Final Report

to **Cooperative Program for Operational Meteorology, Education and Training (COMET)**

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Type of Project (Partners or Cooperative): Partners
Project Title: Variations in Thunderstorm Interactions with Lake Erie
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Section 1: Summary of Project Objective

The project objective is to develop a better understanding of the seasonal and diurnal variations in thunderstorm interactions with the marine boundary layer (MBL) of Lake Erie and help answer several perennial operational forecast questions. We proposed to develop this understanding through two efforts: 1. Climatological analysis of interactions between pre-existing convective storms and Lake Erie and 2. Observational and numerical modeling analysis of the severe 26 July 2005 case during which an intense squall line crossed Lake Erie.

Section 2: Project Accomplishments and Findings

We will discuss the project accomplishments in two sub-sections, reflecting the two major efforts given in Section 1.

2a. Climatological Analysis of Storm interactions with Lake Erie

A manuscript describing the results of this component of our research has been accepted for publication in the journal *Weather and Forecasting*. The manuscript is currently in press. A summary is given below; detailed methods and findings can be found in the journal article.

It is well known that on climatic time scales the Great Lakes suppress clouds and precipitation, particularly in regions downwind of the lakes (e.g., Augustine et al. 1994, Scott and Huff 1996). However, operational weather forecasts for these regions must account for the rate of change of storm intensity across the lakes as well as situations where the storm evolution differs from climatology. Few published studies have examined how the lakes and their associated over-lake boundary layers affect pre-existing deep convective storms, particularly in the warm season where the water surface is predominately cooler than the surrounding land. This study seeks to examine these interactions through examination of convective storms crossing over Lake Erie during 2001-2009.

Appropriate events (pre-existing convective storms that advected from land to over Lake Erie) were identified by a three-step process: 1) surface observations were used to identify dates when significant rain occurred, 2) composite radar reflectivity imagery was used to remove events where the observed precipitation was clearly not associated with convective storms moving over Lake Erie, and 3) more detailed analyses of WSR-88D Level II data were conducted to identify which of the remaining events were appropriate for this study. This process identified 111 events during 2001-2009. Environmental conditions and storm evolution of these events were examined using observations from Weather Surveillance Radar – 1988 Doppler (WSR-88D), surface, buoy, and rawinsonde sites.

