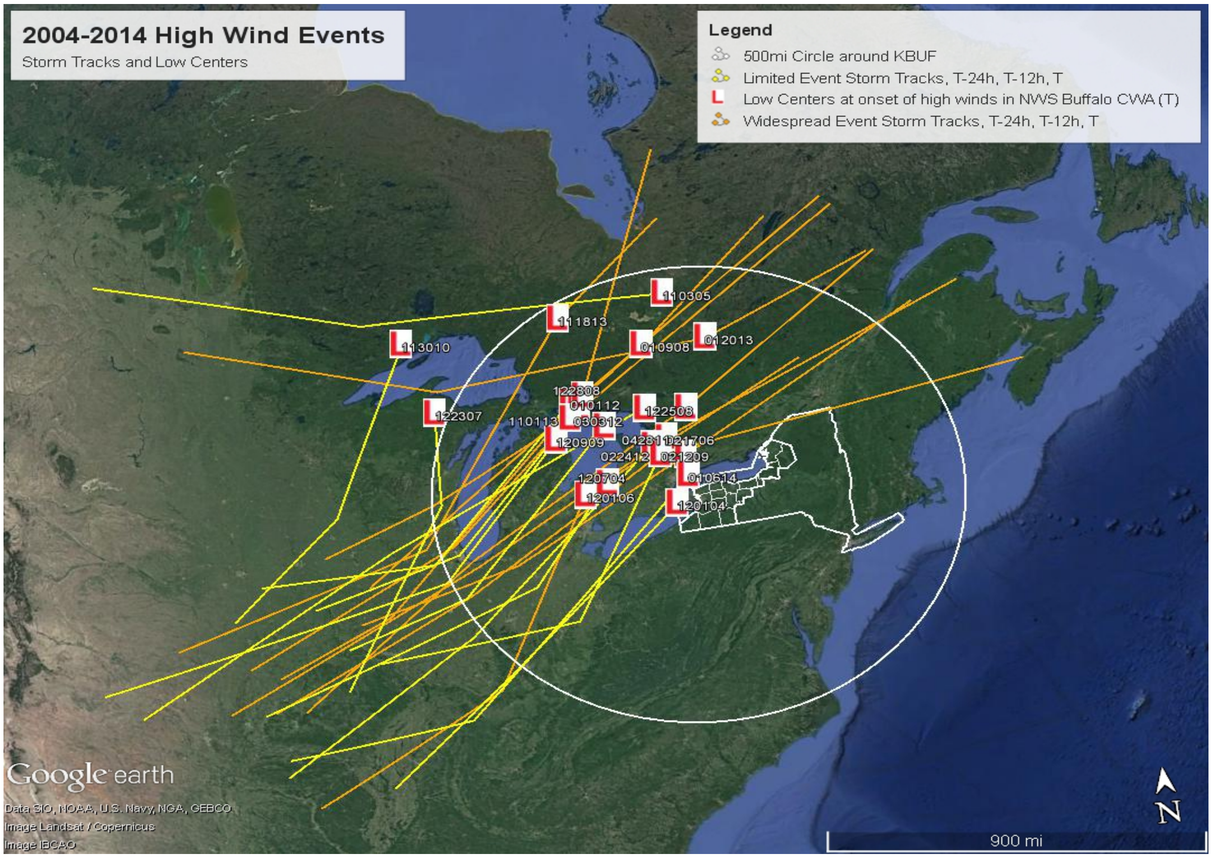


Figure 10. Surface low pressure tracks of High Wind Events during the study period. Orange tracks are Widespread events with points 24 hours before, 12 hours before, at onset and 12 hours after onset of high winds in the NWS Buffalo CWA. Yellow tracks are for Limited events 24 hours before, 12 hours before and at onset.

f. Potential Impact Tables

The Potential Impact Tables were designed using two predictors which best differentiated between category types. Two predictors are needed because Table 6c shows an XY scatter plot of 850 hPa wind speed verses MSLP for the three event types with results reflecting that these two predictors are not well correlated. Thus, it is not recommended to only use one predictor to determine the potential impact of an event. Think of this as using both Convection Available Potential Energy (CAPE) and Wind Shear to forecast severe weather. One parameter may help you out but both parameters provide more forecast detail. Additionally, little value would be obtained with a single result of "May Fit Any Wind Event". Therefore, using two predictors, you can use one to help clarify the other.

These tables are provided as a tool to help improve forecaster confidence on whether a potential wind event might produce Widespread impacts, Limited impacts or simply Advisory-only type impacts, based off of data collected from study cases. This improved confidence should then lead to an improvement in both LT for all events and FAR especially for Limited type events which were shown in Tables 2a-b as having a mean FAR from 2008-2014 of 0.49. After evaluating the synoptic pattern and focusing in on a possible onset time for high winds, a forecaster can get a quick evaluation of potential impact by simply inputting forecast values of MSLP and 850 hPa wind speed into the tables at the forecasted onset time of high winds to receive a potential impact category. It should be noted that these tables were designed only for westerly flow non-convective high winds which occur post frontal. While south or southeast gusty winds can occur pre-frontal, a low level inversion often prevents the highest gusts from reaching the surface.

In order for the tables to prove any value, they were tested against three years of high wind events during the 2014-2017 cold seasons (Table 8). During this time, the following wind events occurred: 2 Widespread, 9 Limited, 18 Advisory-only and 14 non-events. One of the Widespread events, 02 March 2017, was originally forecast as an Advisory event but upgraded to a Limited event with 11 High Wind Warnings issued. This event however verified as Widespread with 14 zones receiving damage reports. One of the Advisory events, 22 November 2015, was actually forecast with High Wind Warnings as a Limited high wind event but only Advisory level winds were observed. Finally, one of the non-events, 27 February 2016 was forecast as an Advisory without Advisory level gusts reported. There were 6 events that were not used since they were downslope wind events under southeast flow which are not the focus of this study.
For each tested event, values of MSLP and 850 hPa wind speed at the onset time of observed high gusts in the NWS Buffalo CWA were entered into each table. If the table output the correct event type or the event type correctly fit within one of the outputs that includes two categories or within the "May Fit Any Wind Event" category then a 'y' mark was given for correct detection. If the table miss-identified the event type, then the table was marked as a false alarm with a "n+ or n-" mark with the plus and minus symbols indicating the false alarm was due to an over-forecast or under-forecast (Tables 9a-e). NWS Buffalo POD/FAR performance for forecasting the correct event was also included to compare with table results. It is important to note that the performance scores tallied for NWS Buffalo were not done using the methods of the NWS Performance Branch in a county/zone approach but were computed as POD/FAR of forecasters getting the event type correct.

Overall results from testing the Potential Impact Tables are included in Tables 10a-b and were calculated as a POD and FAR respectfully and tallied up by event type. The Potential Impact Tables successfully identified a correct result for all wind events which had MSLP or 850 hPa wind speed values that fell within one SD above or below the event category means. The MSLP and 850 hPa wind Limited and Advisory event values which fell outside of one SD of the mean, almost always scored a false alarm result. These outlier values usually occurred with Limited and Advisory events which exhibited either an anomalously deep or weak low with 850 hPa winds near or within 1 SD of the mean or an event with an anomalously strong or weak 850 hPa jet and MSLP near or within one SD of the event mean. An example of this is the Limited event from 24 November 2014 where a 976 mb low was 1.8 SD below the Limited mean MSLP value but the 58 kt (30 m/s) 850 hPa jet nearly matched the Limited mean value. In this case the tables identified the jet as "May Fit Any Wind Event" but the MSLP as a Widespread event however only 5 forecast zones received wind damage. The problem with false alarms for values falling outside of one SD mentioned above would not occur for anomalies greater than one in Widespread events as the tables have no upper limit for the Widespread category.

There were no clear high or low false alarm biases with the tables when separating out the Unlikely Event scores as a near equal amount of false alarms that were too high (7) or too low (10) occurred. The MSLP table for Unlikely Events did however seem to have an over-forecast bias mainly with deeper lows which did not have a strong 850 hPa jet that tracked over the NWS Buffalo CWA.

Table 8. Wind Events and non-events for Nov 2014 – Apr 2017 cold seasons with onset time. These events were used to test the high wind potential impact tables. Note: Non-event times were closest pass of extratropical low.
* 02 Mar 2017 event forecast as Limited (11 zones) but verified as a Widespread event (14 zones)
**22 Nov 2015 event was forecast as a Limited but only verified as Advisory
***27 Feb 2016 event forecast as Advisory event but obs only verified as Non-event

Widespread Events	**Advisory-only Events**	**Non- Events**
08 March 2017 18z	14 Apr 2015 00z	12 Nov 2014 12z
*02 Mar 2017 00z	21 Apr 2015 18z	20 Nov 2014 09z
	*22 Nov 2015 06z	17 Dec 2014 06z
Limited Events	11 Dec 2015 18z	28 Dec 2014 12z
24 Nov 2014 21z	15 Dec 2015 00z	01 Nov 2015 21z
25 Dec 2014 06z	24 Dec 2015 15z	***27 Feb 2016 18z
04 Jan 2015 18z	26 Jan 2016 18z	25 Mar 2016 09z
10 Apr 2015 15z	03 Feb 2016 12z	12 Apr 2016 06z
12 Nov 2015 18z	29 Feb 2016 21z	21 Nov 2016 12z
11 Jan 2016 00z	17 Mar 2016 18z	01 Dec 2016 12z
04 Jan 2017 18z	29 Mar 2016 00z	27 Dec 2016 12z
11 Jan 2017 06z	31 Mar 2016 18z	07 Apr 2017 12z
04 Apr 2017 18z	10 Nov 2016 18z	21 Apr 2017 12z
	20 Dec 2016 18z	28 Apr 2017 12z
	31 Dec 2016 18z	
	08 Feb 2017 18z	
	18 Feb 2017 18z	
	25 Feb 2017 15z	

Downslope Events (not included)
19 Nov 2015 00z
29 Dec 2015 06z
20 Apr 2015 09z
20 Feb 2016 18z
07 Apr 2016 00z
28 Nov 2016 06z

Tables 9a-e. Individual results from testing the Potential Impact Tables on 2014-2017 events. A y indicates a correct result or forecast, a n+ indicates an incorrect result due to over-forecast, a n- indicates an incorrect result do to under-forecast. Total POD and FAR are computed for each event category and summarized in Tables 10a-b.

