COMET Partner's Grant Final Report

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Partners or Cooperative Project: *The Effect of the Great Lakes on the Maintenance of Mesoscale Convective Systems*

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I. PROJECT OBJECTIVES AND ACCOMPLISHMENTS

Overall, the aim of this research paper is the development of a short-term climatology through the identification of MCS events that have impacted southern lower Michigan, including the Grand Rapids, MI county warning area (CWA), over the past seven years. Once events are identified, radar, satellite, surface (including buoy and lighthouse observations), and lake surface temperature data are examined in order to yield insights into environmental conditions affecting the evolution of the MCS passing over Lake Michigan. Finally, conceptual models and forecast methodologies are developed to help anticipate MCS morphology as they approach and interact with a Great Lake.

A. Case Identification and stratification

Sixty-one MCS events that occurred over the Grand Rapids CWA since 1996 were originally identified for potential inclusion into the study. Some events were removed from the study in that they did not meet the severe weather criteria outlined later in the report while others were dropped because detailed data sets were unavailable. Of the identified events, 37 have been analyzed by examining radar, satellite, surface and lake surface temperature data. A variety of climatological information including the initiation time and location, centroid track, trend as the MCS crossed Lake Michigan, symmetry, and nature of the MCS has been catalogued.

1. MCS initiation times and seasonal frequencies

This analysis is conducted in order to delineate temporal consistencies in MCS evolution due to changing lake surface temperatures (LST). Evidence suggests that the temperature difference between the buoy air temperature and water temperature plays a major role in determining sustaining versus dissipating severe MCSs that cross over Lake Michigan. A much higher thermal gradient was evident in events that sustained over the Lake and is indicative of a stable marine boundary layer (MBL) that becomes decoupled and allows convection to become elevated and ingest elevated unstable air. Surface-based MCSs that encountered a stable MBL sustained over the Lake, and most surface-based MCSs that encountered a well-mixed MBL dissipated or weakened. However, events in the late summer season encounter Lake waters in excess of 70°F and were more likely to sustain, even if they were surface-based.

Seasonally, Great Lakes MCSs are most likely to occur during the months of June through August and are characterized as “weak forcing” MCSs. “Dynamic” MCSs typically occur during the spring season, specifically April and May, and during the fall season. Interestingly, nearly all of the dynamic events were sustained over the Lake, whereas only 61% (11 of 18) of the weak forcing events maintained their strength. This is not too surprising of a result, as the MBL is more likely to be stable and decoupled in the early spring months at a time when dynamic events are most likely to occur. In fact, the average temperature gradient within the MBL during dynamic events is 6.8ºF. This means that the vertical temperature profile just above the Lake surface is characterized by increasing temperatures with height, a condition of thermal stabilization.

2. Synoptic analyses and pattern grouping

Delineation of synoptic pattern types is essential in aiding GRR forecasters who make short-term convective forecasting decisions. The ability to recognize patterns conducive to Great Lakes MCS initiation is a first step in assessing the risk of severe weather downstream of the lake. Pattern types of 37 Great Lakes MCSs were investigated to depict commonalities among events characterized by pattern type and large-scale forcing features. Overall examination revealed consistencies that grouped the MCSs into eight pattern types.

<u>Deep SW Flow</u> (7 Events)

Moderate to strong mid-level flow characterizes events are common with this type of pattern, which is most likely to occur during the early spring or fall months. Generally, patterns are in the form of a high amplitude longwave trough with its axis close to the western Great Lakes region and digging deep into the central U.S. (Figure 1). Most of the troughs are negatively tilted. This is coupled with an adjacent high amplitude downstream ridge over the eastern Great Lakes region, which promotes a more southwesterly and locally diffluent flow just west of Lake Michigan. Most events initiate within the left exit region of strong mid-level speed maxes that are rounding the base of the trough. In general, strong flow and better large-scale forcing characterize these events. The mid levels were very moist as a result of the strong southerly component of the flow. Strong upper-level ridging is present over southern Canada, many with speed maxes rounding the apex of the ridge resulting in right entrance region divergence and contributing to jet coupling over the western Great Lakes. The low-level response is that of a strong low-level jet with its axis over mid-Mississippi River Valley nosing northward into southeastern WI and Lake Michigan. This is more meridionally oriented and slightly stronger than SW flow pattern LLJ characteristics. The convective systems are more likely serial in nature and occur within the warm sector along a strong undercutting cold front associated with deep mid-latitude cyclones that are centered over western Minnesota (Figure 2).

<u>SW Flow</u> (5 Events)

There is a propensity toward positively tilted longwave troughs inherent within this pattern. The trough axes are displaced much further west into the inter-mountain region promoting broad diffluence over the northern Plains and Great Lakes. Ridging downstream of the trough is further east and weaker to non-existent (Figure 3). Main forcing is induced by shortwaves/speed maxes (particularly at 500 and 700mb) embedded within the broad southwesterly flow over the northern Plains and upper Midwest. Forcing for upward ascent in the upper levels is generally generated by upper right entrance jet region divergence (as opposed to jet exit divergence with Deep SW Flow events). The LLJ is SW/NE oriented over IL/MO with parcel trajectories originating from a warm sector that is warmer and moister than for Deep SW Flow events. Forcing for initiation and maintenance is very dependent on low-level convergence on the terminus of the LLJ than large-scale forcing. 500mb air is less moist than Deep SW Flow events, with dewpoint depressions mostly between 10-20 C. A surface low pressure is more likely to be centered back in the central and northern Plains with a warm front extending eastward into the Great Lakes region and over Lake Michigan. MCSs propagate along and north of the front and traverse Lake Michigan (Figure 4).

Northern Plains Trough (6 Events)

These events occur within weak to moderate mid-level flow scenarios. A speed max typically rounds the base of a neutral Northern Plains trough that triggers a negative tilt and deepening of the mid-level low. This increases low-level frontal convergence and midlevel cooling contributing to enhanced instability. Mid and upper tropospheric westerlies have migrated well into Canada and the northern tier U.S. (Figure 5). Most events exhibited diffluent mid-level flow at the base of a Northern Plains trough with a speed max exiting on the eastern flank. This promotes right entrance region divergence and upward motion over the western Great Lakes region. Large-scale LLJ development is far north of the initiation region and not a factor in Lake Michigan MCS development (Figure 6). Very moist conditions characterize the mid levels. 500mb specific humidity composite suggests a connection with the late-summer Southwest U.S.

monsoon moisture plume, as a band of moisture streams around the periphery of the a southwest U.S. subtropical ridge into the initiation region just west of Lake Michigan.

<u>Ridge Riders</u> (7 Events)

Shortwave toughs within weak mid-level flow eject out of the mountain West and propagate along the northern periphery of a large subtropical ridge centered over southern Oklahoma and northeast Texas (Figure 7). As the shortwave and associated speed max shifts out into the northern Plains/Upper Midwest, the exit region exposes a good deal of the MN and WI regions to upper divergence and upward ascent. Forcing is typically best well west of Lake Michigan. In the upper levels, a Dominant subtropical ridge persists over central/southern U.S. with mid-level shortwave propagating along its northern fringe. Many of the events exhibit secondary shortwave ridging over the eastern Great Lakes and southern Canadian regions. Upper level speed maxes rotating around the top of the secondary ridge combine with speed maxes approaching the secondary ridging, contributing to enhanced vertical motion through jet streak coupling over the western Great Lakes region. The low-level response is that of a LLJ that is situated west of Lake Michigan, with its terminus over central/western Wisconsin. This LLJ position is further west than most other patterns. Initiation of the MCS occurs north of a surface quasi-stationary front extending from low pressure in the northern/central Plains (Figure 8). MCSs sustain along and north of the surface boundary and encounter the lake later in their life cycles. Thus, they have eluded optimal forcing and are much more vulnerable to lake processes in their evolution.

<u>Wv in Zonal</u> (3 Events)

This pattern is similar to the ridge riders in that strong ridging persists over the south/central U.S.; commonly centered over lower Mississippi River valley (Figure 9). The subtropical ridge is less expansive for this pattern type than for other warm-season, weak flow situations, but equally intense. A mid-level cold-core closed low exists near Vancouver, B.C., Canada with slight downstream ridging over the northern mountainous region. Largely zonal flow exists over the northern tier U.S. with vigorous shortwave troughs progressing along into the Great lakes region promoting locally enhanced mid-level diffluence and speed divergence over the initiation region in northern/central Minnesota and Wisconsin. A LLJ develops in response to the upper disturbance helping to focus convection over Lake Michigan. At the surface, weak low pressure develops in over northern Wisconsin with an attendant cold front. Initiation of convection occurs along the cold front, while convergence is enhanced by the LLJ wind field within the warm sector (Figure 10).

<u>Weak NW Flow</u> (2 Events)

Anticyclonic curvature around large central U.S. ridge promotes NW mid and upper level flow over the northern tier and Great Lakes regions. Characterized by dominant subtropical ridge centered over the central Plains, which is further north than other weak flow scenarios (Figure 11). In addition, strong ridging extends northwestward into B.C., Canada enhancing the meridional component of the upper flow. Weak speed maxes (~35-45kt) propagate around the ridge and dive southeastward toward the Great Lakes region. Forcing for large-scale ascent manifests itself within the exit region over the western Great Lakes region. Ridging extends northwestward into western Canada. Thermal fields (at 925-700mb) are characterized by max temperatures over the central Plains and central intermountain West, with thermal ridging into the upper Midwest. This low-tropospheric warmth is advected northward into the initiation region under cooling 500mb air to contribute to extreme instability. Generally weak surface low pressure over southern Manitoba and Ontario, Canada moves eastward transporting cold air southward into the Great Lakes region. Deep convergence and lift occurs along the cold front dropping into very moist and unstable air just west of Lake Michigan in the late afternoon and evening hours (Figure 12).

Zonal (3 Events)

Zonal flow with very little meridional component characterized by the presence of 65-70kt speed maximums at the base of progressive neutral to positively tilted shortwaves within the flow describes this pattern (Figure 13). MCS development occurs at or near Lake Michigan within the left exit region forcing in the vicinity of a weak east/west oriented surface frontal boundary (Figure 14). Upper divergence induces a strong LLJ, which noses out favorably over southern Lake Michigan with its axis extending back into central MO. 40-50kt flow characterizes the strength of the LLJ, which is a primary source of buoyant return flow on the back side of Southeastern U.S. ridging. This sloped buoyant flow results in rapid elevated destabilization and nocturnal convective initiation along and north of the boundary.