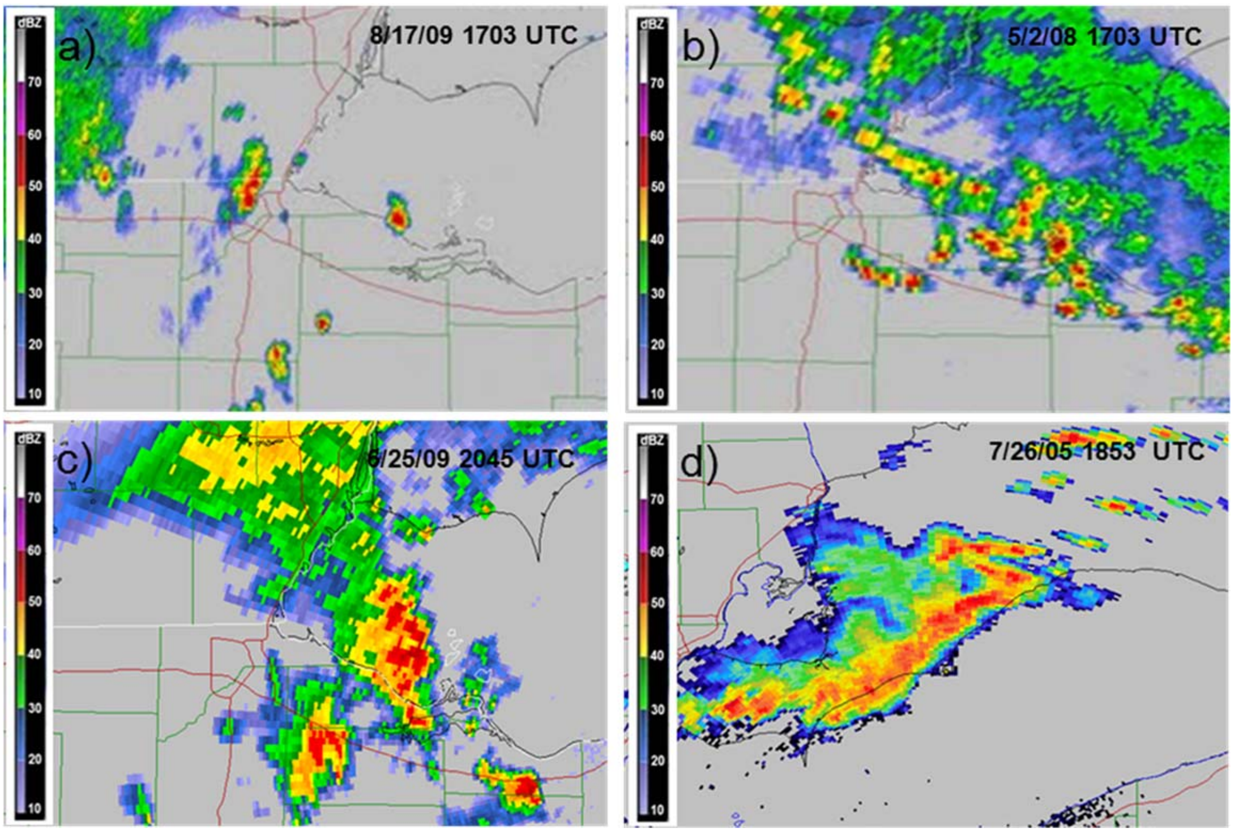

Figure 1. Base reflectivity images from the Cleveland, OH WSR-88D radar showing examples of (a) isolated, (b) cluster (c) complex and (d) linear storm modes used in this study. From Workoff et al. (2012).

Storms during each event were classified by mode to investigate its role in convective evolution over the lake. Each of the 111 events were classified into one of four convective modes (linear, isolated, multicellular, and non-linear mesoscale convective complex, Figure 1), based on their appearance before moving over Lake Erie. Radar reflectivity changes were used as an indication of storm intensity variations. The maximum base reflectivity, recorded to the nearest whole decibel, at the 0.5^{o} elevation angle was determined from KCLE Level II data for each volume scan (approximate time interval of 5 minutes). Maximum reflectivity was recorded from 30 minutes before (-30 mins) the time the storm moved over the water (TMOW) to at least 60 minutes following the TMOW (+60 min), or until the storm arrived at the downwind shoreline. A series of atmospheric parameters describing surface conditions over land and over the lake, wind speeds above the surface, and atmospheric stability were obtained to describe the environment in which the storms evolved.

Several aspects of storm evolution after interacting with Lake Erie were identified by these analyses. The largest frequency (76%) of storms moving over Lake Erie occurred in the months of May-August, with the maximum in July (Figure 2). Isolated, complex and linear storms showed similar

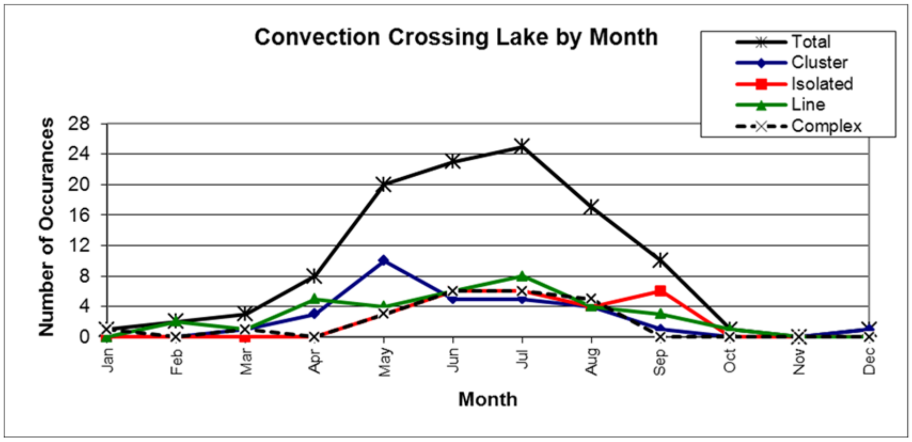

Figure 2. Number of occurrences (111 total) of each storm mode by month.

monthly trends while cluster storms exhibited a peak in May. As expected, storms were more frequent during the afternoon and evening hours (Figure 3) with differences in timing between modes. Cluster and isolated storms had a relative maximum during the late afternoon and evening (1400-2200 LST), indicative of the importance of surface buoyancy to their development. Linear storms showed a broad maximum during the late morning to late evening (1000-0200 LST) and minimum near sunrise (0600-1000 LST). The relative maximum for complex storms occurred during the overnight (2200-0200 LST) and morning (0600-1000 LST) hours, similar to the pattern of initial convective development observed by Ashley et al. (2003). This is consistent with the findings of Graham et al. (2004) and Parker (2008) that MCS events can maintain their evolution over shallow stable layers.