a. Widespread Events

Event Date	Event Type	MSLP Table Result	850 hPa Wind Table Result	NWS Buffalo
2017030200	Widespread	y	y	n-
2017030818	Widespread	y	y	y
		2 of 2	2 of 2	1 of 2
	POD	100%	100%	50%
	FAR	0%	0%	50%

b. Limited Events

Event Date	Event Type	MSLP Table Result	850 hPa Wind Table Result	NWS Buffalo
2014112421	Limited	n+	y	y
2014122506	Limited	y	y	y
2015010418	Limited	n-	y	y
2015041015	Limited	y	y	y
2015111218	Limited	y	y	y
2016011100	Limited	y	y	y
2017010418	Limited	y	n-	n-
2017011106	Limited	n+	n+	n+
2017040418	Limited	y	n-	y
		6 of 9	6 of 9	7 of 9
	POD	67%	67%	78%
	FAR	33%	33%	22%

c. Advisory Events

Event Date	Event Type	MSLP Table Result	850 hPa Wind Table Result	NWS Buffalo
2015041400	Advisory	y	y	y
2015042118	Advisory	y	n-	y
2015112206	Advisory	n-	y	n+
2015121118	Advisory	y	y	y
2015121500	Advisory	y	y	y
2015122415	Advisory	n+	y	y
2016012618	Advisory	n-	y	y
2016020312	Advisory	y	n+	y
2016022921	Advisory	y	y	y
2016031718	Advisory	n-	n-	y
2016032900	Advisory	y	y	y
2016033118	Advisory	y	n+	y
2016111018	Advisory	n+	n-	y
2016122018	Advisory	n-	y	y
2016123118	Advisory	y	y	y
2017020806	Advisory	y	y	y
2017021818	Advisory	y	y	y
2017022515	Advisory	y	y	y
		12 of 18	13 of 18	17 of 18
	POD	67%	72%	94%
	FAR	33%	28%	6%

d. Non-events

Event Date	Event Type	MSLP Table Result	850 hPa Wind Table Result	NWS Buffalo
2014111212	Non-event	y	y	y
2014112009	Non-event	n+	y	y
2014121706	Non-event	y	y	y
2014122812	Non-event	n+	y	y
2015110121	Non-event	y	y	y
2016022718	Non-event	n+	y	n+
2016032509	Non-event	y	n+	y
2016041206	Non-event	y	y	y
2016112112	Non-event	n+	n+	y
2016120112	Non-event	n+	y	y
2016122712	Non-event	n+	n+	y
2017040712	Non-event	n+	y	y
2017042112	Non-event	y	y	y
2017042812	Non-event	n+	y	y
		6 of 14	11 of 14	13 of 14
	POD	43%	79%	93%
	FAR	57%	21%	7%

e. Combined Results

Combined All Events		MSLP Results	850 hPa Results	NWS Buffalo
		26 of 43	32 of 43	38 of 43
	POD	60%	74%	88%
	FAR	40%	26%	12%

Table 10a. POD results from testing the Potential Impact Tables on 2014-2017 events. Results are listed as: Number of events correctly identified/Total events (percent correct) {miss forecasted as W=Widespread, L=Limited, A=Advisory, N=Non-event}
*Advisory events and Non-events verification independently determined by surface observations

Test Results	MSLP Table	850 hPa Wind Table	NWS Buffalo POD for event type
Widespread Events	2/2 (100%)	2/2 (100%)	1/2 (50%) {L}
Limited Events	6/9 (67%)	6/9 (67%)	7/9 (78%) {W,N}
Advisory-only Events*	12/18 (67%)	13/18 (72%)	17/18 (94%) {L}
Non-events*	6/14 (43%)	11/14 (79%)	13/14 (93%){A}
Combined Events Results For Each Table	26/43 (60%)	32/43 (74%)	38/43 (88%)

Table 10b. FAR results from testing the Potential Impact Tables on 2014-2017 events. Results are listed as: Number of events incorrectly identified/Total events (percent correct)
*Advisory events and Non-events verification independently determined by surface observations

Test Results	MSLP Table	850 hPa Wind Table	NWS Buffalo FAR for event type
Widespread Events	0/2 (0%)	0/2 (0%)	1/2 (50%)
Limited Events	3/9 (33%)	3/9 (33%)	2/9 (22%)
Advisory-only Events*	6/18 (33%)	5/18 (28%)	1/18 (6%)
Non-events*	8/14 (57%)	3/14 (21%)	1/14 (7%)
Combined Events Results For Each Table	17/43 (40%)	11/43 (26%)	5/43 (12%)

g. MSLP High Wind Potential Impact Table

The MSLP table correctly identified both Widespread events for a POD of 100% and FAR of 0%. Performance dropped some for Limited and Advisory events with the table correctly identifying 6/9 and 12/18 or a 67% POD/33% FAR. As mentioned before these false alarms were mainly due to events with MSLP more than one SD above or below the event means. Most often, when an anomalously deep low pressure system only produced Limited type impacts it was due to an 850 hPa jet that was weaker than 57 kt (29 m/s) tracking over the NWS Buffalo CWA. When testing Non-events, the MSLP table had its lowest performance, only correctly identifying 6/14 events for a POD of 43%. This is also due to a deep low with very weak jet which does not produce Advisory level gusts at the surface. Combining the detection accuracy of the MSLP table for all event types showed 26 of 43 events were correctly identified or 60% POD which is not surprising considering the tables were designed to capture events within one SD (68%) of mean event type values.

h. 850 hPa High Wind Potential Impact Table

The 850 hPa wind table also correctly identified both Widespread events with a very similar performance in testing Limited and Advisory events with 6/9 or 67% POD for Limited and 13/18 or 72% POD for Advisory events. For Non-events, performance was much higher with the 850 hPa wind table at 11/14 correct events or 79% POD. This is likely due because 850 hPa winds of non-events typically fall lower than 41kt (21 m/s). Combining the accuracy of the 850 hPa wind table for all events showed 32 of 43 events were correctly identified or 74% POD which is better than the one SD that the tables were designed to capture.

i. Potential Impact Table Results compared to NWS Buffalo Performance

When comparing performance scores of the Potential Impact Tables with NWS Performance scores, again measured as whether or not the final Warning/Advisory or no action matched the study categories, it is clear that human forecasters are hard to beat. NWS Buffalo performance scores for each of the event categories were higher than the tables in every category except Widespread events which had a small two event sample. All in all there were only 5 "False-alarm" events including one Widespread event forecasted as Limited, One Limited event forecasted as Widespread and one as a Non-event, one Advisory event forecasted as a Limited high wind event and one Non-event forecasted as an Advisory event. Perhaps some results in the table outputs when forecasting for the Widespread event could have increased forecaster confidence to add a few more zones into a High Wind Warning or perhaps assisted with issuing a High Wind Warning for the Limited event forecasted as a non-event.

j. Handling Mixed Results

When testing events for 2014-2017 cases, the MSLP and 850 hPa wind Potential Impact Tables would quite often (23/43 events) output different event type results. For example, the MSLP table may indicate an event as a "May Fit Any Wind Event" type but the 850 hPa wind table would indicate a Widespread event type. In order to simplify mixed results, the author recommends that forecasters lead toward the 850 hPa wind result. The reason for this is because the high wind composites showed the most pronounced signal when separating out event types while the combined results for the 850 hPa wind table from Table 9e also shows the 850 hPa wind table scored a higher POD than the MSLP table. Therefore, in the given example, it is recommended to lean toward the Widespread event result from the 850 hPa table to clear up the multi-category result in the MSLP table.

Due to the narrow ranges of values for the categories in the two tables, it is very hard to get matching results. During testing of the tables, matching results only occurred 20/43 events tested. Therefore, POD of the tables in matching results is extremely low, in this case just 47%. It is also not recommended to only use one table. View the use of both the MSLP and 850 hPa Wind tables similar to how one would use both CAPE and Wind Shear to forecast severe weather. Matching results, however for either a Widespread event or an Unlikely event should give a forecaster very high confidence in forecasting either an extremely widespread damaging wind event if matching Widespread results or leaning against a Wind Advisory or High Wind Warning if matching Unlikely results.

One example of mixed results which could have led to a reduced FAR for NWS Buffalo would be the 22 November 2015 event. The MSLP table mis-identified this as an Unlikely event with a center pressure of 999 hPa but correctly identified the 56kt (29 m/s) 850 hPa jet as fitting a Limited or Advisory event. Perhaps the Unlikely event MSLP result could have swayed a forecaster to lean more towards an Advisory (with Advisory level wind gusts observed) instead of a High Wind Warning which would have prevented a false alarm forecast.

One may ask the question, "Why were the tables not designed to capture MSLP and 850 hPa wind values within two SD of study means to produce better results?" This was considered when designing the tables but box and whisker plots of the data at two SD showed that the center category, May Fit Any Wind Event, was significantly wider which would not provide valuable to determining the impact of an event. Numerically, the May Fit Any Wind Event category at the current one SD for 850 hPa wind speed ranges from 57 to 60 kt (29 to 31 m/s) but at two SDs this range jumped to a range of 50 to 68 kt (26 to 35 m/s). The Widespread and Unlikely categories however, are open ended with greater than and less than symbols. For Widespread events this allows the tables to capture high wind events with extremely anomalous MSLP and 850 hPa wind speed and at the bottom end assign an Unlikely result to very weak MSLP and 850 hPa wind speed forecast values.

4. Example Case- 10 April 2015 Limited High Wind Event

A 995 hPa surface low pressure over southern Wisconsin on the evening of 09 April 2015 deepened to 987 hPa north of Lake Huron and 986 hPa over central Quebec through 10 April 2015. (Figs. 11 a-c) A strong 31 m/s (60 kt) low level jet over Indiana (Figs. 12 a-c) ahead of the surface low weakened to 28 m/s (54 kt) while crossing the eastern Great Lakes and Saint Lawrence River Valley. Incoming cold air behind an occluded front steepened low level lapse rates during the morning hours of 10 April which allowed strong winds from the low level jet to reach the surface. This was sampled by consecutive NWS Buffalo soundings between 00z 10 April and 00z 11 April (Figs. 13 a-c).

Winds and associated damages from this storm were significant as indicated by the summary Local Storm Report (Fig. 14). A map showing the location but not magnitude of these reports can be found in Fig. 15. Damaging winds developed across counties downwind of Lakes Erie and Ontario with measured gusts of 62 mph at the Buffalo Airport, 60 mph at the Rochester Coast Guard Station and 58 mph at the Niagara Falls Airport. The strong winds downed trees and powerlines across 8 counties (9 zones) which closed several roads and left tens of thousands without power. Other significant reports included a collapsed barn in Clarendon, large air vents torn off roofs of two restaurants in Batavia and utility poles snapped off in Batavia and Albion. Estimated damages from the storm topped $190,000. Nine of NWS Buffalo's 17 forecast zones received damages verifying high wind warnings therefore classifying this as a Limited high wind event (Fig. 16).

Comparisons of the Limited composite charts developed from this high wind study with NARR reanalysis graphics for the 10 April wind event matched very well with respect to the location of each parameter at each time step. During the event, the 500 hPa trough deepened while approaching the eastern Great Lakes which matches the progression of the trough in the composite but the event trough was not as deep as the Limited composite (Fig. 17a). This is likely due to the late in the cold-season timing of the event where troughs typically are not as deep as troughs found in the middle of the cold season. The track and change in MSLP with time of the event surface low at each time step matched the Limited composites with a deepening low from 12 hours before onset to onset time tracking northwest of Buffalo then weakening some at 12 hours after onset (Fig. 17b). The event 850 hPa low level jet maintained strength leading up to onset time and persisted 12 hours after onset time which fits closer to the Widespread composite (Fig. 17c). Overall, if used as forecast guidance, the NARR composites should confirm to a forecaster the track of the low center and 850 hPa jet fits the pattern of an oncoming high wind event. Although the specific magnitudes for this event should not be compared with composite MSLP and 850 hPa magnitudes due to a watered-down signal in composites, comparing the trends in the magnitudes whether strengthening, weakening or persisting should certainly give hints to event type.