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Two mid-level longwave trough features exist within this pattern that contribute to large-scale forcing for ascent over the upper Midwest and Great Lakes region (Figure 15). A large west coast cold-core low established off the coast of California ejects smaller-scale southern stream shortwaves and speed maxes northeastward toward the northern tier U.S. In south/central Canada, shortwaves rotate around a positively tiled trough. Upper air composites reveal strong jet streak coupling, particularly at 300mb near the juxtaposition of southern and northern stream jet streak divergence regions near MCS initiation times. A strong LLJ oriented perpendicular to an east/west oriented surface frontal boundary that bisects the upper Midwest and lower Lake Michigan transports ample unstable air into the pre-convective environment over southern Minnesota and Wisconsin (Figure 16). Surface low pressure is present over the northern Plains, and MCS initiation occurs just to the northeast of the low's center.

3. Climatology Information

Thirty-seven events are included in the MCS climatology at this point. MCS events for this research were defined utilizing the AMS Glossary definition: "*A cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area on the order of order 100 km or more in horizontal scale in at least one direction.*" Since the focus for the research was on

MCSs that produce severe weather for an event to be included in the sample the MCS had to generate at least five severe weather reports upstream of Lake Michigan (typically this would be in eastern Wisconsin). Once the events were identified they were stratified by whether they maintained their intensity as they crossed Lake Michigan or weakened/dissipated as they crossed the lake. Additional parameters that were tracked included the location of MCS formation (and three hourly tracks of the centroid of the MCS), time that the MCS crossed the lake, duration that the MCS spent over Lake Michigan, whether the MCS was progressive or serial in nature, and whether the echo structure was symmetric or asymmetric.

If an MCS maintained it's reflectivity structure and produced a similar number of severe weather reports upstream and downstream of Lake Michigan it was put in the "Maintained" category. However, if the MCS completely dissipated over the lake or the reflectivity structure weakened and the MCS produced substantially fewer severe weather reports downstream of the lake (at least a 50% reduction in reports) then the MCS was grouped into the weakened/dissipated category. Of the thirty-seven MCSs included in the climatology twenty-five maintained their intensity as they crossed Lake Michigan while twelve weakened or dissipated. It was found that events were more likely to dissipate or weaken over the lake in the summer months than they were in the spring or the fall. A total of twenty-one events in the study occurred in June, July, or August. Ten of the twenty-one events (~48%) that occurred in these months weakened or dissipated. In fact, ten of the twelve (83%) events that weakened or dissipated over the lake occurred in the months of June, July or August (Figure 17). Conversely, of the sixteen events that occurred in the spring or fall (March through May and September through November, respectively) only two (12.5%) weakened or dissipated.

MCS events were also divided by echo structure based on the Johns and Hirt (1987) classification of derecho events into 'progressive' and 'serial' types. Of the thirty-seven events in the climatology twenty-five were 'progressive' in nature while twelve were 'serial' in nature. Progressive events were more likely to weaken or dissipate as they crossed Lake Michigan. For comparison, 36% (9 of 25) of the 'progressive' MCSs weakened or dissipated while only 25% (3 of 12) of the 'serial' MCSs weakened or dissipated. Progressive events were most likely to occur during the late spring and summer months with 22 of the 25 events occurring during the May through August (inclusive) time frame. Serial events on the other hand were more likely to occur in the Spring or Fall with 7 of the 12 occurring in the April-May time frame or the September to November time frame (Figure 18). Several concepts can be gleaned from the statistics. The progressive events tend to occur in more weakly forced warm season environments and may be more likely to dissipate as they cross Lake Michigan due to lesser forcing and also due to the weaker stable layer that is in place over Lake Michigan in the summer months when the lake-land contrast is not as great. Conversely, serial events tend to be more strongly forced as they are typically associated with stronger upper level features in the spring and fall. Also, the serial systems which occur in the spring months are more likely to encounter a very stable marine layer (i.e., with cold water temperatures and warm air aloft) which allows them to become elevated and, therefore, not ingest the stable air from the marine environment. In the fall, the serial events are more likely to cross the lake when the relatively warm waters of Lake Michigan may act to further destabilize the air over the lake.

Additional parameters that were looked at include the time at which the MCSs moved across Lake Michigan as well their residence time over the lake. The majority of the MCSs moved over Lake Michigan between 1900 UTC and 0300 UTC with twenty-five (~68%) of the events reaching Lake Michigan during this time frame (Figure 19). There is a strong minima in MCS occurrence between 1200 UTC and 1800 UTC with only two of the thirty-seven (~5%) events moving onto Lake Michigan during this time frame. MCSs were slightly more likely to weaken or dissipate if they moved over the lake overnight (between 0600 UTC and 1200 UTC) with five of seven (~71%) such occurrences weakening or dissipating. In contrast, only six of the twenty-five events (24%) that moved onto the lake during the occurrence maximum between 1900 UTC and 0300 UTC weakened or dissipated. A partial explanation for this is certainly that some of the MCSs that were moving onto the lake during the overnight hours were simply at the end of their life cycle. The vast majority of the MCSs that crossed Lake Michigan were over the lake for less than three hours with twenty-six of thirty-seven events (~70%) moving across the lake in under three hours. There were identifiable trends with respect to residence time over the lake and the proclivity for an MCS to maintain its intensity or to weaken/dissipate.

B. Surface, radar, and MBL analysis

Evidence obtained from this analysis has yielded insights into MCS radar echo morphologies and elementary hypotheses into the environmental conditions surrounding the events as they cross Lake Michigan.

1. Surface, radar, and MBL analysis

Nighttime (0Z – 12Z) events were more likely to dissipate than daytime events. This is likely due to the fact that nighttime MBL conditions are more likely to be unstable and well mixed than stable and decoupled, resulting in convection that remains surface-based. This illustrates the importance of diurnal radiative processes in creating a vertical thermal profile that is favorable for convection.

Nearly all events considered in this study that were dynamically induced sustained as they crossed the Lake. The reason for this is two-fold: 1) Convection that is dependent upon larger-scale processes is less dependent on mesoscale processes such as those which occur over the Lake during the maintenance of severe MCSs. 2) During the early spring season when dynamic events are most likely to occur, the MBL is more likely to be stable and decoupled from the low-levels.

Many of the severe MCSs that sustained over the Lake also showed signs of strengthening due to processes related to the Lake. Enhancement due to cell merging between the main convective line and Lake-induced eastern shoreline convection characterized many of the events. Convection formed over the Lake downstream of the main convective line in many events as a result of: 1) Frictional convergence along the eastern coastline as a consequence of increased friction to the flow as it encounters land. Enhanced convergence of this type results in development parallel to the eastern coast or slightly inland. 2) Acceleration of inflow resulting in enhanced convergence over the lower-friction Lake and/or increased convergence along an accelerated gust front. This convergence leads to development that is well off shore and out over the Lake.

Three of the MCSs experienced enhanced RIJs as they met the eastern shoreline as a consequence of strengthened mid-level buoyancy gradients. The strengthened buoyancy gradient resulted from: 1) Enhanced positive buoyancy in the FTR flow due to cell merging; and/or 2) Ingested cooler, lower buoyancy air from over the Lake into the rear of the MCS. The enhanced RIJ led to very strong winds at the surface just downwind of the Lake, and even induced tornadic bookend vortices in two of the cases.

Thermal boundaries that extended across Lake Michigan were enhanced by the thermal gradient evident over the Lake, particularly in the spring season, and played a major role in intensifying convection as it traversed the Lake. Increased baroclinicity along the enhanced boundary lead to the development of meso-low pressure centers close to the eastern shore during two of the MCSs. This intensified convection by creating a more favorable region of thermal and moisture advection just inland of the eastern shore in response to enhanced southerly flow. Also, slightly backing winds into the meso-low pressure created an improved environmental shear profile crucial for MCS maintenance. Furthermore, a nontornadic supercell within one an MCS approaching the western shore of Lake Michigan became tornadic along the shoreline. Evidence suggests this was a result of horizontal streamwise vorticity, baroclinically produced within a strong Lake-induced thermal boundary being ingested into a supercell and subsequently vertically tilted in the rear-flank downdraft, and stretched by the updraft.

2. Sounding parameter analysis

For each of the events observed sounding data was collected for fifteen upper sites stretching from North Platte, NE to Buffalo, NY (Figure 20). Sounding information was collected for the three sounding cycles enveloping the occurrence of the MCS. Typically, this would consist of 1200 UTC soundings the morning of the event, 0000 UTC soundings from the evening of the event, and 1200 UTC soundings the morning following the event. Twenty-two parameters were recorded at each sounding site for each sounding cycle. Some of the parameters included Most Unstable CAPE (MUCAPE), Lifted Index, Convective Inhibition (CINH), Level of Free Convection (LFC), Equilibrium Level (EQL), Precipitable Water values (PW), 0-6km Shear values, and 0-3km Storm Relative Helicity. After the data was collected the events were separated into the eight Composite Pattern Types that had been identified as part of this study. Arcview was then utilized to complete objective analyses on the data for each pattern type. To this point the analyses have only been completed for the 0000 UTC cycle on the evening of MCS occurrence. A summary of some of the significant findings follows.

Deep SW Flow –

These cases exhibited the lowest MUCAPE values on average of all of the pattern types in the study. This is to be expected as these are typically spring and fall events that tend to be more strongly forced. Typically, the highest MUCAPE values are found in the Ohio Valley region where values on average are 1000-2000 J/kg (Figure 21). A sharp gradient in MUCAPE exists in these events with values dropping to 300-750 J/kg across lower Michigan. Convective Inhibition is limited in Deep Southwest Flow events with values zero to -20 J/kg from the Dakotas south through Kansas decreasing to -50 to -100 J/kg across lower Michigan. Equilibrium Heights are low in these events, typically in the 20,000 to 30,000 feet agl range. This is fitting in that these cases tend to be serial MCSs consisting of low topped convection. Max Theta-E differences, which are a measure of downdraft potential, in the profiles are in the 15 to 20 degree Kelvin range which is comparatively low when looking at some of the other pattern types. Meanwhile, the 0-6 km Mean Wind Speed is in the 30-40 knot range across the lower Great Lakes with a 40+ knot 850 mb jet across the Ohio Valley.

SW Flow -

Southwest flow cases have a corridor of MUCAPE values between 2000-3000 J/kg stretching from Kansas into southwest Wisconsin (Figure 22). There is a relatively sharp MUCAPE gradient to the north of this region and into the central Great Lakes region where MUCAPEs drop off to the 500-1000 J/kg range.

Equilibrium levels are higher in Southwest Flow cases than in the Deep Southwest Flow cases with EQLs typically in the 30,000-35,000 foot range. Mid level lapse rates are also higher with 700-500 mb Lapse Rates generally in the 6.5-7 C/km range across the Great Lakes. Again the Theta-E difference values are not as high as some of the other pattern types with values of 15-20 stretching from the Northern Plains into the Ohio Valley. A tongue of higher precipitable water values around 1" runs from the Tennessee Valley north into Michigan and Wisconsin. While these PW values are higher than in the Deep Southwest Flow cases they are lower than those exhibited in several of the other pattern types.