The evolution of storm intensity, estimated by changes in the maximum base reflectivity, were examined as a function of time over Lake Erie and storm mode. Regardless of storm mode, increases of ≥3 dBZ were rare (5% of events) and no storms exhibited major strengthening (≥8 dBZ). At +30 min, the majority of storms experienced no change in intensity (-2/+2 dBZ), with smaller percentages of all storms experiencing moderate weakening (-3/-7 dBZ) and significant weakening (≤-8 dBZ). This was consistent for all storm modes. On average, maximum base reflectivity only changed by -1 to -2 dBZ from the time the storm crossed the upwind shore. In contrast, excluding storms that moved onshore, by +60 min only about a third of all storms experienced no change in reflectivity and 28% of the storms experienced major weakening. Average reflectivity changes ranged from -2 to -9 dBZ at +60 min from TMOW.

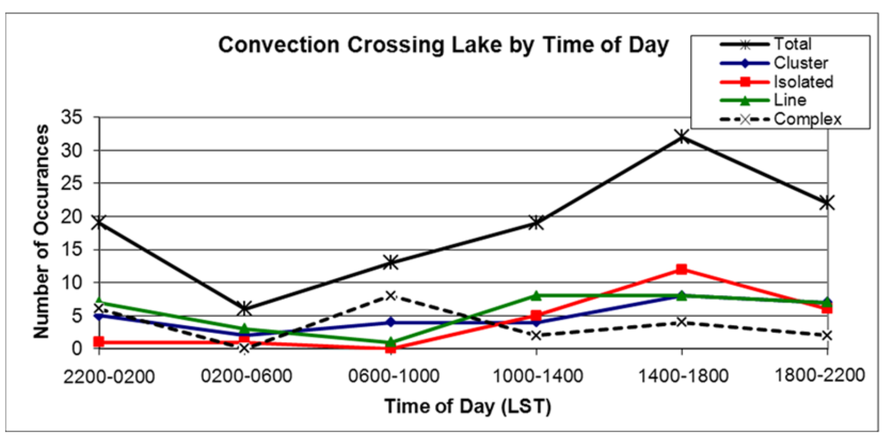

Figure 3. Number of occurrences (111 total) of each storm mode by time of day (using the time the convection moved over the water, TMOW). Time of day shown in local standard time (LST=UTC – 4/5 hr).

Differences in storm evolution over Lake Erie were noted between storm modes at +60 min. Linear and complex storms tended to weaken less than isolated and cluster storms (Figure 4). For example, average reflectivity changes were only -2 to -3 dBZ for linear and complex storms, while

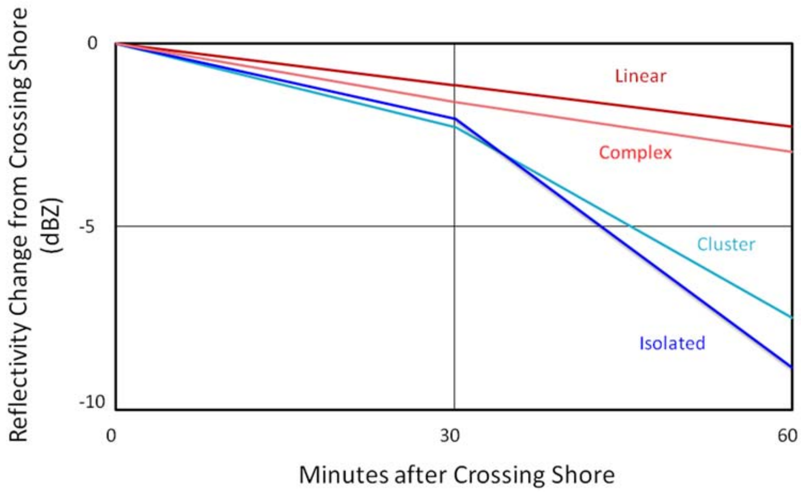

Figure 4. Average changes in maximum base reflectivity as function of time after crossing the Lake Erie upwind coastline. From Workoff et al. (2011).

for isolated and cluster storms the average reflectivity changes were about -7 to -9 dBZ. Additionally, only 10-15% of linear and complex storms experienced major weakening at +60 mins, compared to 40% of isolated and cluster storms. Clearly, the level of organization of the convection before moving over Lake Erie plays an important role on the rate of storm weakening.