The Potential Impact Tables for this event worked well when used together despite each table producing different results. The MSLP closest to the onset time of high winds was 987 hPa with a 52 kt (27 m/s) max 850 hPa low level jet over the Buffalo CWA. The MSLP table output was "May Fit Any Wind Event" which unfortunately does not help with warning decision making using it alone. This output only tells a forecaster that a wind event of some sort, anything ranging from Advisory level up to Widespread, is possible. When this result is given it is recommended to take a look at the 850 hPa wind speed result for further refinement. Using 52 kt (27 m/s) into the 850 hPa wind speed table yields a result of "Limited or Advisory". Based on this result, forecasters should expect that they are not looking at a Widespread event due to the jet speed not reaching into the Widespread range on the tables. In order to help resolve the difference between table results, forecasters can turn to finding the closer matching composite or take a closer look at point forecast soundings at various locations with BUFKIT.

10 April 2015 03z
12 hours before event onset time

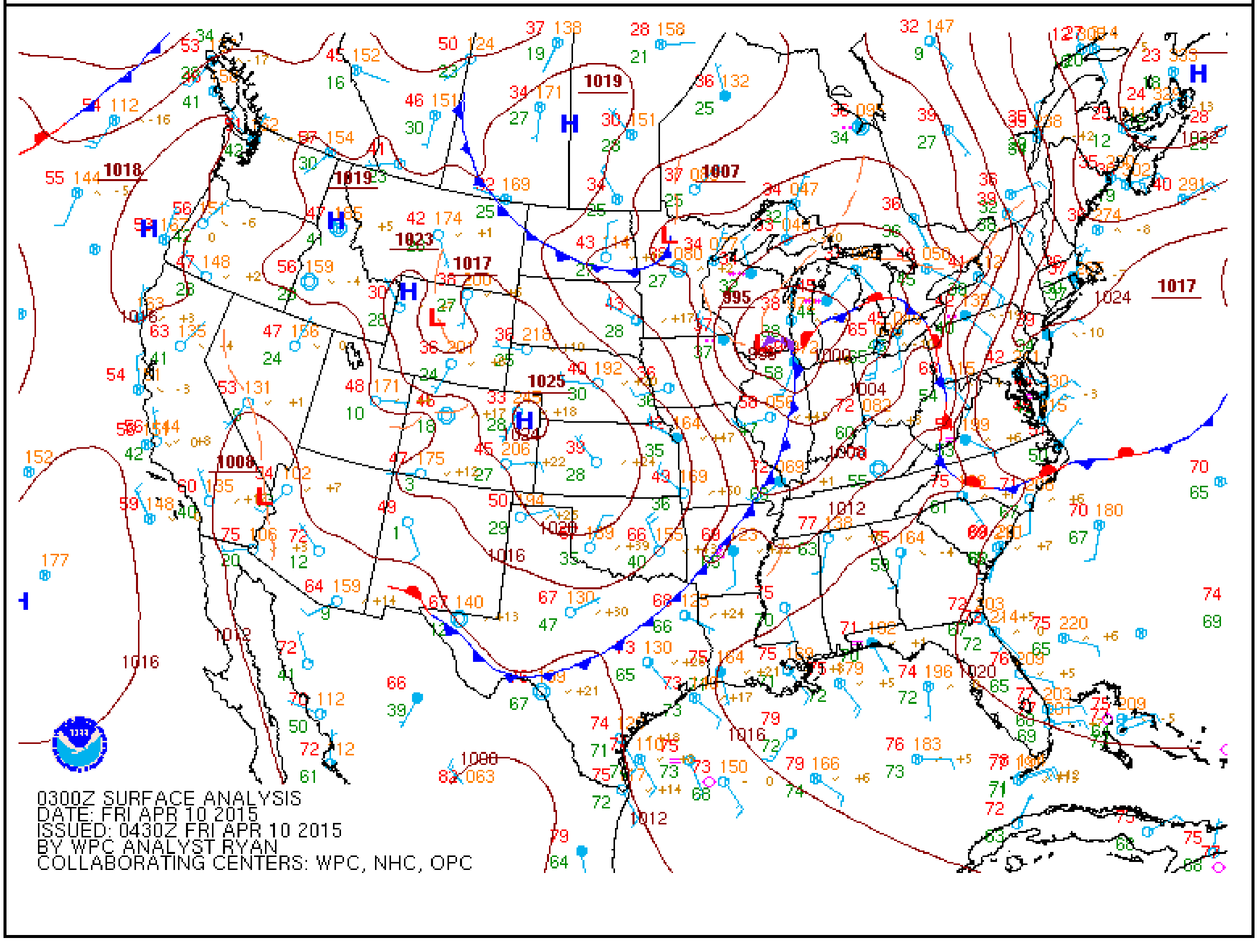


Figure 11a. Surface Analysis for 03z 10 April 2015 Event. Figure from Weather Prediction Center.

10 April 2015 15z
At event onset time

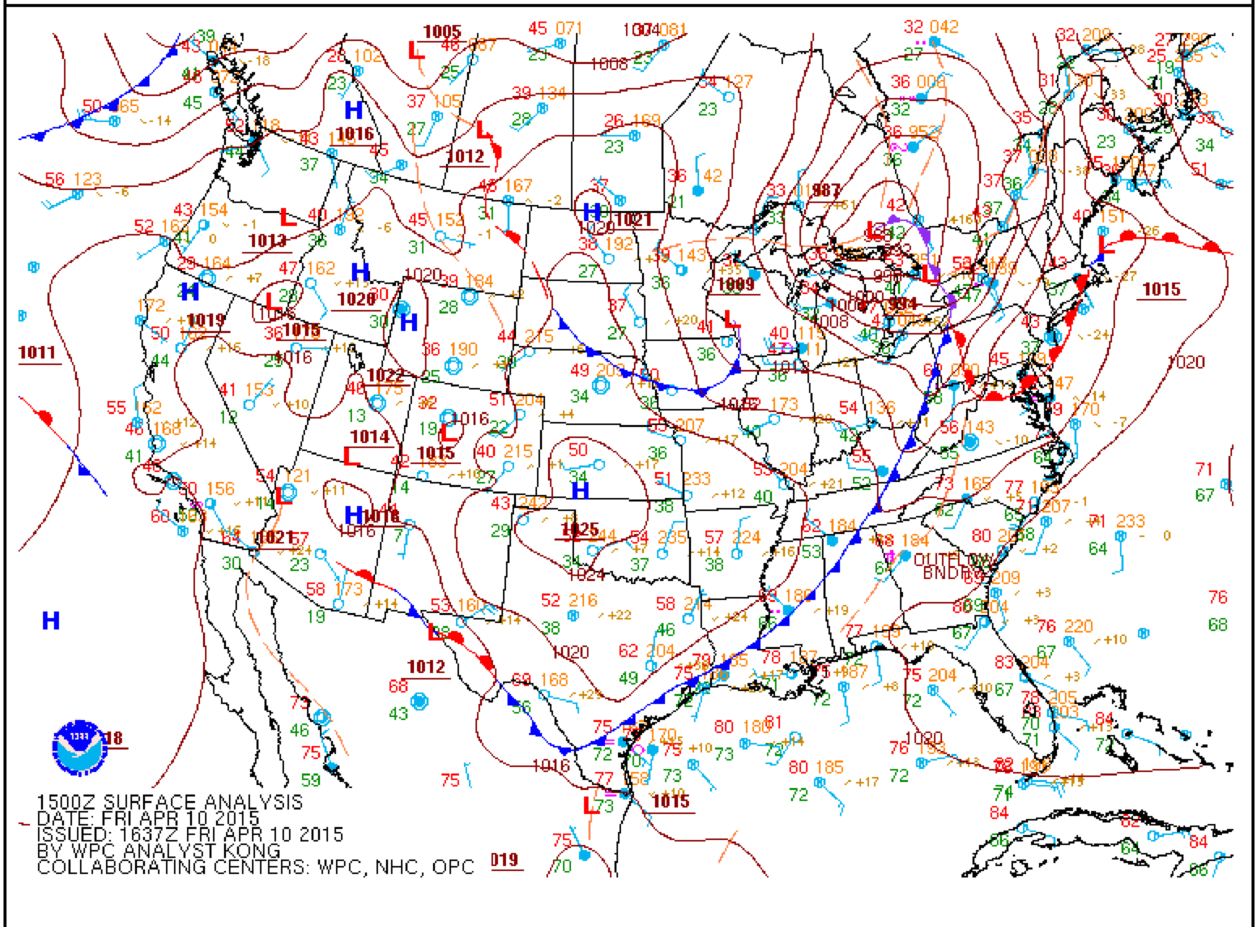


Figure 11b. Surface Analysis for 15z 10 April 2015 Event. Figure from Weather Prediction Center.