Northern Plains Trough –

Northern Plains Trough events exhibit a ridge of high MUCAPE values, approximately 2000-3000 J/kg, extending from Kansas across southern Iowa and into Illinois (Figure 23). To the north of this region MUCAPE there is a gradient in the MUCAPE field as values drop to around 1000 J/kg across northern Minnesota and Wisconsin. The sharpest gradient in the MUCAPE values would be from central Illinois (2000 J/kg) in to lower Michigan (<1000 J/kg). It is in this gradient (and on the Wisconsin side of the lake) where the MCS event sin this pattern type tend to develop. These cases have lower CINH amounts -50 to -100 J/kg in place from northern Minnesota into lower Michigan. Theta-E difference values are not particularly impressive with values of 15 to 20 from the Northern Plains through the Ohio Valley. An area of higher Theta-E differences (20 to 25) stretched from eastern Kansas and all of Missouri into extreme southern Wisconsin. Precipitable Water values were rather high in these events with 1-1.5" values stretching from Kansas to Wisconsin and covering all areas to the east of this line (Figure 24). The core of highest Precipitable Water vales (1.25 to 1.5") covered the Ohio Valley and stretched north into eastern Wisconsin and lower Michigan.

Ridge Riders –

Ridge Riders events exhibited a core of high MUCAPE values in the 2500-3500 J/kg range from Kansas and Missouri into northern Iowa and southwest Wisconsin (Figure 25) Similar to the Northern Plains Trough events there was an MUCAPE gradient across lower Michigan. MUCAPE values of 2000 J/kg across western Lake Michigan decreased to 400 J/kg across north lower Michigan and around 800 J/kg across southeast Michigan. These cases exhibited high 700-500 mb Lapse rates with values generally in the 6.5 to 7.0 C/km range from the Northern Plains into the Ohio Valley. Ridge Rider events also exhibited a considerable potential for dry mid level air. Maximum Theta-E difference values (Figure 26) were in the 25 to 30 range from Kansasto southern Minnesota and east into southern lower Michigan and eastern Ohio.

Wv in Zonal –

These events tend to exhibit a great deal of instability across the Central Plains and western Great Lakes region while maintaining moderate 0-6 km wind speeds. An axis of 2000-3000 J/kg MUCAPEs stretches from near Topeka, KS to Green Bay, WI (Figure 27). There is an east-west gradient in place across lower Michigan with approximately 2000 J/kg of MUCAPE over eastern Wisconsin decreasing to ~850 J/kg MUCAPE in southeast lower Michigan. Convective

Inhibition (CINH) in these events tends to be weak generally in the -25 to -50 J/kg range across the domain. Given the large degree of instability and the low CINH values it would appear that strong forcing is not required to initiate and maintain MCSs in these environments. A corridor of high Equilibrium Heights extends from eastern Kansas into eastern Wisconsin with EQL values of 40,000-45,000 feet (Figure 28). Also, an area of Theta-E difference values of 25-30 stretches from the Central Plains to Michigan's Upper Peninsula. This may be an indication that there is drier air in the mid levels available for the maintenance of strong downdrafts in this pattern type. This pattern type also exhibits very high PW values with a tongue of 1.5" precipitable water values stretching from the Central Plains into the Upper Peninsula.

Weak NW Flow -

A core of very unstable air extends from eastern Kansas in western Illinois. MUCAPE values in this area are in the 4000-5000 J/kg range with a sharp gradient in the MUCAPE values north of the area. Equilibrium Levels are relatively high in the 30,000 to 37,000 foot range from the eastern Dakotas into lower Michigan with values in excess of 40,000 feet to the south of this area. One parameter that truly stands out in the Weak Northwest Flow events is the maximum Theta-E differences. Values of 25 to 40 run from the Minneapolis and Green Bay southwest through Kansas (Figure 29). This is an indication that there is likely a wedge of dry air in the mid levels in these cases. The 0-6 km Mean Wind Speed is a little lower in these cases than in most of the others with mean wind values of 20 to 30 knots across much of the domain and 30-35 knots from northern Minnesota into Ohio.

Zonal

In the Zonal events there was an MUCAPE gradient that ran from Eastern South Dakota into eastern Ohio (Figure 30). Just on the north side of this gradient the MUCAPE values were typically in the 800-900 J/kg range while to the south values rose into the 2000-3000 J/kg range. MCSs in this pattern type tended to propagate along the MUCAPE gradient. Little inhibition is noted in these cases with the majority of the domain exhibiting CINH values of zero to -50 J/kg. As one would expect, given the orientation of the MUCAPE values, there is a north-south gradient in Equilibrium Values. From the northern plains into the central Great Lakes EQL is typically in the 25000-35000 foot range. While from Nebraska through north Ohio and to the south the EQL heights are in the 35000 to 40000 foot range. Maximum Theta-E differences were relatively low in these cases with values largely in the 15 to 20 range from Minnesota into the Ohio Valley (Figure 31). The 0-6 km Mean Wind Speed in these cases was a little higher than in most of the other pattern types with values of 30-40 knots across the domain.

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Strong MUCAPE gradient stretches from South Dakota into the Southern Great Lakes. Values from North Dakota to Michigan's Upper Peninsula range from 500-1500 j/kg while 2000-4000 j/kg CAPE values stretch from Nebraska east into the Ohio Valley (Figure 32). Equilibrium Heights were relatively high in these cases running 30,000-40,000 feet from the Northern Plains into the Great Lakes. These cases exhibited steep mid level lapse with 700-500mb Lapse Rates in excess of 7.5 C/km fom South Dakota into Indiana. Maximum Theta-E difference values were generally in the 20s across most of the domain. The 0-6km Mean Wind Speeds were rather high in these cases with values of 40-45 knots stretching from Minnesota into lower Michigan.

II. Outreach Program collaboration without COMET funding

Many constructive achievements resulted from the collaboration and research between the Grand Rapids WSFO and Northern Illinois University that were unanticipated by either participant. The realization of accomplishments beyond that which was outlined in the initial proposal illustrates the success of this partnership.

C. Work conducted by the University

Three presentations have been given on this research that were not originally in the proposal. One presentation was made at the Chicago NWS Office in early May 2003 while others were given at the AGU/EGU/EGS Joint Assembly in mid April 2003 and at the American Geophysical Union (AGU) Conference in San Francisco, CA in December 2003. Travel funding for the latter two presentations was awarded based upon the merits of the research by the American Geophysical Union (AGU).

D. Work conducted by the NWS

The contributing forecasting partners have given two presentations on this research at the NWS office in Grand Rapids, MI. Additionally, a presentation was given on 1 October 2003 at the Great Lakes Operational Meteorology Workshop in London, Ontario. The initial results of the research will presented to the National Weather Service staffs at the Marquette, Gaylord, Detroit, and Grand Rapids offices in early April 2004.

III. Summary of Benefits

E. *Academic Partner*

Numerous benefits have occurred based on this research. First and foremost, Jesse Sparks, successfully completed and defended his Master's Thesis based upon this research and obtained employment in forecasting convective storm development and radar interpretation of aviation hazards at the NWS's Aviation Weather Center. Additionally, insights into the role of the marine boundary layer in altering MCSs has been gained by the principal investigator and integrated into a mesoscale meteorology class. Finally, increased collaboration with meteorologists at the Grand Rapids NWS Office has yielded positive results not only in guaranteeing the success of this research project, but also in likely working on future research issues as well.

F. Forecasting Partner

There have been several benefits from the initial stages of this research. Initial research results have been utilized on several occasions to successfully ascertain the impact of Lake Michigan on existing convection. The early stages of the MCS Climatology have yielded insight on the expected frequency and evolution of MCSs during the spring and summer months. The initial work on this project has also resulted in increased awareness, discussion, and understanding of the role of the marine layer on convection. The forecast staff in Grand Rapids will benefit greatly from the knowledge gained as part of this research. Anticipation of severe MCS events will be improved and a more robust understanding of land-lake interactions will result from this research. Collaboration with NIU and SPC meteorologists has yielded additional insights on the behavior of MCSs over Lake Michigan that has been useful to forecasters at the Grand Rapids NWS office. The relationships built with researchers at both NIU and SPC has been very fruitful and may very well lead to additional collaborative research.

IV. Presentations and Publications

Sparks, J., 2003: The influence of the Great Lakes on the maintenance of severe mesoscale convective systems that traverse over them: An observational investigation M.S. Thesis, Northern Illinois University, 123 pp.

Sparks, J., Bentley, M. L., and R. Graham, 2003: The role of the Great Lakes on Mesoscale Convective Systems that pass over them. Presentation, Chicago National Weather Service Forecast Office, May 4.

Bentley, M. L., Sparks, J., and R. Graham, 2003: The Effect of the United States Great Lakes on the Maintenance of Mesoscale Convective Systems. Poster Presentation, AGU/EGU/EGS Joint Assembly, Nice, France, April.

Bentley, M. L., Sparks, J., and R. Graham, 2003: The Effect of the United States Great Lakes on the Maintenance of Mesoscale Convective Systems. Poster Presentation, AGU Conference, San Francisco, CA, December.

Graham, R., and Dukesherer, R., 2003: Climatology of Mesoscale Convective Systems Traversing Lake Michigan. Seminar Presentation, Grand Rapids National Weather Service Forecast Office, May 5.

Graham, R., Dukesherer, R, Sparks, J., and Bentley, M. L., 2003: Climatology of Mesoscale Convective Systems Traversing Lake Michigan. Presentation, Great Lakes Operational Meteorology Workshop, London, Ontario, October 1.

V. Summary of Problems Encountered

A. Academic Partner

Problems were encountered that involved the acquisition of data and data viewing capabilities. This resulted in analyses that included only a subset of the cases.

B. Forecasting Partner

The only problems encountered have been related to data set acquisition for several cases. Several alternative data sets were identified which allowed several additional cases to be included in the study. However, for other events no resolution has been reached as of this time.

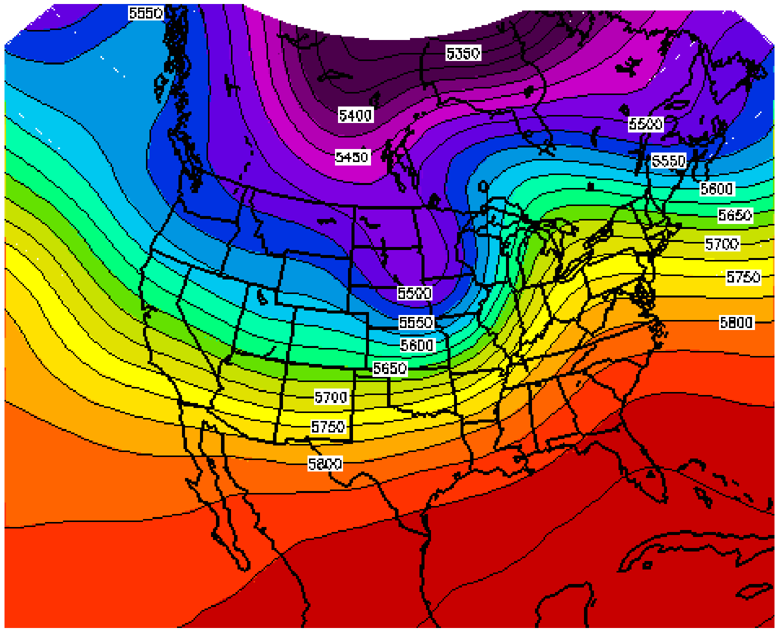

Figure 1 – Deep Southwest Flow Mean 500 mb heights. Composite image is from 00Z the evening of the MCS event(s).