Limitations in observations available operationally limit our ability to determine the role of environmental conditions on storm evolution near the Great Lakes. The available environmental condition parameters exhibiting the greatest relationship with storm intensity changes, identified using stepwise linear multivariable regression (SLMR) analyses, were over-lake air temperature (LAT) for cluster and complex storms, horizontal temperature differences (LAT-UWT) for isolated storms and 3 km wind speed for linear storms. For unorganized cluster and isolated convective modes, over-lake temperature decreases led to statistically significant decreases in storm intensity. Interestingly, for mesoscale complexes, cooler over-lake temperatures were associated with decreased storm weakening over Lake Erie. “Flow charts” were developed to illustrate how different modes of convection behaved as functions of over-lake air temperatures and over-lake/lake temperature differences. See the paper in press for details.

2b. Case Study of Linear Convective System Moving over Lake Erie

A study of the 26 July 2005 quasi-linear convective system (called squall line hereafter) event was conducted to identify processes by which the squall line interacted with a cool MBL, as well as the effects on the convection caused by the movement from land to water. On this date, a squall line developed over eastern Michigan and propagated eastward over the relatively cool surface of Lake Erie (~5^{o}C cooler than the surrounding land).

The convection developed in the warm sector in an area of strong warm air advection (surface wind ~210^{o} at 5-8 m s^{-1}) and high surface-based instability (~2500-3000 J kg^{-1}, as determined from the 1800 UTC GFS40 model initialization). Comparison of regional sounding data suggests that the air being advected into the Lake Erie region during the afternoon was drier at the mid-levels and contained increased instability above the surface. VAD shear profiles determined from WSR-88D Level III data show ~21 m s^{-1} of 0-2.5 km U-wind shear at KDTX at 1700 UTC (time of convective initiation near Detroit) and ~19 m s^{-1} at KCLE at 1900 UTC (ahead of the convective precipitation at Cleveland). Surface air temperatures in northern Ohio and western Michigan were ~31-32^{o}C at 1700 UTC; data from buoys

45005 and 45132 on Lake Erie show the water temperature was ~26^{o}C. As a result, a cool mesoscale airmass formed over Lake Erie in response to the cooler water surface.

The southern end of the squall line was the first to reach Lake Erie at approximately 1830-1835 UTC. Figure 5 shows that at 1853 UTC, shortly after moving over the water, a small scale bow echo developed on the southern end. Examination of the SRV field revealed that the erect front-to-rear flow at the leading edge of the storm was no longer evident, suggesting that the updraft of the squall line had become tilted. The rear-inflow also strengthened to >20 m s^{-1} and became shallower within the squall line. As expected for storms with rearward-tilting updrafts, the storm weakened on the southern end which can be seen by the decrease in base reflectivity values (Figure 5c). Another bow echo and continued tilting and weakening of the storm continued after the northern end of the squall line moved over the Lake.