11 April 2015 03z
12 hours post event onset time

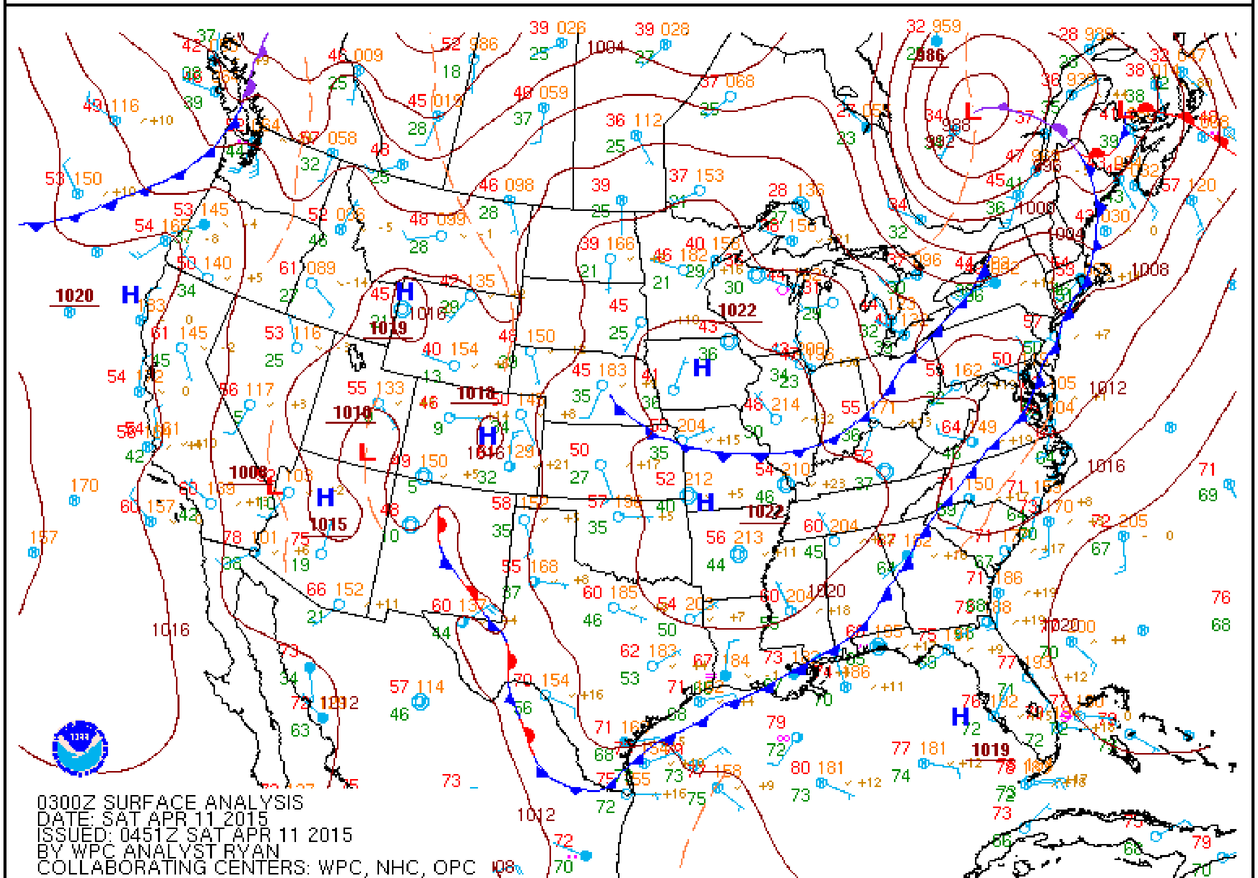


Figure 11c. Surface Analysis for 03z 11 April 2015 Event. Figure from Weather Prediction Center.

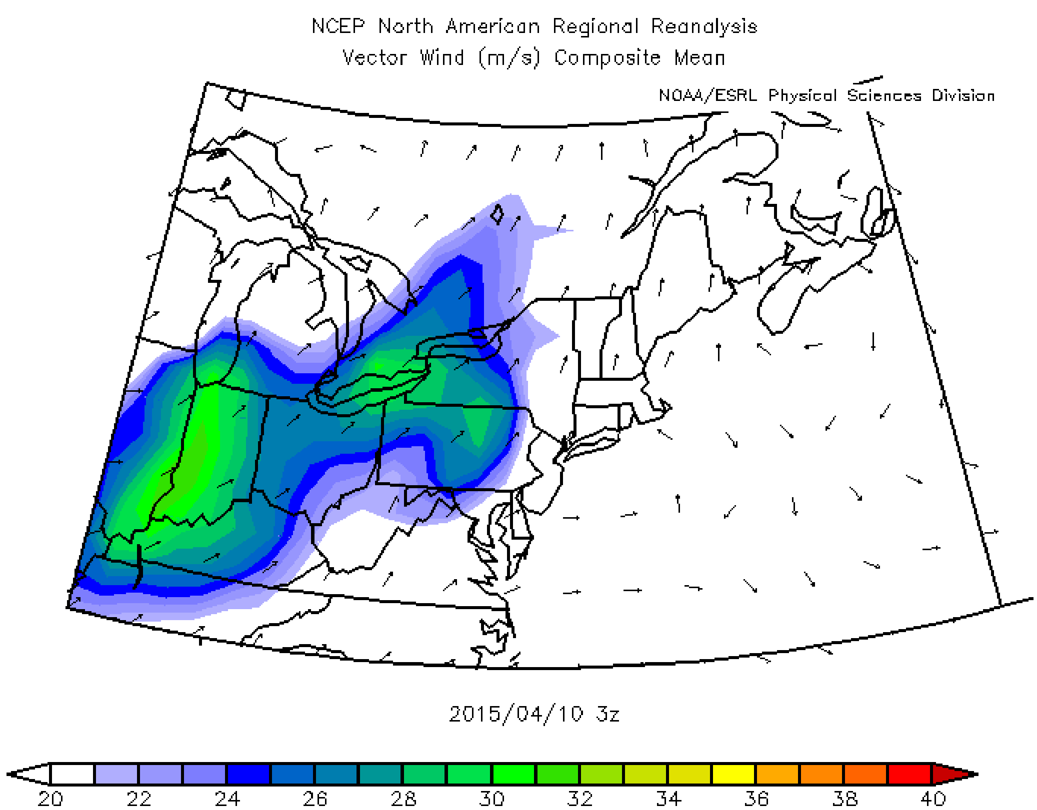
10 April 2015 03z 12 hours before event onset time


Figure 12a. NARR Reanalysis of 850 hPa Vector Wind (m/s) for 03z 10 April 2015.

10 April 2015 15z
At event onset time

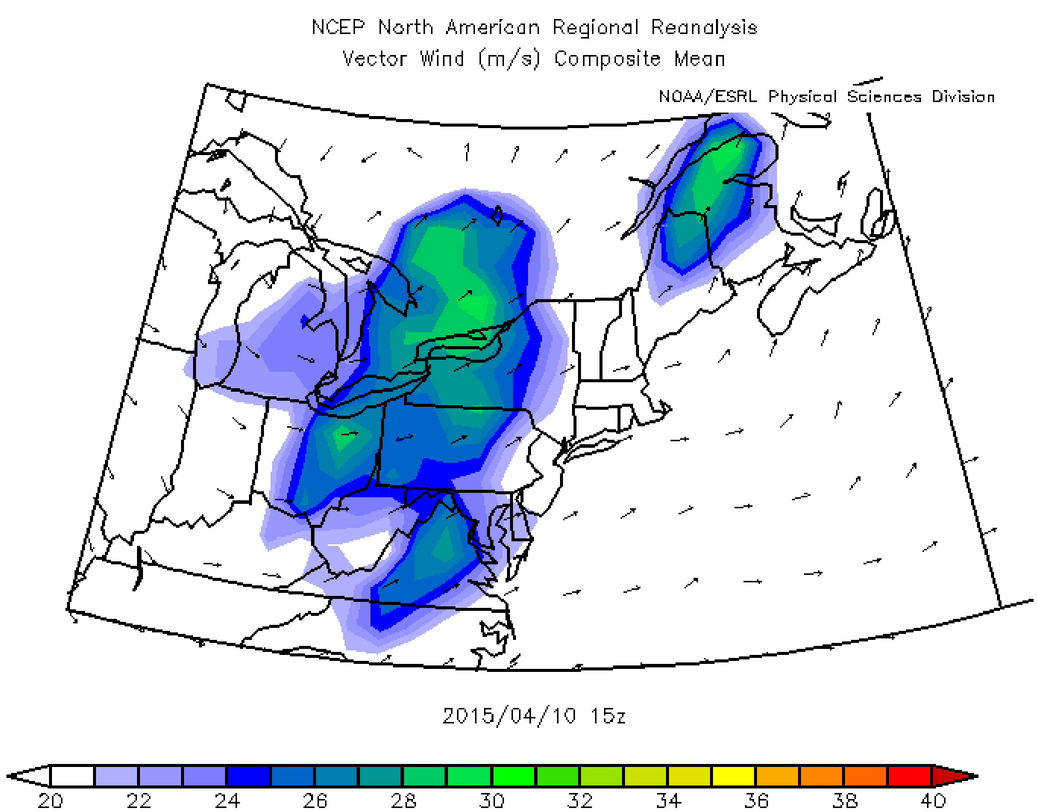


Figure 12b. NARR Reanalysis of 850 hPa Vector Wind (m/s) for 15z 10 April 2015.

11 April 2015 03z
12 hours post event onset time

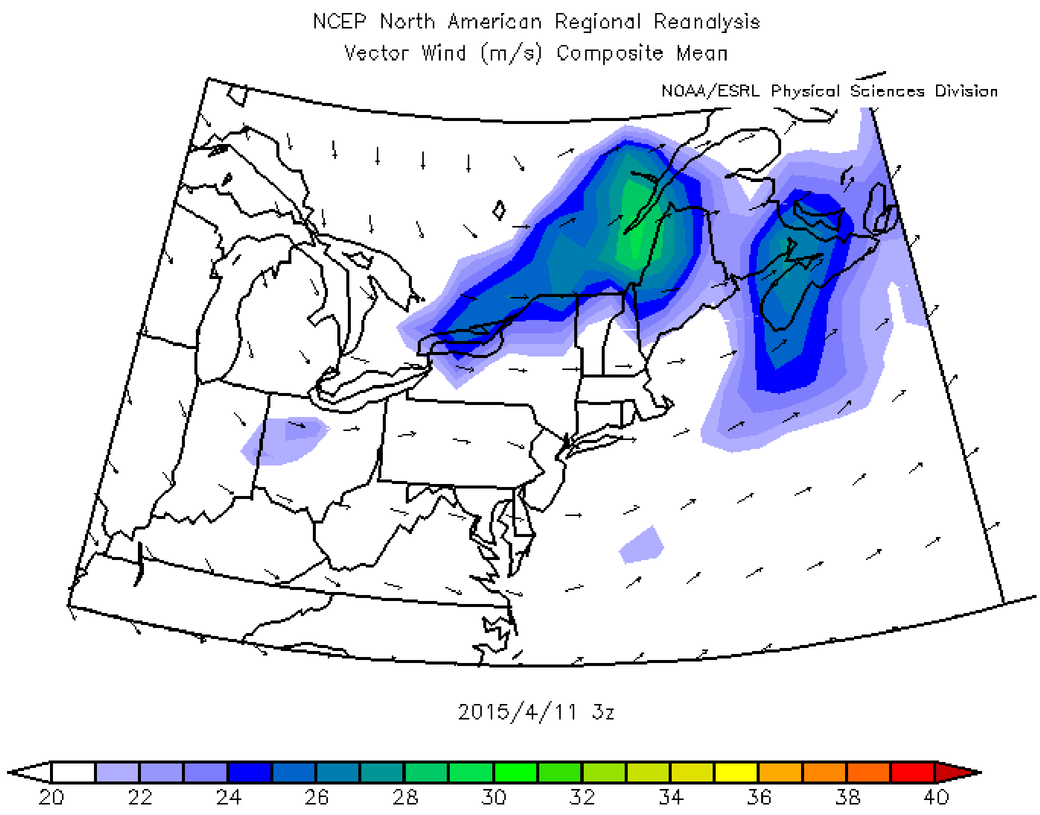


Figure 12c. NARR Reanalysis of 850 hPa Vector Wind (m/s) for 03z 11 April 2015.