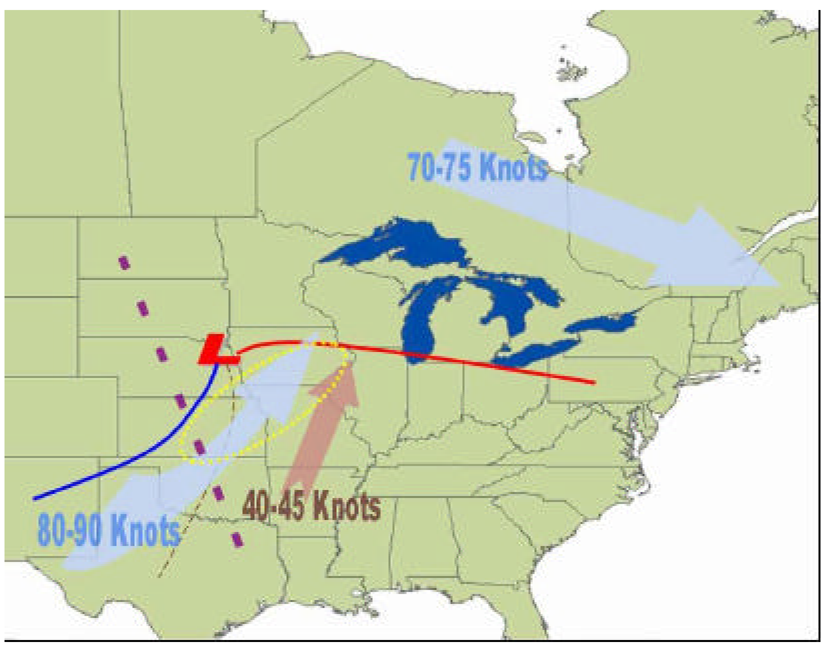

Figure 2 – Deep Southwest Flow Composites image near time of MCS initiation. Warm and cold fronts are noted by solid red and blue lines, respectively. Purple dashed line denotes location of 500 mb trough axis. Pale blue arrows highlight 250 mb jet cores. Pale red arrow indicate 850 mb jet core. Dashed yellow line encompasses area of MCS generation.

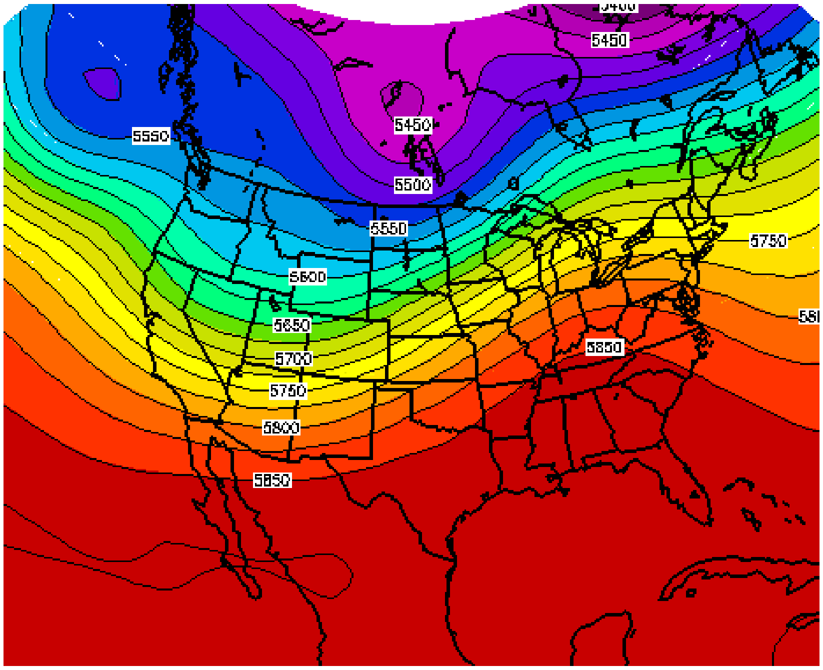

Figure 3 – 500 mb heights for Southwest Flow events. Composite image is from 00Z the evening of the MCS event(s).

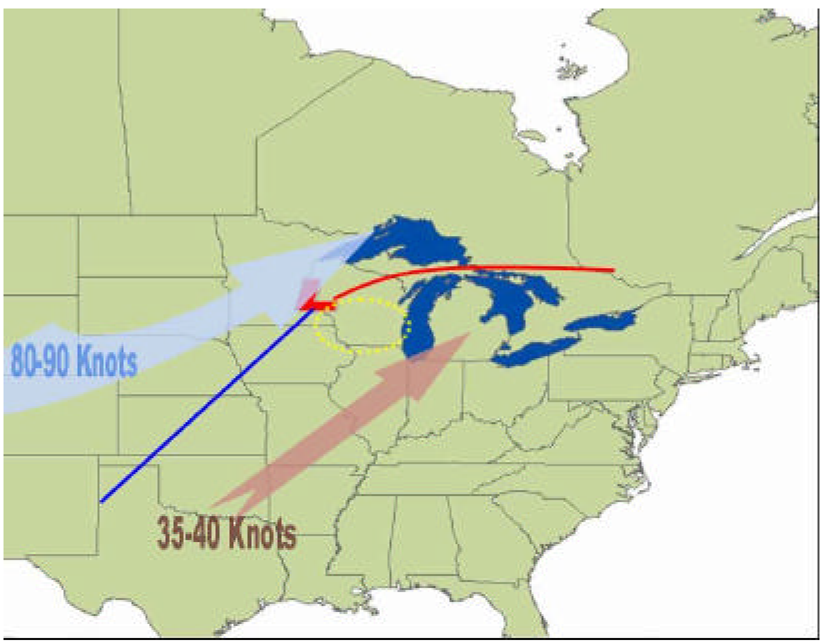

Figure 4 – Southwest Flow events. Details are the same as in Figure 2.

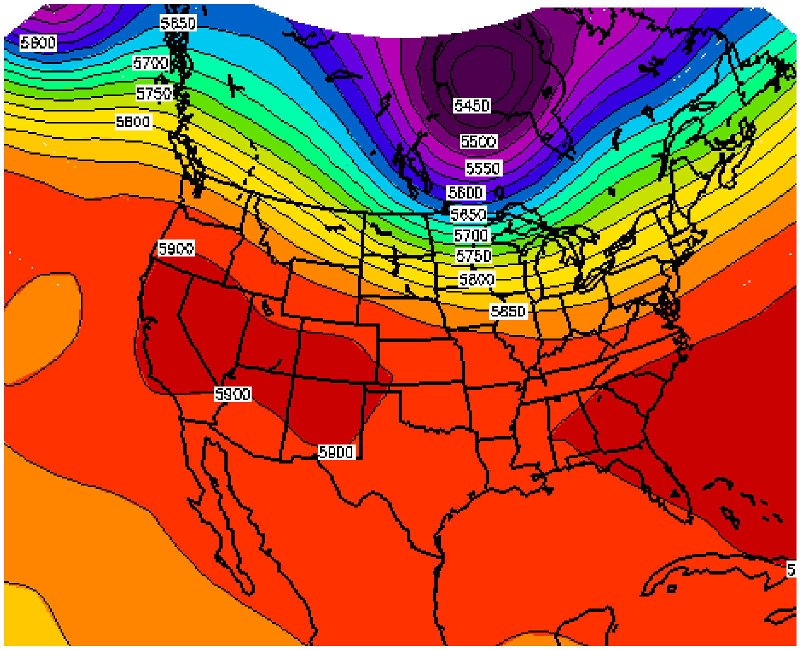

Figure 5 – 500 mb heights for Northern Plains Trough events. Composite image is from 00Z the evening of the MCS event(s).

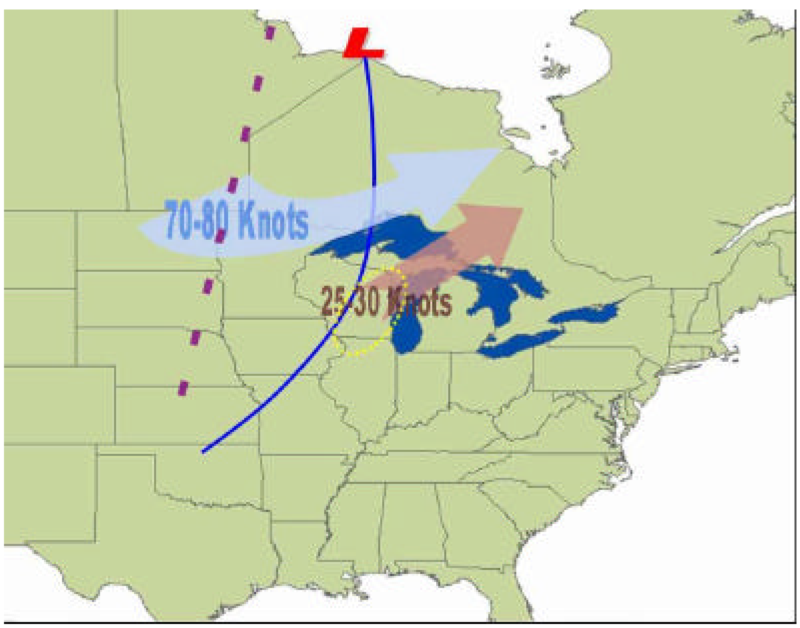

Figure 6 – Northern Plains Trough events. Details are the same as in Figure 2.