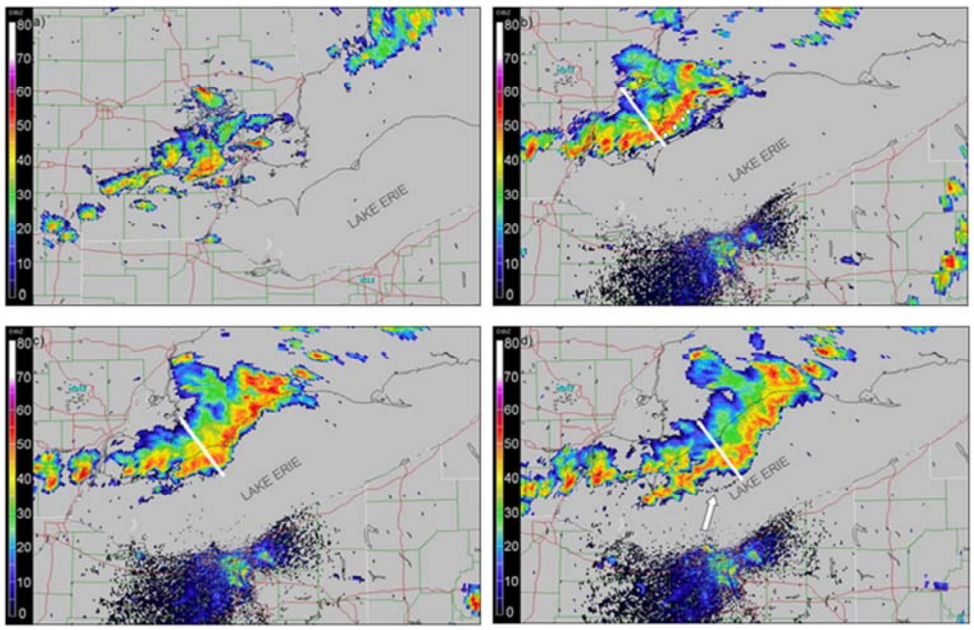

Figure 5.Plan view of radar reflectivity (a-d) from 26 July 2005. Base reflectivity from a) KDTX at 1717 UTC, b) KCLE at 1822 UTC, c) KCLE at 1853 UTC and d) KCLE at 1913 UTC. The white lines on panels (b), (c) and (d) highlight a bowing section of the squall line. White diamonds in panel b) show latitudes where average storm velocity and base reflectivity were measured. White arrow in panel d) denotes location of outflow boundary.

As the squall line moved out over Lake Erie there was an observed increase in average speed by both radars of ~5-7 m s^{-1} associated with the convection moving from land to water. This increase is consistent with the decreased friction associated with the water surface, also allowing the cold pool to accelerate forward when it moved out over the lake, which may explain the rapid tilting of the updraft. As a result of the tilting, the strength of the convection decreased over Lake Erie. While limited observations hampered our ability to understand all of the reasons for the observed storm evolution, it is apparent that the presence of the lake played an important role in altering the storm structure and intensity.

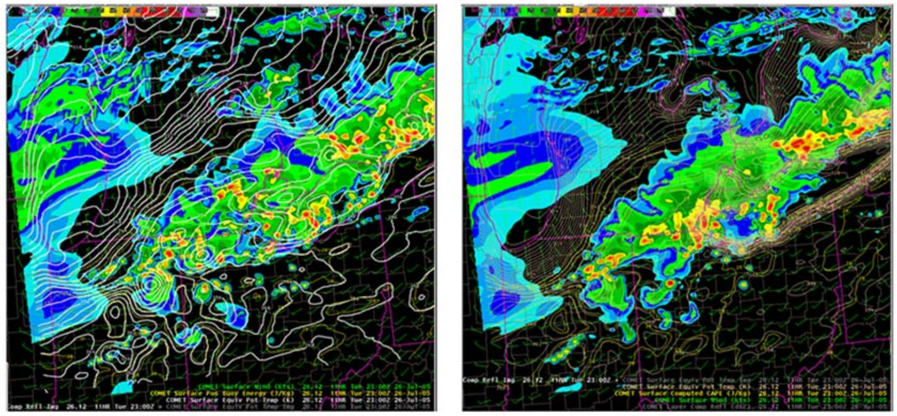

Figure 6) Plan view of WRF-generated radar reflectivity on 26 July 2005, 23 UTC. Lake surface temperatures were equal to those observed on this date (warm lake, left) and those observed on a fall case (cool lake, right).

The National Weather Service office in Cleveland simulated the 26 July 2006 case with the Workstation WRF model with the Great Lakes surface water temperature analysis available on that date and with a cooler water analysis from the early autumn of 2006. Conducting two simulations with different water temperatures were performed to explore what affect the variation in stability of the marine boundary layer may have had on convective evolution. Figure 6 compares plan views of WRF-simulated composite reflectivity and surface CAPE valid at 23 UTC on 26 July 2006 for the warmer and cooler lake scenarios. A linear convective band formed in both simulations and moved over the Lake Erie area. The time period shown is for about an hour after the time the convection first moved over the water (TMOW). Both convective lines exhibited a bowed segment ahead of the main line, reaching near the downwind shore. A large difference was the rapid development of convection along the downwind shore in the warmer-lake case, possibly due to the advection of lake-stabilized air over the eastern shore.