10 April 2015 00z

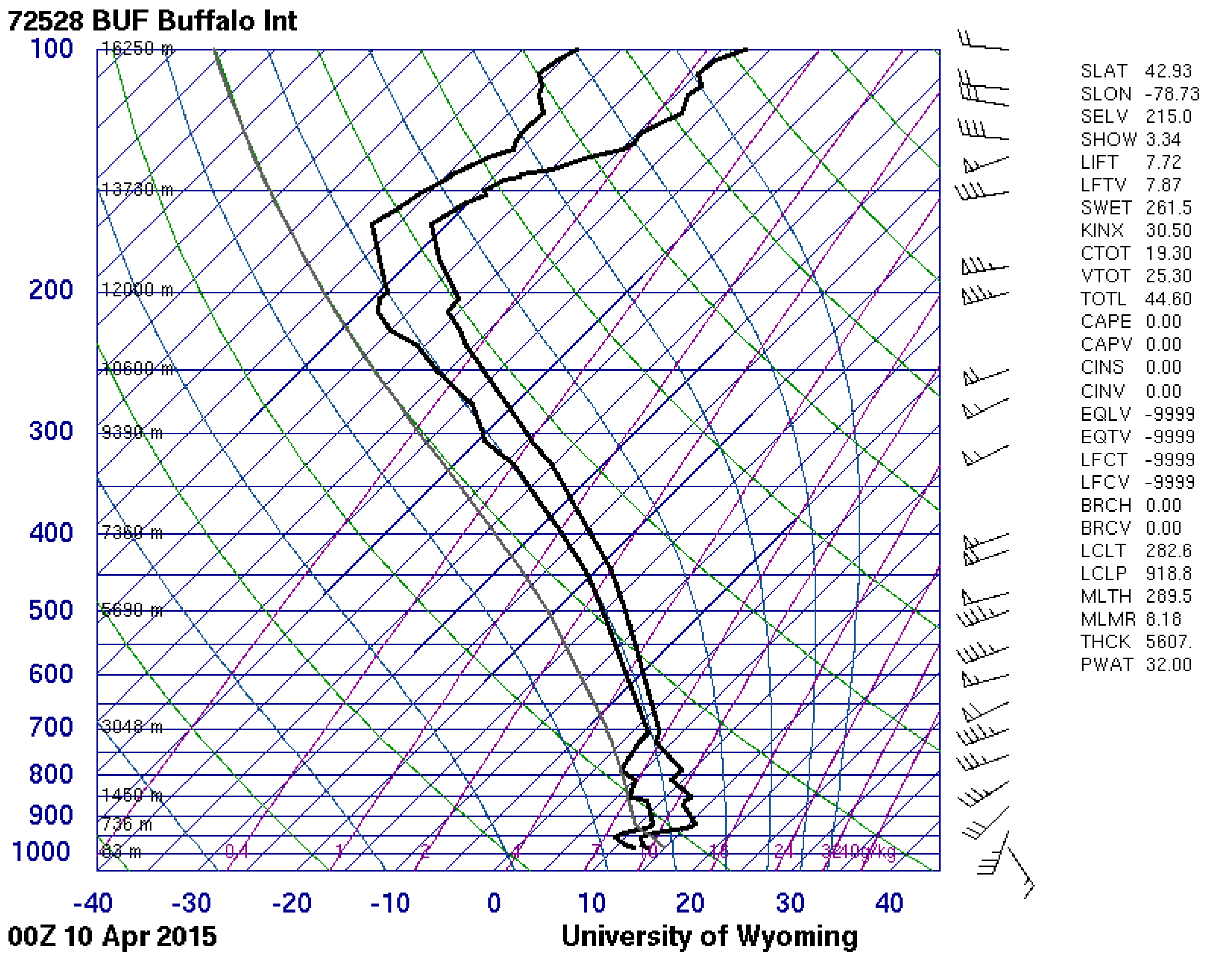


Figure 13a. Soundings from Buffalo, NY during 10 April 2015 Limited high wind event. Figure from University of Wyoming. College of Engineering. Department of Atmospheric Science.

10 April 2015 12z

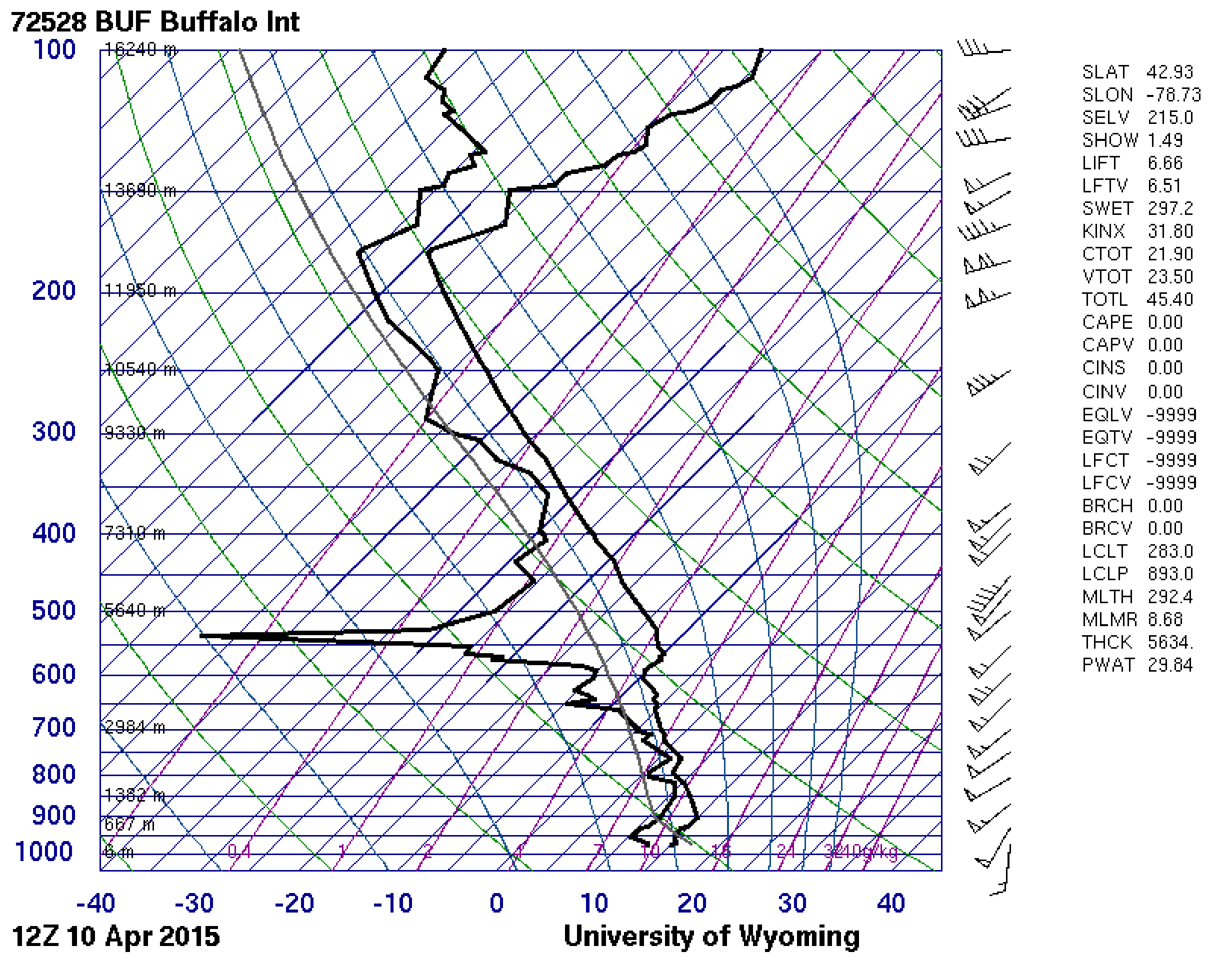


Figure 13b. Soundings from Buffalo, NY during 10 April 2015 Limited high wind event. Figure from University of Wyoming. College of Engineering. Department of Atmospheric Science.

11 April 2015 00z

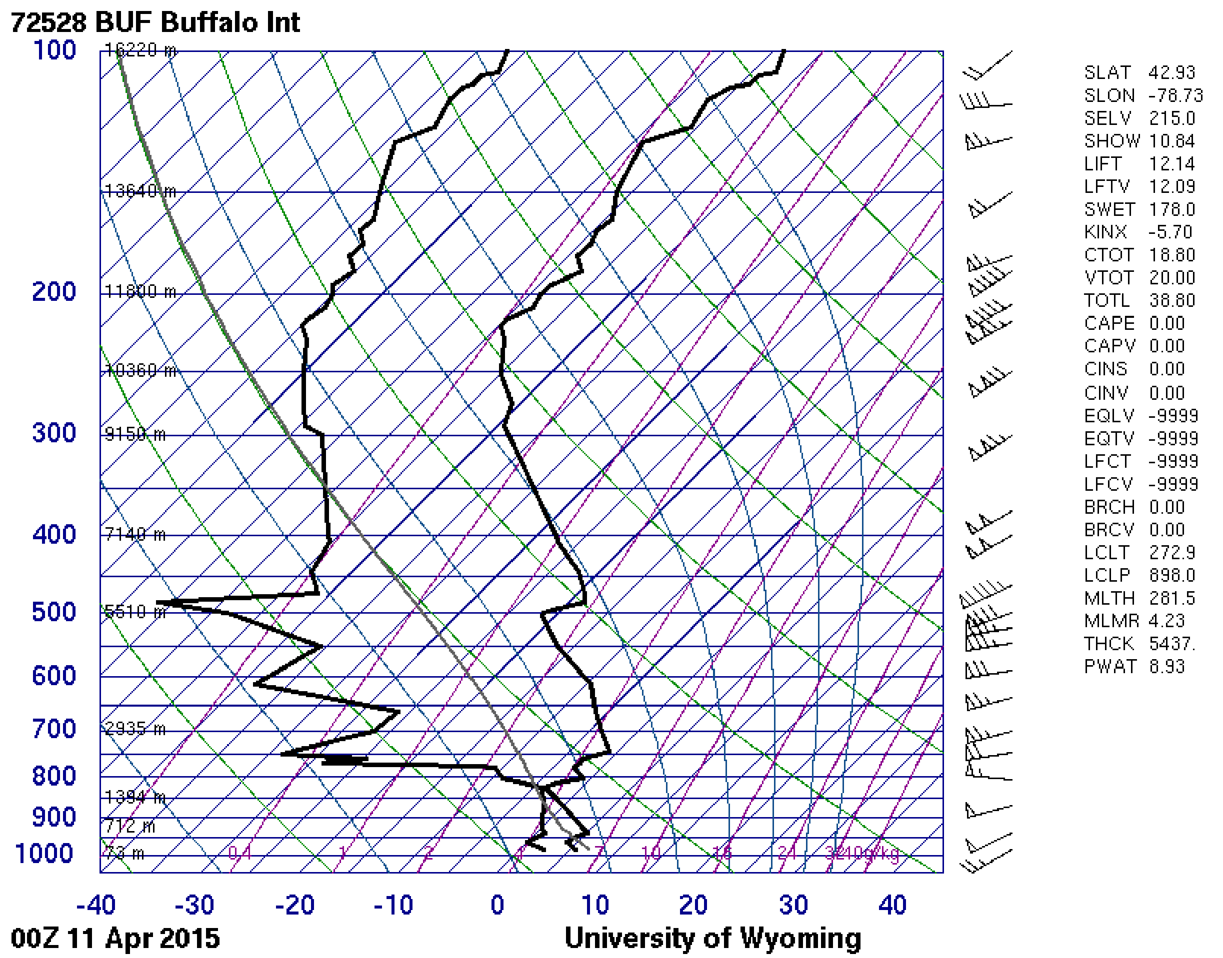


Figure 13c. Soundings from Buffalo, NY during 10 April 2015 Limited high wind event. Figure from University of Wyoming. College of Engineering. Department of Atmospheric Science.