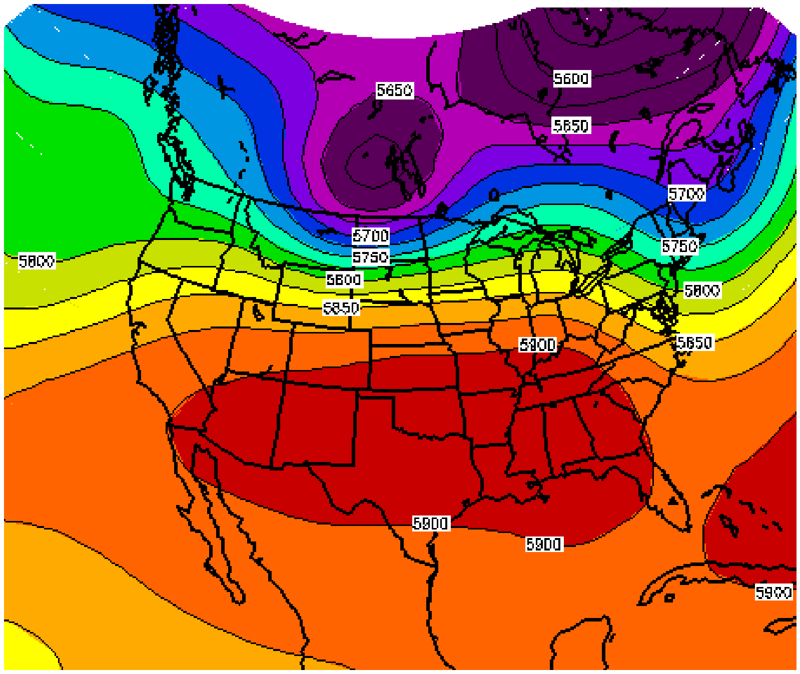

Figure 7 – 500 mb Heights for Ridge Rider events. Composite image is from 00Z the evening of the MCS event(s).

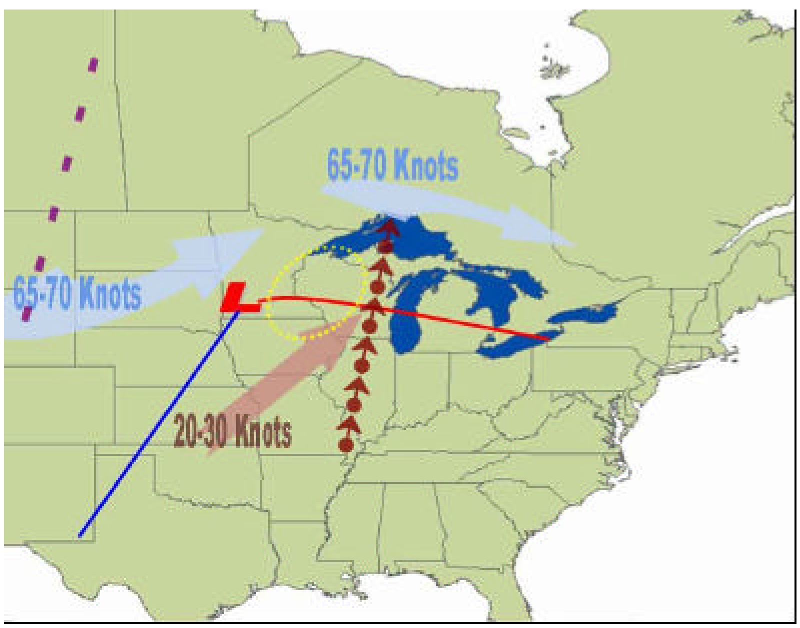

Figure 8 –Ridge Rider events. Details are the same as in Figure 2. Note: Short maroon arrows mark location of 500 mb ridge axis.

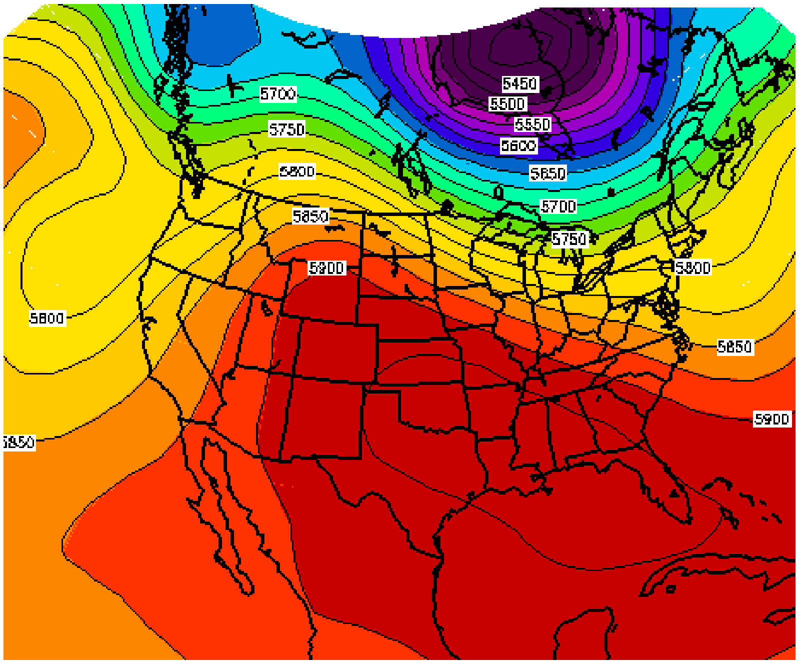

Figure 9 – 500 mb Heights for Weak Northwest Flow events. Composite image is from 00Z the evening of the MCS event(s).

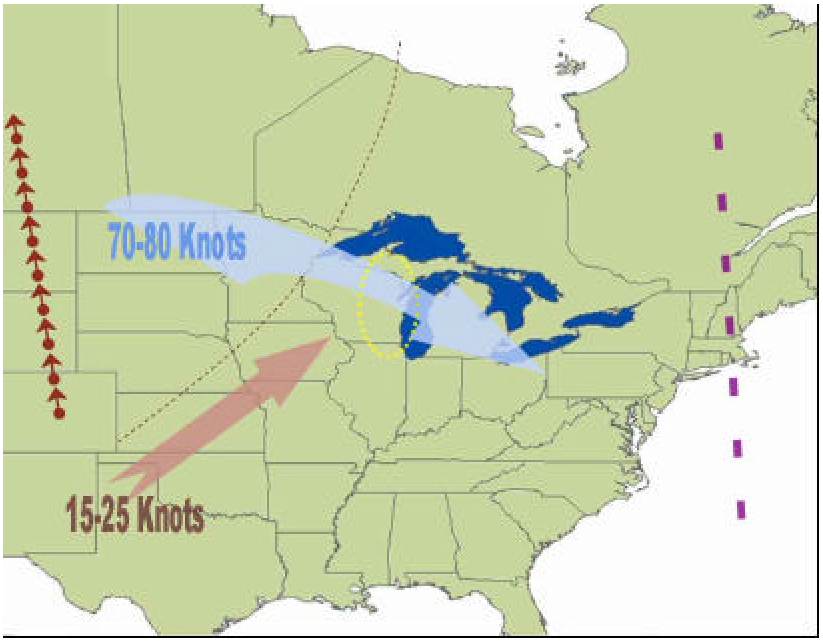

Figure 10 – Weak Northwest Flow events. Details are the same as in Figure 2.
Note: Short maroon arrows mark location of 500 mb ridge axis.

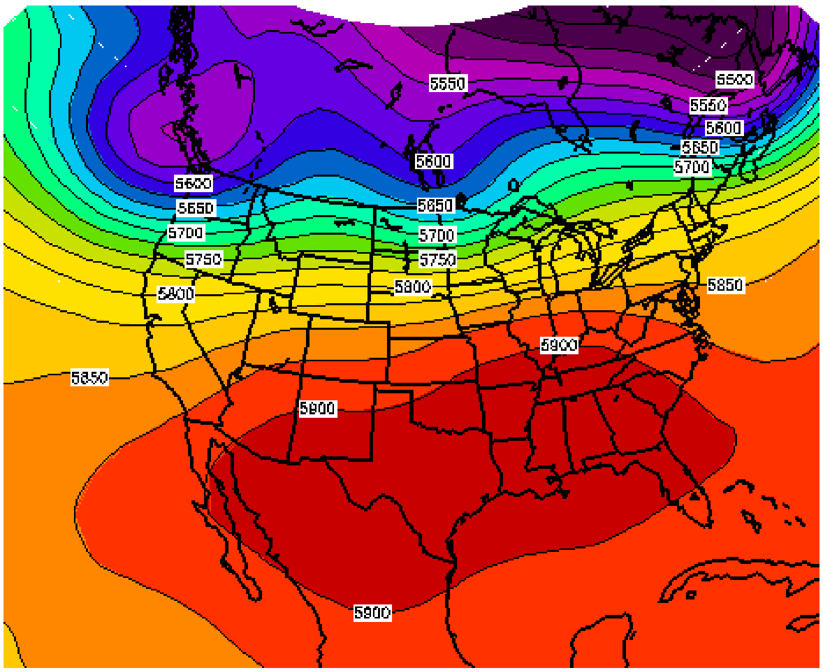

Figure 11 – 500 mb Heights for Wave in Zonal Flow events. Composite image is from 00Z the evening of the MCS event(s).

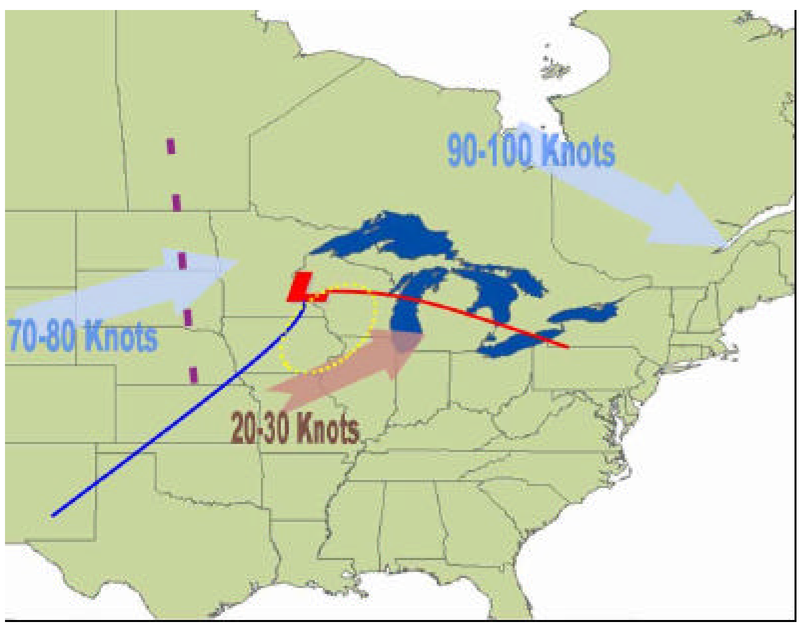

Figure 12 - Wave in Zonal events. Details are the same as in Figure 2.