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

This project has provided forecasters with additional knowledge about anticipating convective evolution when storms cross the Great Lakes, with Lake Erie in particular. The observational study helped solve persistent questions about the interaction of convective storms and the Lake Erie boundary layer. The study helped explain why some storms weaken rapidly while crossing Lake Erie while other storms remain somewhat steady state, or exhibit slow weakening. The results of the observational study can be readily applied to operational short-term convective forecasting. Storm behavior while crossing Lake Erie is dependent, in part, on storm size, and the difference in temperature of the air over the lake and the air over the land near the lake. These characteristics are readily observable in an operational setting and assist the forecaster in anticipating storm evolution as storm approach and cross Lake Erie. Forecasters training aids and operational procedures are being developed to apply the concepts learned in the study.

Some lessons learned: The Numerical modeling aspects of this study were somewhat more difficult to conduct than earlier anticipated. Modifying the initial temperature of the Lake Erie surface temperature for the WRF model proved difficult. Consequently, archived surface water temperature for Lake Erie was substituted to simulate cooler surface water. Considerable effort was expended to select initial and boundary conditions for the WRF model that would allow the model to simulate convection similar to the observed conditions.

Section 4: Benefits and Lessons Learned: University Partner Perspective

This Partners Project provided our research group with the opportunity to expand research carried out under a separate grant from the National Science Foundation, to include a more explicit examination of operational perspectives on storms crossing the Great Lakes. Experience gained by the National Weather Service Cleveland office was readily shared with the PI and students, which provided a much more complete perspective of the importance and complexity of these storms. More specifically, we gained an appreciation for the importance of mesoscale convective structure on the evolution of storms as they cross the Great Lakes as well as the potential role on lake-air temperature differences on squall line evolution.

This research raised many questions that should be examined in future projects. Such questions include the following: Does the structure of large storms "shield" interior convective structures from the influence of stable over-water air? Does instability over the downwind shore enhance convective squall lines when the air just above the lake surface is very stable? What is the importance of lake surface smoothness as well as interactions between the storm cold pool and the over-lake boundary layer air? It is our hope that such questions can be explored by continued collaboration both between the University of Illinois and the NWS Cleveland office, but also by other similar types of collaborations.

Section 5: Publications and Presentations

Publications and presentations with partial support from COMET:

Workoff, T. E., D.A.R. Kristovich, N. F. Laird, R. LaPlante, and D. Leins, 2012: A climatological analysis of deep convective interaction with the Lake Erie marine boundary layer. *Wea. Forecasting*. In press.

Workoff, T., D.A.R. Kristovich, N. Laird, R. LaPlante, and D. Leins, 2011: *Thunderstorm Encounters with Lake Erie*. National Weather Service Forecast Office, Cleveland, OH. 24 June. In attendance were staff from WFO Cleveland and adjacent CWSU aviation facility.

Workoff, T. E., D. A. R. Kristovich, N. F. Laird, R. LaPlante, and D. Leins, 2011: A climatological analysis of deep convection interactions with the Lake Erie marine boundary layer. *24th Conf. Weather and Forecasting*, American Meteorological Society, Seattle. Oral presentation only.

Workoff, T., 2010: *A Study of the Effect of Lake Erie on Deep Convective Systems*. M. S. Thesis, Department of Atmospheric Sciences, University of Illinois. 87 pp.

Workoff, T.E., and D.A.R. Kristovich, 2009: A Study of the Effect of Lake Erie on a Severe Squall Line. *Conf. Mesoscale Processes*. Amer. Meteor. Soc. Oral presentation only.

Section 6: Summary of University/Operational Partner Interactions and Roles

Staff at both the University of Illinois and the National Weather Service office in Cleveland participated in all aspects of this research. However, it was expedient for each group to lead different aspects. The University of Illinois led the observational case study and climatologic analyses. These were carried out primarily by Graduate Research Assistant Thomas Workoff, supervised by David Kristovich. The National Weather Service office in Cleveland led the numerical modeling aspects of the research effort. Daniel Leins was primarily responsible for conducting the simulations, with supervision by Robert LaPlante. Collaborations were carried out through phone calls and electronic communications. David Kristovich visited the NWS office in June 2011 to discuss results.