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PRELIMINARY LOCAL STORM REPORT...SUMMARY
NATIONAL WEATHER SERVICE BUFFALO NY
932 PM EDT FRI APR 10 2015

..TIME...   ...EVENT...      ...CITY LOCATION...     ...LAT.LON...
..DATE...   ....MAG....      ..COUNTY LOCATION..ST.. ...SOURCE....
            ..REMARKS..

1045 AM     NON-TSTM WND GST BUFFALO INTL ARPT       42.94N  78.73W
04/10/2015  M58 MPH          ERIE               NY   ASOS

0100 PM     NON-TSTM WND DMG AKRON                   43.02N  78.50W
04/10/2015                   ERIE               NY   NWS EMPLOYEE

            PINE TREE DOWN ON CRITTENDON RD. TIME ESTIMATED.
```

```
0105 PM     NON-TSTM WND GST NIAGARA FALLS         43.09N  79.02W
04/10/2015  M58 MPH          NIAGARA            NY   ASOS

            CORRECTION TO MAX WIND SPEED REPORTED EARLIER AT
            KIAG...SHOULD BE 58 MPH...NOT 59 MPH.

0110 PM     NON-TSTM WND DMG MIDDLEPORT            43.21N  78.48W
04/10/2015                   NIAGARA            NY   NEWSPAPER

            MULTIPLE REPORTS OF TREES AND POWERLINES DOWN.

0110 PM     NON-TSTM WND DMG 6 N CARTHAGE          44.07N  75.60W
04/10/2015                   JEFFERSON          NY   LAW ENFORCEMENT

            TREE DOWN ON AVERY ROAD NEAR NORTH CROGHAN ROAD.

0130 PM     NON-TSTM WND DMG BATAVIA               43.00N  78.18W
04/10/2015                   GENESEE            NY   NEWSPAPER

            LARGE AIR VENT TORN OFF ROOF OF KENS CHARCOAL PITS AND
            CITY SLICKERS RESTAURANTS.

0130 PM     NON-TSTM WND DMG BATAVIA               43.00N  78.18W
04/10/2015                   GENESEE            NY   NEWSPAPER

            DOWNED TREE AT THE BLIND SCHOOL.

0130 PM     NON-TSTM WND DMG BATAVIA               43.00N  78.18W
04/10/2015                   GENESEE            NY   NEWSPAPER

            UTILITY POLE SNAPPED OFF AND LYING ON POWERLINES AT
            9524 CLIPNOCK ROAD.

0130 PM     NON-TSTM WND DMG BATAVIA               43.00N  78.18W
04/10/2015                   GENESEE            NY   NEWSPAPER

            TREE DOWN ON WIRES AT 240 STATE STREET... NEAR HART
            STREET.

0140 PM     NON-TSTM WND GST IRONDEQUOIT           43.27N  77.63W
04/10/2015  M60 MPH          MONROE             NY   COAST GUARD

0242 PM     NON-TSTM WND GST BUFFALO INTL ARPT     42.94N  78.73W
04/10/2015  M62 MPH          ERIE               NY   ASOS

            CORRECTION TO MAX WIND SPEED REPORTED EARLIER AT
            KBUF...SHOULD BE 62 MPH... NOT 63 MPH.

0300 PM     NON-TSTM WND DMG AMHERST               43.02N  78.72W
04/10/2015                   ERIE               NY   PUBLIC

            TREES DOWN ON MAPLE AVE.

0300 PM     NON-TSTM WND GST BATAVIA               43.03N  78.17W
04/10/2015  M59 MPH          GENESEE            NY   AWOS
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```
0300 PM     NON-TSTM WND DMG EAST AURORA            42.77N  78.62W
04/10/2015                   ERIE              NY   NWS EMPLOYEE

            TREE DOWN IN YARD AT THE CORNER OF GIRARD AVE AND MAPLE
            ST.

0315 PM     NON-TSTM WND DMG ALBION                 43.24N  78.22W
04/10/2015                   ORLEANS           NY   LAW ENFORCEMENT

            POWER POLE TOPPLED ALONG RTE 31.

0315 PM     NON-TSTM WND DMG CLARENDON              43.20N  78.07W
04/10/2015                   ORLEANS           NY   LAW ENFORCEMENT

            BARN COLLAPSE ON RTE 237.

0315 PM     NON-TSTM WND DMG BARRE CENTER           43.19N  78.20W
04/10/2015                   ORLEANS           NY   LAW ENFORCEMENT

            WIRES DOWN ON BARRE ROAD.

0328 PM     NON-TSTM WND DMG WATERTOWN              43.97N  75.91W
04/10/2015                   JEFFERSON         NY   LAW ENFORCEMENT

            WIRES DOWN AT 1049 HUNTINGTON STREET.

0330 PM     NON-TSTM WND DMG HANOVER CENTER         42.52N  79.14W
04/10/2015                   CHAUTAUQUA        NY   LAW ENFORCEMENT

            TREES DOWN ON POWERLINES.

0330 PM     NON-TSTM WND DMG PORTLAND               42.37N  79.47W
04/10/2015                   CHAUTAUQUA        NY   LAW ENFORCEMENT

            TREES DOWN ON POWERLINES.

0330 PM     NON-TSTM WND DMG SHELBY                 43.19N  78.39W
04/10/2015                   ORLEANS           NY   LAW ENFORCEMENT

            WIRES DOWN ON SOUTH GRAVEL ROAD.

0330 PM     NON-TSTM WND DMG GAINES                 43.29N  78.22W
04/10/2015                   ORLEANS           NY   LAW ENFORCEMENT

            WIRES DOWN ON EAGLE HARBOR ROAD.

0400 PM     NON-TSTM WND DMG WARSAW                 42.74N  78.13W
04/10/2015                   WYOMING           NY   LAW ENFORCEMENT

            LARGE TREE LIMB DOWN ON MUNGERS MILL ROAD.

0400 PM     NON-TSTM WND DMG WYOMING                42.83N  78.09W
04/10/2015                   WYOMING           NY   LAW ENFORCEMENT
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```
            LARGE TREE LIMB DOWNED...BURNING ON WIRES.

0400 PM     NON-TSTM WND DMG PIKE                     42.56N  78.15W
04/10/2015                   WYOMING            NY    LAW ENFORCEMENT

            WIRES DOWN ON NORTH WATER STREET.

0429 PM     NON-TSTM WND DMG ORCHARD PARK             42.76N  78.75W
04/10/2015                   ERIE               NY    DEPT OF HIGHWAYS

            RTE 20A WEST CLOSED BETWEEN THORN AVE AND SOUTH LINCOLN
            AVE BECAUSE OF DOWNED TREE.

0438 PM     NON-TSTM WND DMG WATERTOWN                43.97N  75.91W
04/10/2015                   JEFFERSON          NY    LAW ENFORCEMENT

            TREES AND WIRES DOWN NEAR THE CORNER OF NORTH RUTLAND
            AND BRONSON STREETS.

0441 PM     NON-TSTM WND DMG WALES CENTER             42.77N  78.52W
04/10/2015                   ERIE               NY    DEPT OF HIGHWAYS