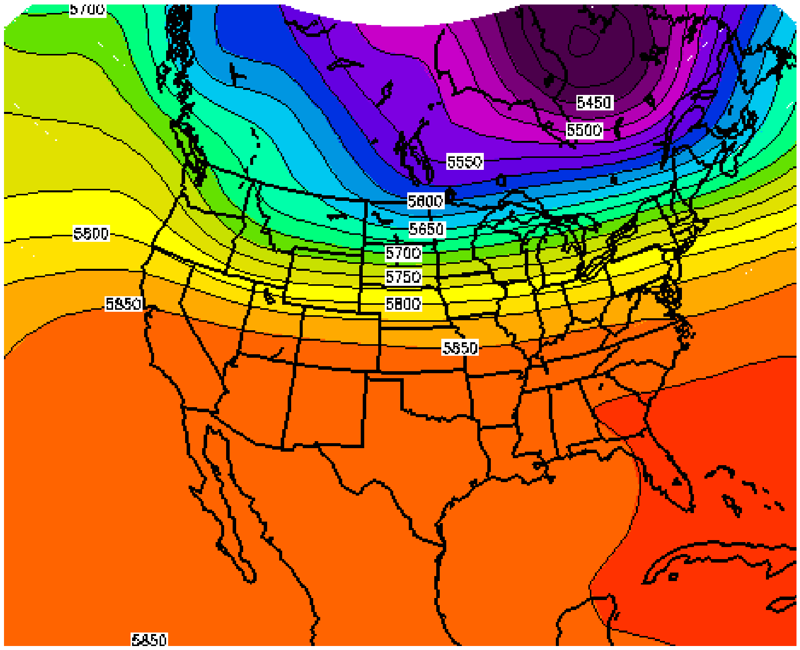

Figure 13 – 500 mb Heights for Zonal Flow events. Composite image is from 00Z the evening of the MCS event(s).

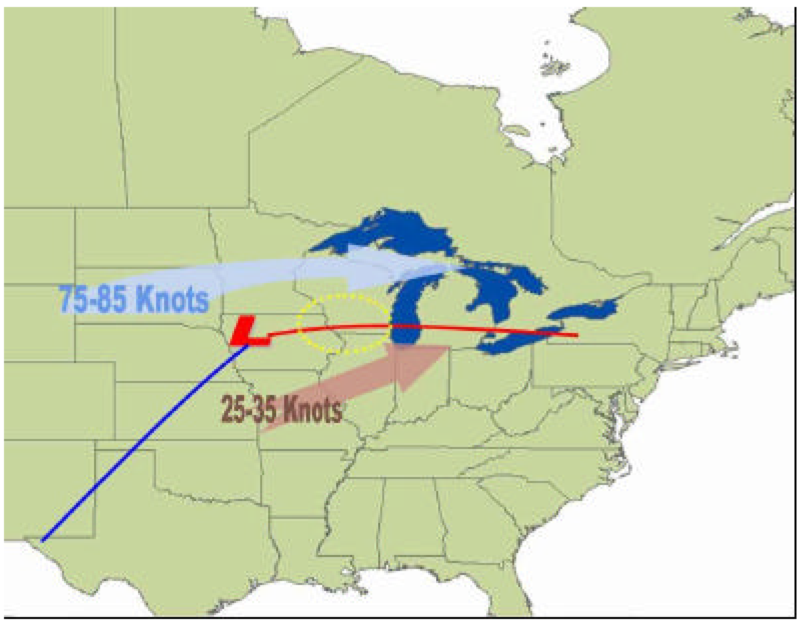

Figure 14 – Zonal events. Details are the same as in Figure 2.

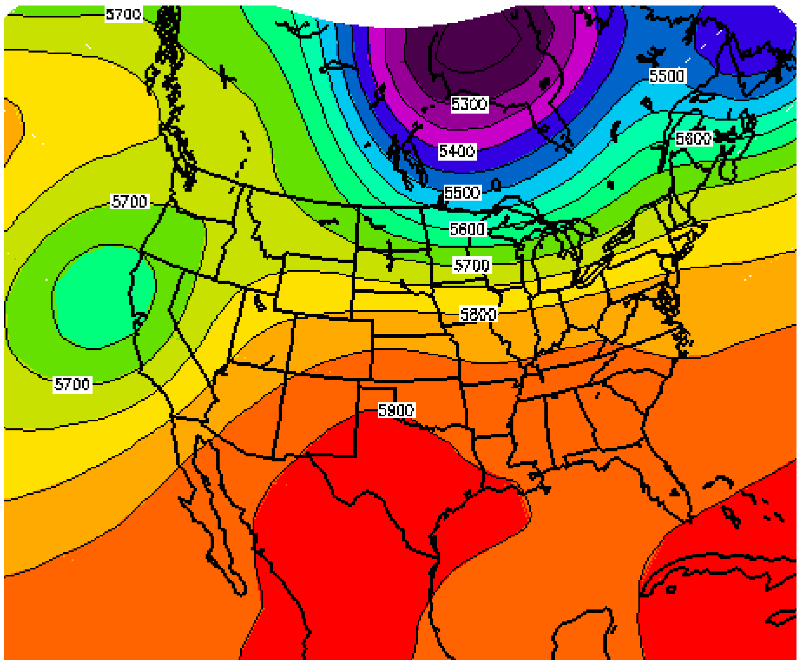

Figure 15 – 500 mb Heights for May98 events. Composite image is from 00Z the evening of the MCS event(s).

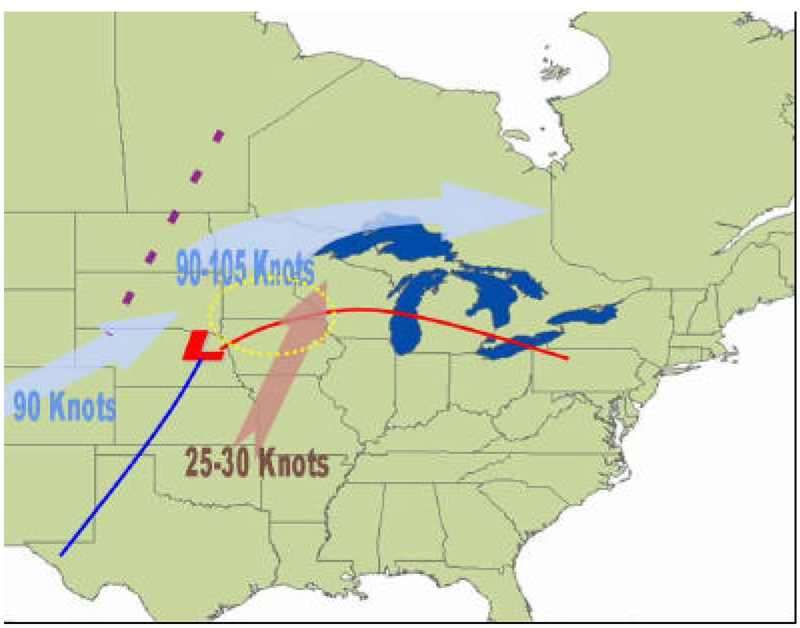

Figure 16 - May98 Events. Details are the same as in Figure 2.

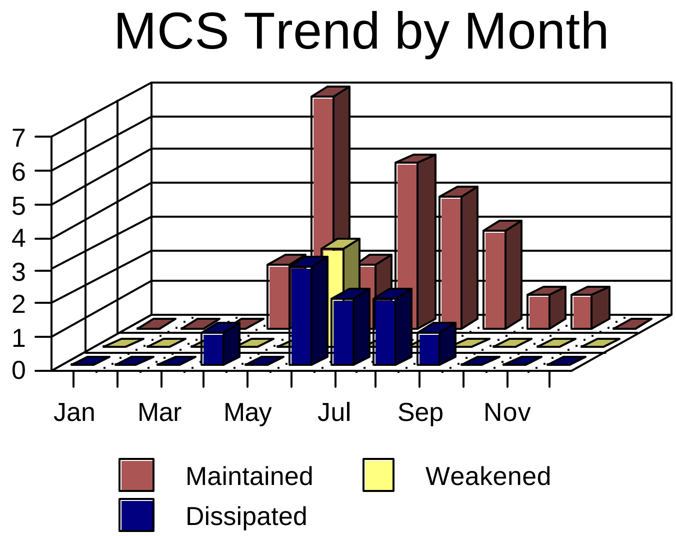

Figure 17 – Trend of MCS events by month.

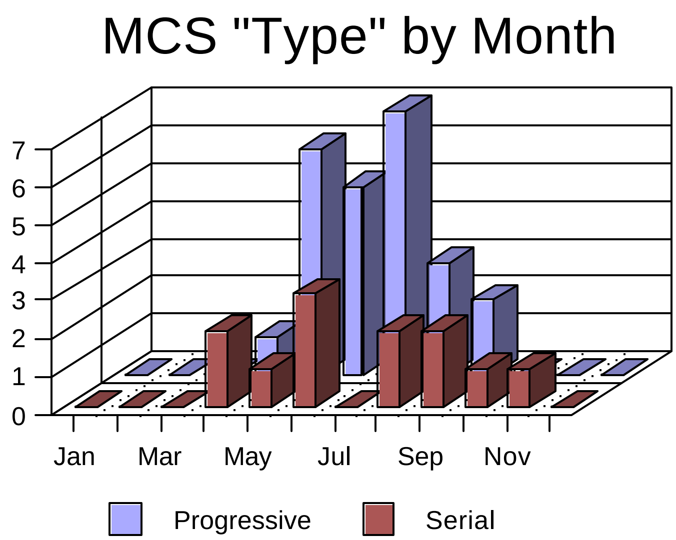

Figure 18 – MCS echo type (Progressive or Serial) distribution by month.