            RTE 16 CLOSED IN BOTH DIRECTIONS BETWEEN RTE 400 AND
            OLEAN RD DUE TO A DOWNED TREE.
```

Figure 14. Local Storm Report Summary from 10 April 2015 Limited High Wind Event.

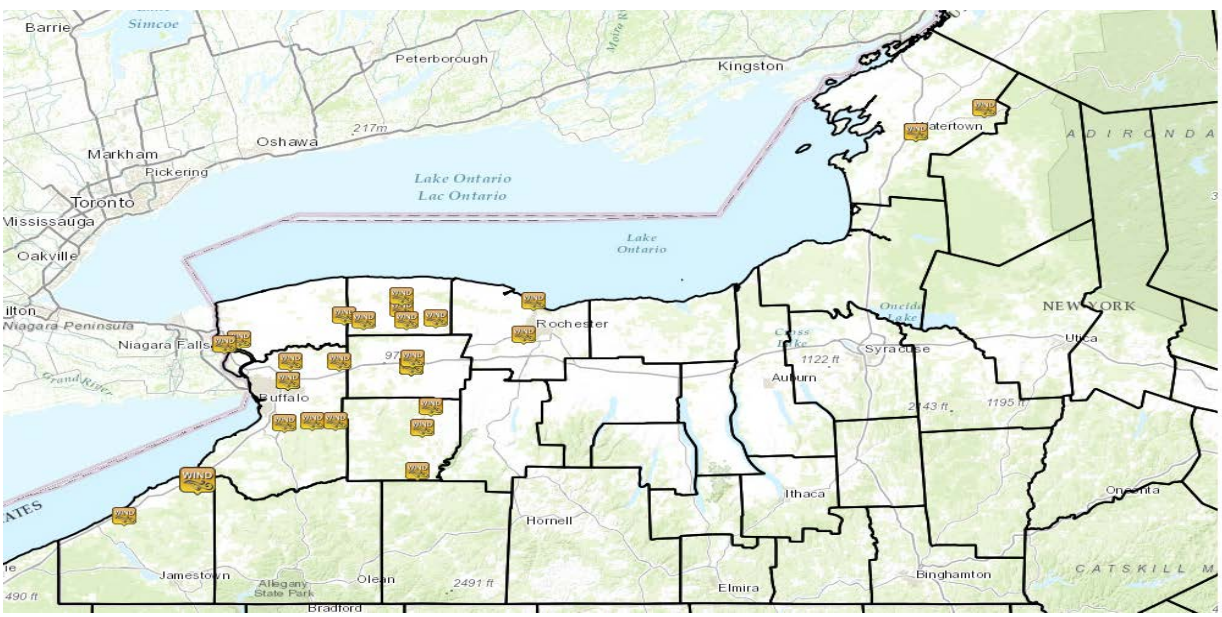

Figure 15. Local Storm Report (LSR) Map from 10 April 2015 Limited high wind event ton show special coverage of damage reports across the NWS Buffalo CWA. Image from [NWSChat Local Storm Report Application](). Each report is marked with a yellow square pin. See LSR [Fig. 14]() for details on each report.

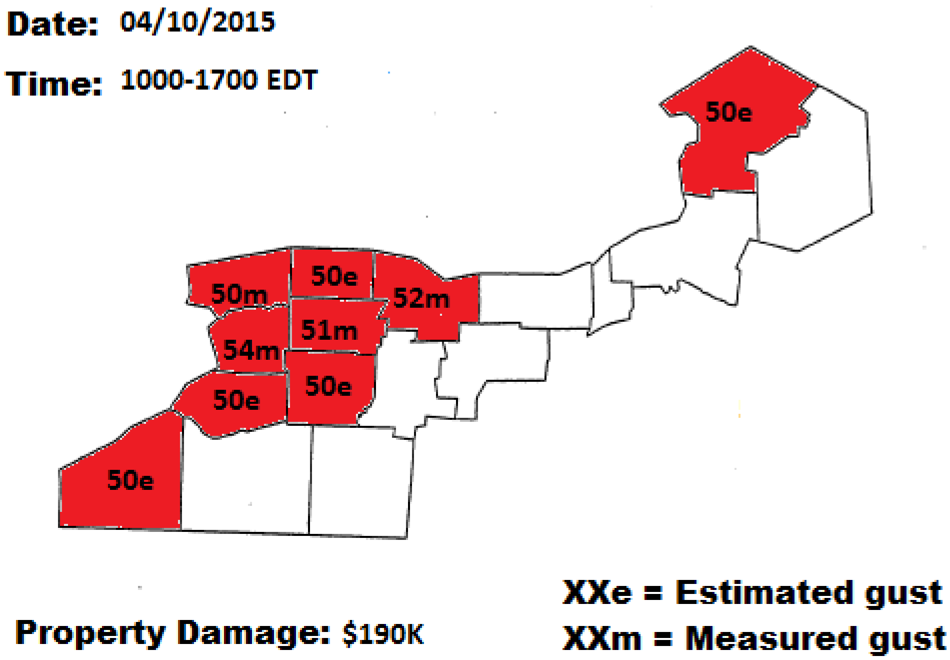

Figure 16. Impact map for Limited High Wind Event on 10 April 2015. Red colored zones are those impacted by high winds with highest magnitude of wind gust included for each zone in knots. A gust with an appended "m" is a measure gust and an "e" is an estimated gust. Total property damage estimates are included for each type of event.

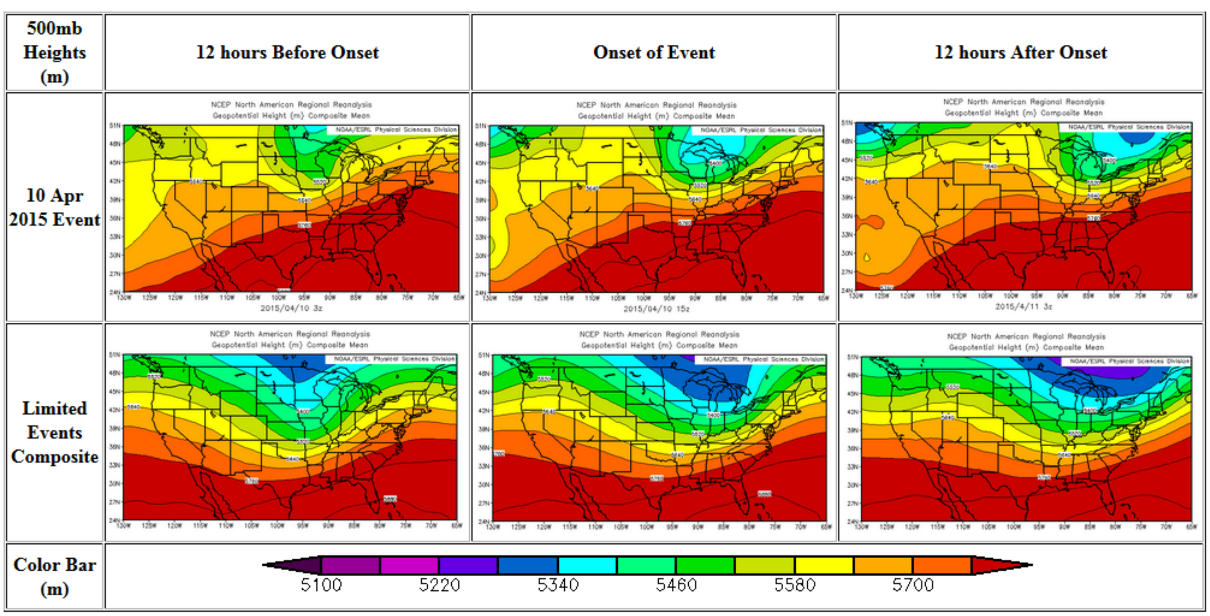

Figure 17a. NARR 500 hPa (m) comparison of 10 April 2015 High Wind Event versus Limited event composites.

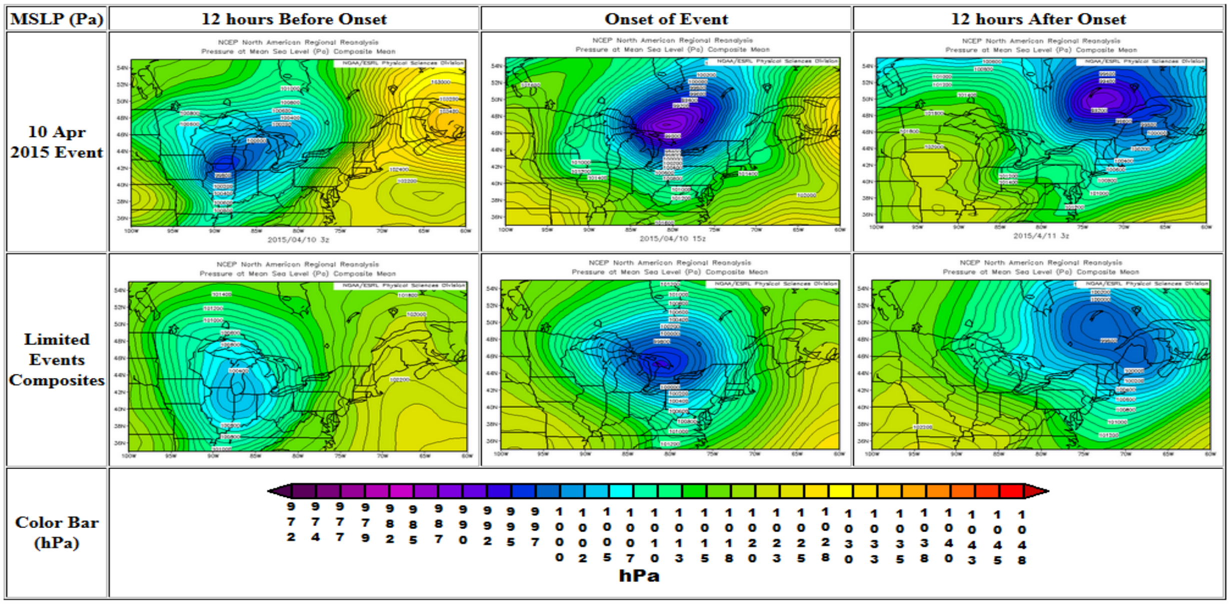

Figure 17b. NARR MSLP (Pa) comparison of 10 April 2015 High Wind Event versus Limited event composites.

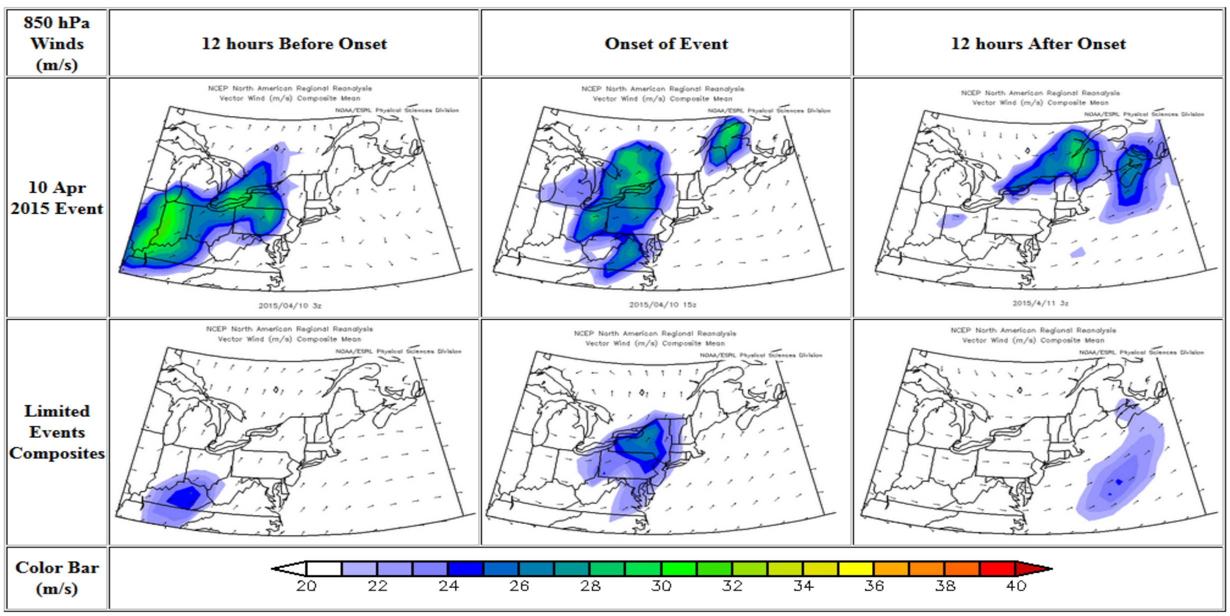

Figure 17c. NARR 850 hPa Vector Winds (m/s) comparison of 10 April 2015 High Wind Event versus Limited event composites.

5. Conclusion

This expanded high wind study was able to confirm foundational findings from the Niziol and Paone (2000) study as well as identify a new parameter to use in assessment of high wind. While the track of a deepening surface low northwest of Buffalo, NY is one requirement, a strong and persistent 850 hPa jet that tracks across western NY is also needed for a Widespread impact high wind event. The mixing of these winds is activated by steepening of low level lapse rates in the wake of a strong cold front passage verified within the 0-3 km lapse rate data collected in Table 5d. While that data does not help with separating event types, you can see that lapse rates averaging 6 C/km where present in all three event types. The NARR composite graphics provide a pattern recognition tool for new forecasters and can help more seasoned forecasters confirm or reject potential wind events based on patterns within model forecasts. This study found MSLP and 850 hPa wind speed to be the two main predictors for high wind events after comparing 5 total parameters in Tables 5a-d and based on patterns found in the NARR composites. Weaker signals between event types from the Lapse Rate, Pressure rise and U wind anomaly parameters prevented them from being included for the Potential Impact Tables. Of the three parameters not used, 2 hour pressure rises (tendency) may provide some use in a future high wind forecast tool such as included in section 6 below.

Separating high wind events into the three categories highlighted trends in MSLP and 850 hPa wind parameters that were used to develop the new Potential Impact Tables. The tables were tested with generally positive results and should be of value to help forecasters quickly assess a potential impact type and extent across the NWS Buffalo CWA. While the tests of the Potential Impact Tables showed they can provide clearer results for events which exhibit strong or weak MSLP and 850 hPa values, the example case showed how even mixed results can be used together to guide a forecaster toward a potential impact result and further reduce the number of counties that are false alarmed.

Results from this study have already begun to provide some assistance at the NWS Buffalo office. Two recent events 11 January 2017 and 2 March 2017 were initially forecasted as Advisory level events but ensuing shifts using findings released to the staff from the study upgraded the Advisories to High Wind Warnings. The 11 January 2017 event verified as a Limited event and the 2 March 2017 event verified as a Widespread event though the upgraded forecast was for a Limited event.

This study was able to build upon foundational high wind forecasting findings from previous research while also producing new tools that operational forecasters can use in assessment of future events. These tools can be used by current and future NWS Buffalo forecasters to build confidence and improve detection and lead time for High Wind Watches/Warnings and Wind Advisories.

6. Future Work

The author wishes to develop a 2-D graphical forecasting tool that combines model 850 hPa wind speed and associated study wind event category thresholds with the location and timing of pressure rises. Pressure rise signatures were found in this study (Tables 5a-d) and in case examples from Niziol and Paone (2000) to be an indicator of the onset of high winds during a high wind event. This procedure would be designed around the NWS Advanced Weather Interactive Processing System (AWIPS) platform with a preliminary example in Fig. 18.

Expansion of this study beyond the NWS Buffalo CWA has been included as a collaborative project within CSTAR (Collaborative Science, Technology and

Applied Research) VI titled "Development of Improved Diagnostics, Numerical Models, and Situational Awareness of High-Impact Cyclones and Convective Weather Events". Future work involves looking into development of new composites and expanding the Potential Impact Tables for high wind events that cover other NWS offices in Eastern and Central Regions. During spring 2017, progress has been made to identify 30 high wind cases with associated data collected that impacted many NWS CWAs at one time. Figure 19, shows an example of one of the event cases with impacts extending from the Ohio Valley into New England.

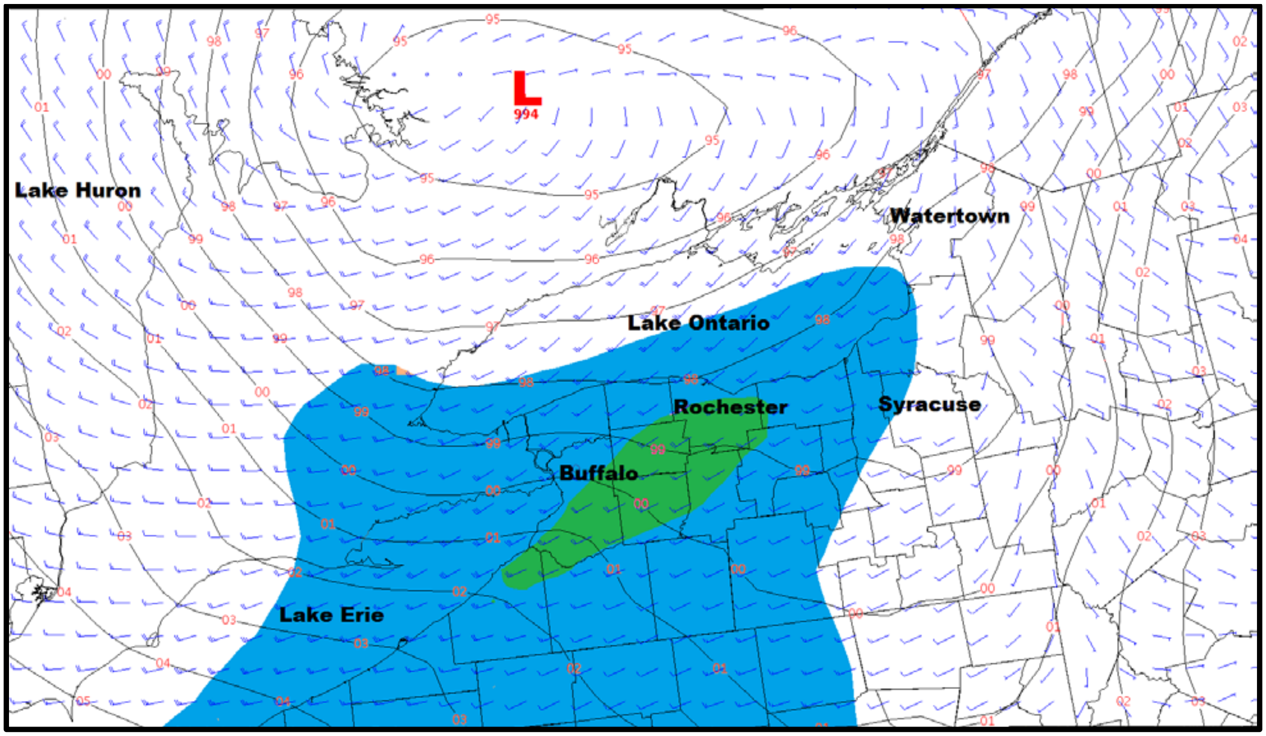

Figure 18. Example of a future high wind potential impact forecasting tool on the AWIPS platform (colors inverted for visual clarity in print). The image covers the eastern Great Lakes and much of upstate New York with the Great Lakes and larger cities labeled. Plotted are GFS model forecast of MSLP in black contours with pressure labeled in red text, surface wind barbs in blue and color filled 850 hPa wind speed using color bins based on the Potential Impact Tables in this study. The 850 hPa wind speeds are only visible where pressure tendency is rising (indicating winds mixing to the surface) while 850 hPa winds were masked where pressure tendency is still falling. In this example, green fill indicates a channel of potential Limited high wind or Advisory level wind gusts from just south of Buffalo to Rochester while the blue fill indicates potential Advisory level wind gusts extending across much of western New York and northwest Pennsylvania. A 994 low can also be seen passing north of Lake Ontario.

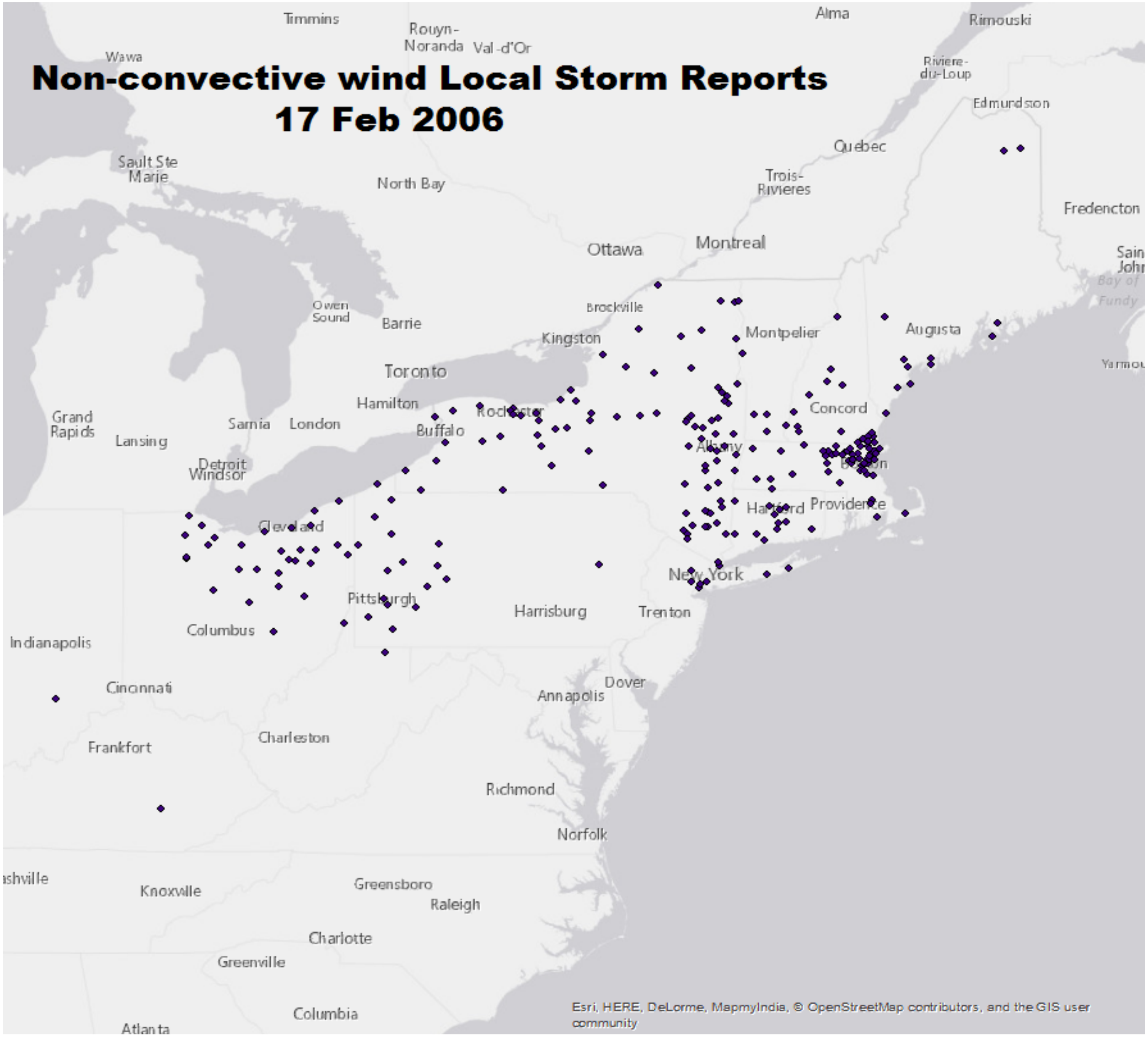

Figure 19. An example of future work to expand the high wind study to cover a larger area then only the NWS Buffalo CWA. This Widespread categorized event for NWS Buffalo also had impacts extending from the Ohio Valley into New England.

7. Acknowledgements

Thanks to David Zaff, Science and Operations Officer, NWS Buffalo, for providing guidance and direction in this study. Judy Levan, Meteorologist in Charge, NWS Buffalo, for assistance with Storm Data. Jefferson Wood, Lead Forecaster NWS Buffalo for assistance with ArcGIS. Anthony Ansuini, Lead Forecaster NWS Buffalo for assistance with TCL/TK programing. David Church, General Forecaster NWS Buffalo for help with JavaScript coding of the web-based version of the Potential Impact Tables. Dr. Charles Graves for NARR Analog Assistance. NOAA/OAR/ESRL PSD, Boulder, Colorado for providing NARR model composite web interface.

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