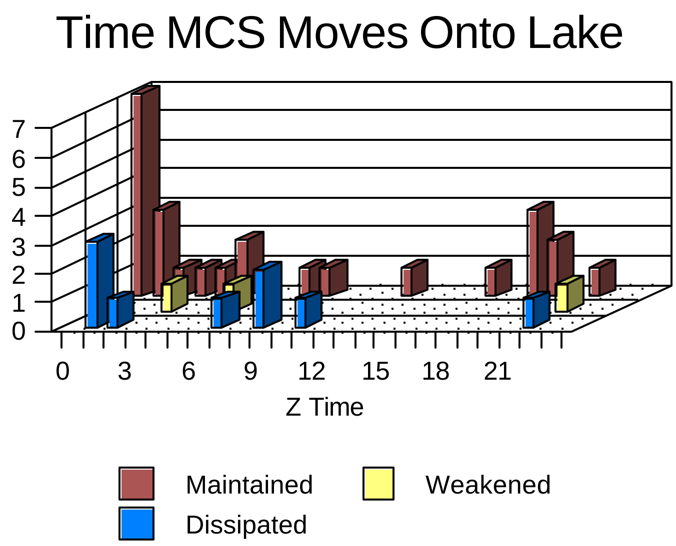

Figure 19 – Time (UTC) at which leading edge of MCS moved over Lake Michigan. Times are stratified by trend of the MCS events (Maintained, Weakened, Dissipated)

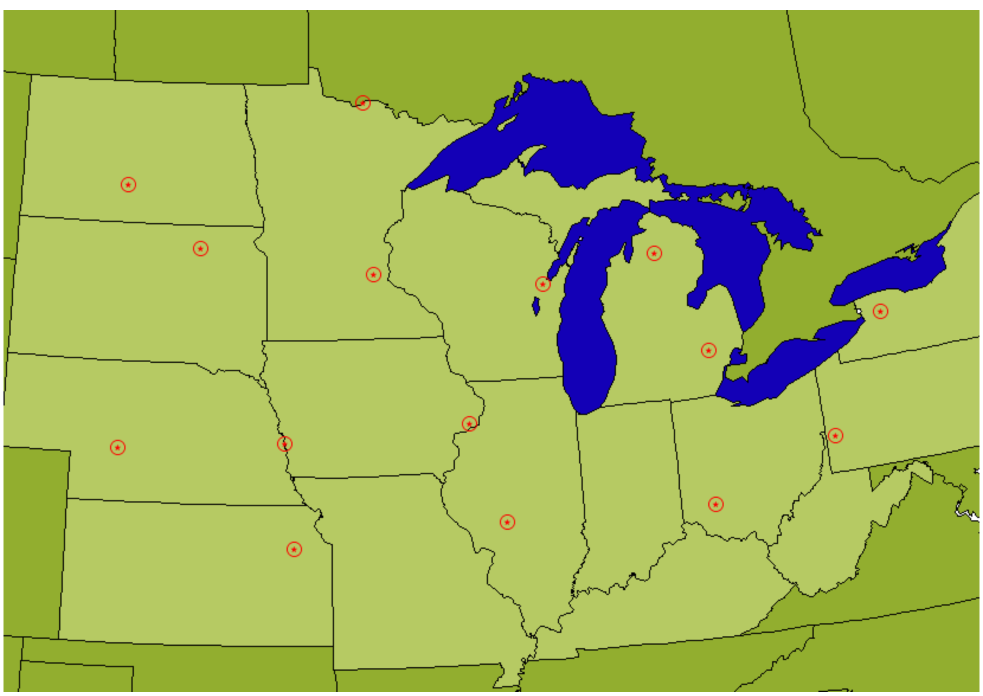

Figure 20 – Location of upper air sounding sites utilized in sounding analysis.

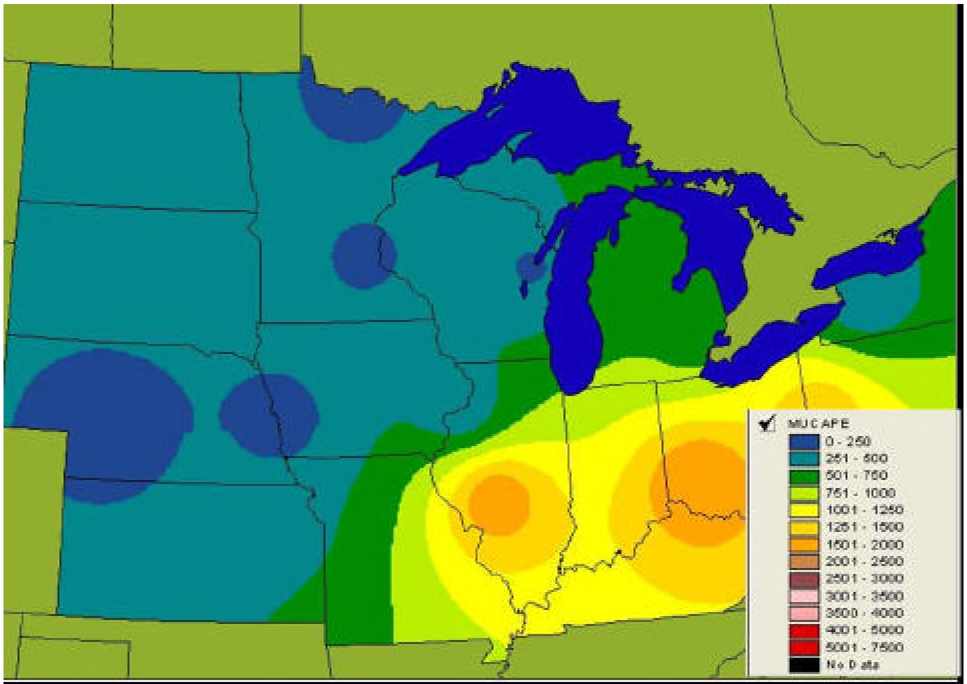

Figure 21 – MUCAPE (J/kg) values for Deep Southwest Flow events.

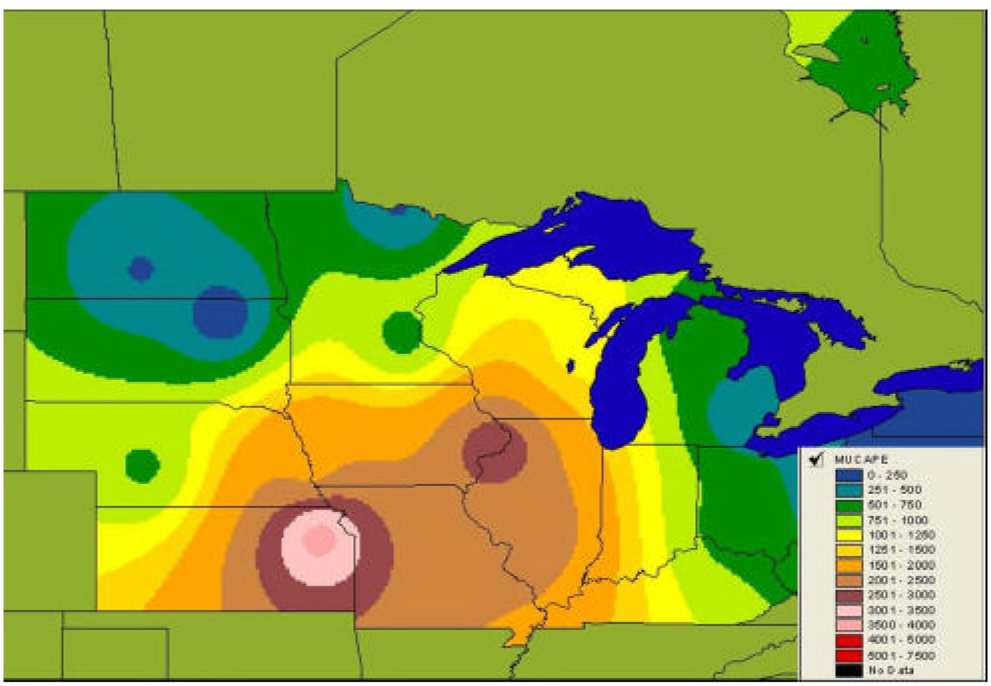

Figure 22 – MUCAPE (J/kg) values for Southwest Flow events.

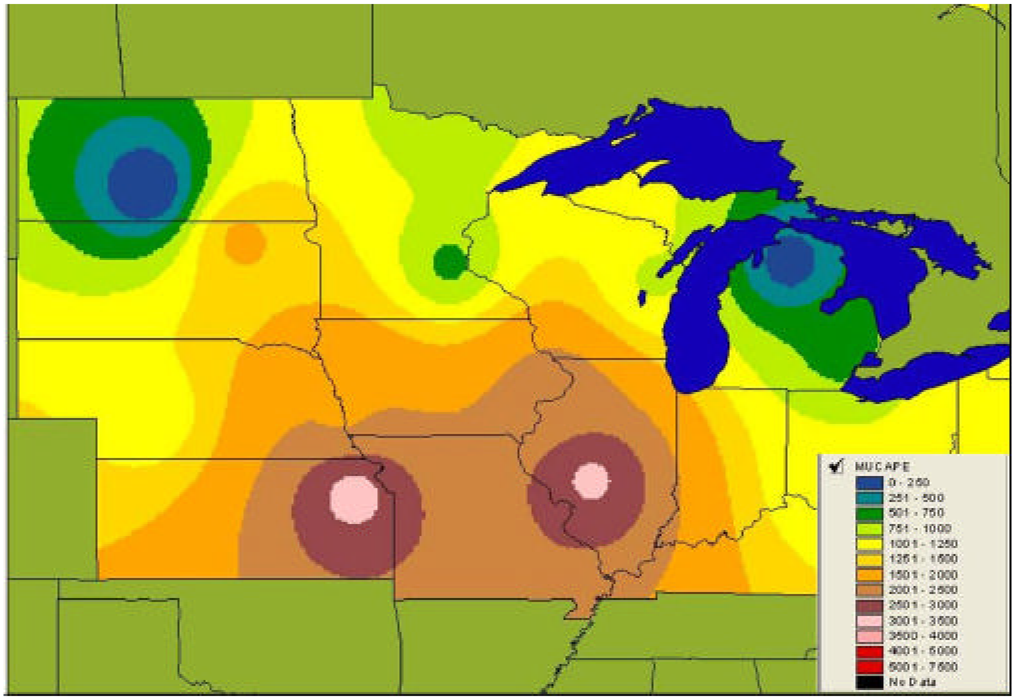

Figure 23 - Northern Plains Trough MUCAPE (J/kg) values.

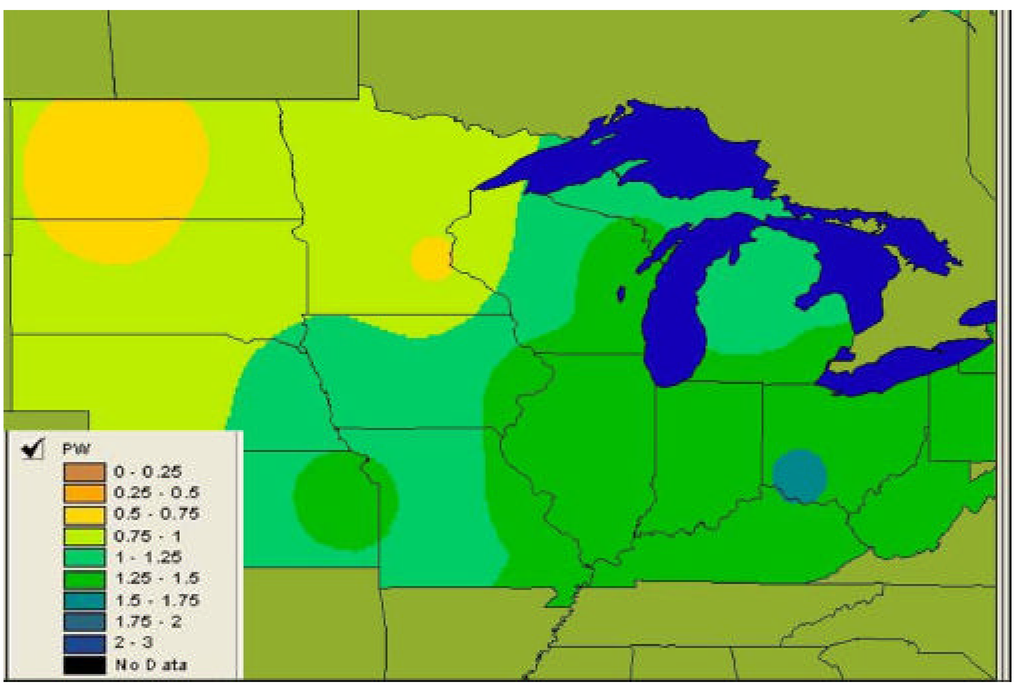

Figure 24 - Northern Plains Trough Precipitable Water Values (inches)

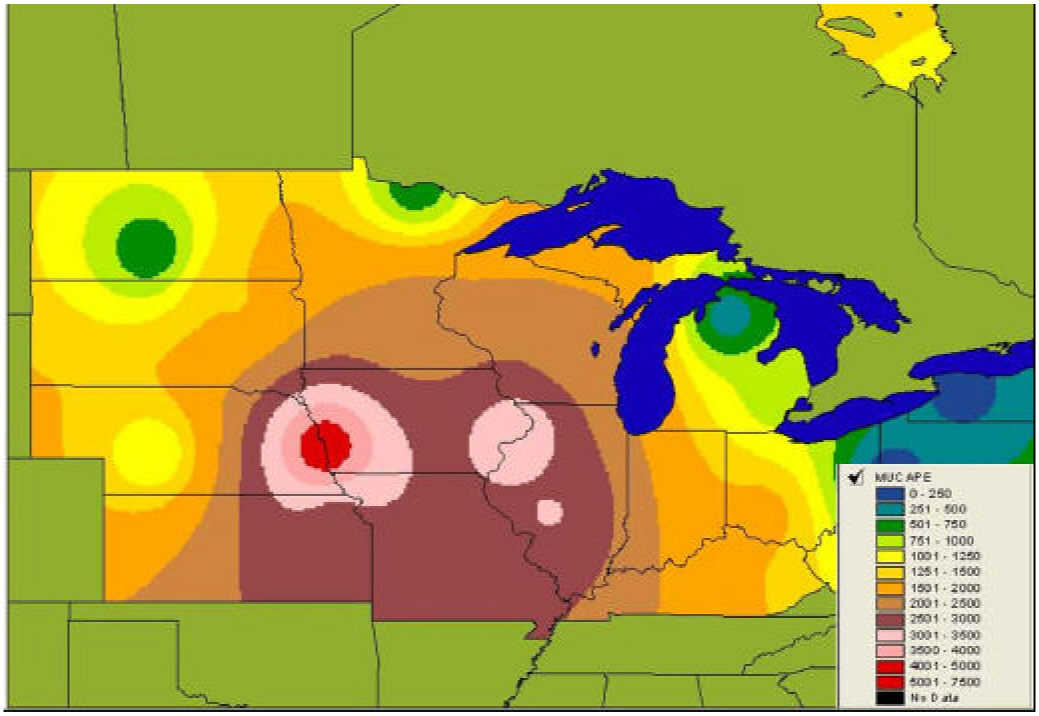

Figure 25 - Ridge Riders MUCAPE values (J/kg)

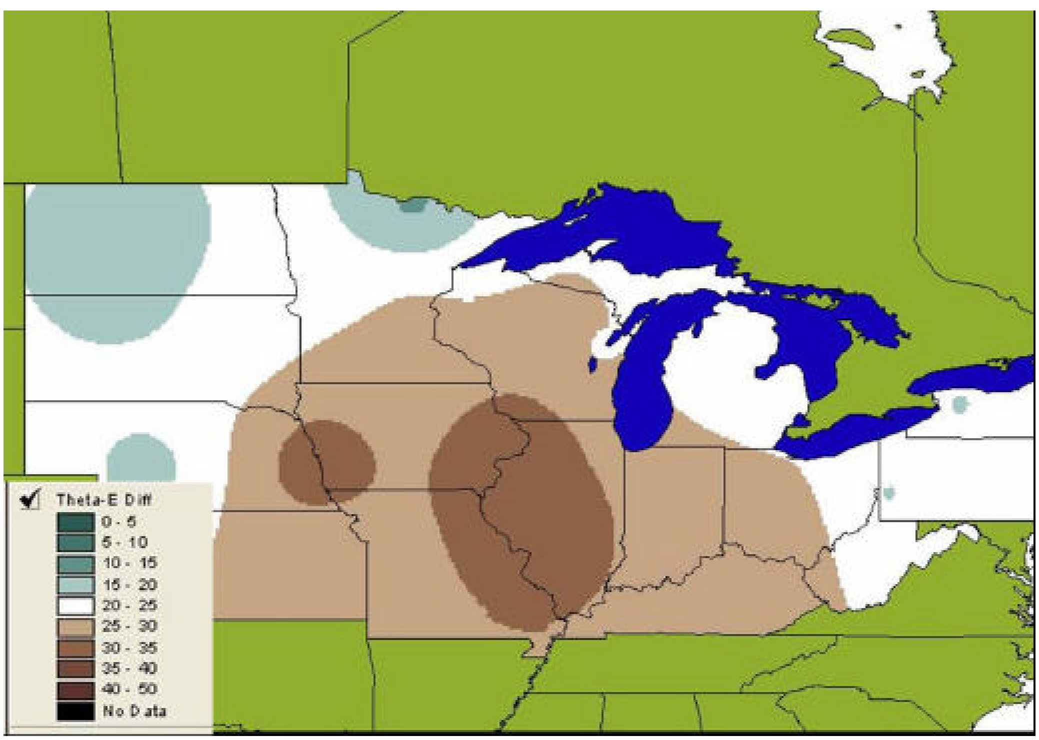

Figure 26 - Ridge Riders Theta-E Difference values (K)

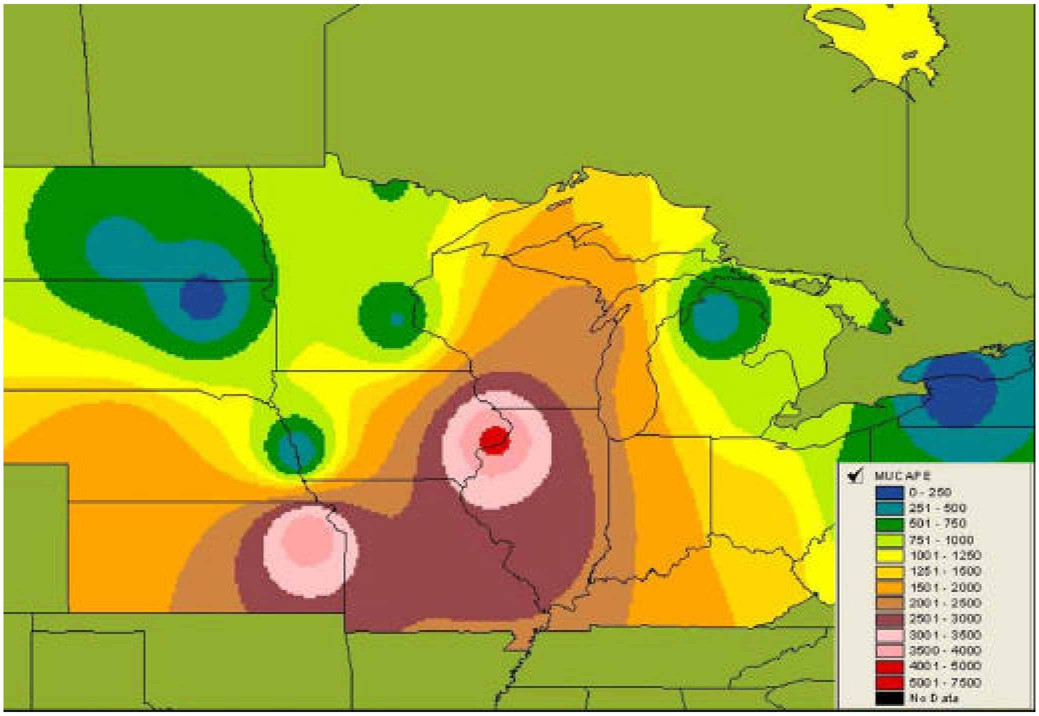

Figure 27 – MUCAPE (J/kg) values for Wave in Zonal Flow events.

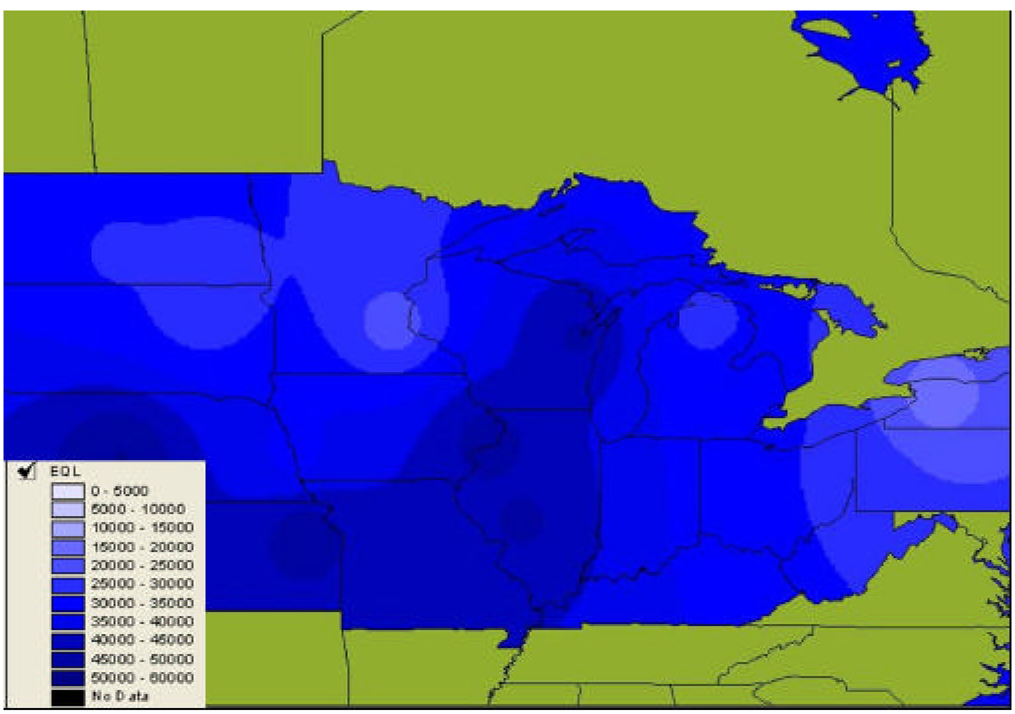

Figure 28 – Equilibrium Heights (EQL) in feet for Wave in Zonal Flow Events.

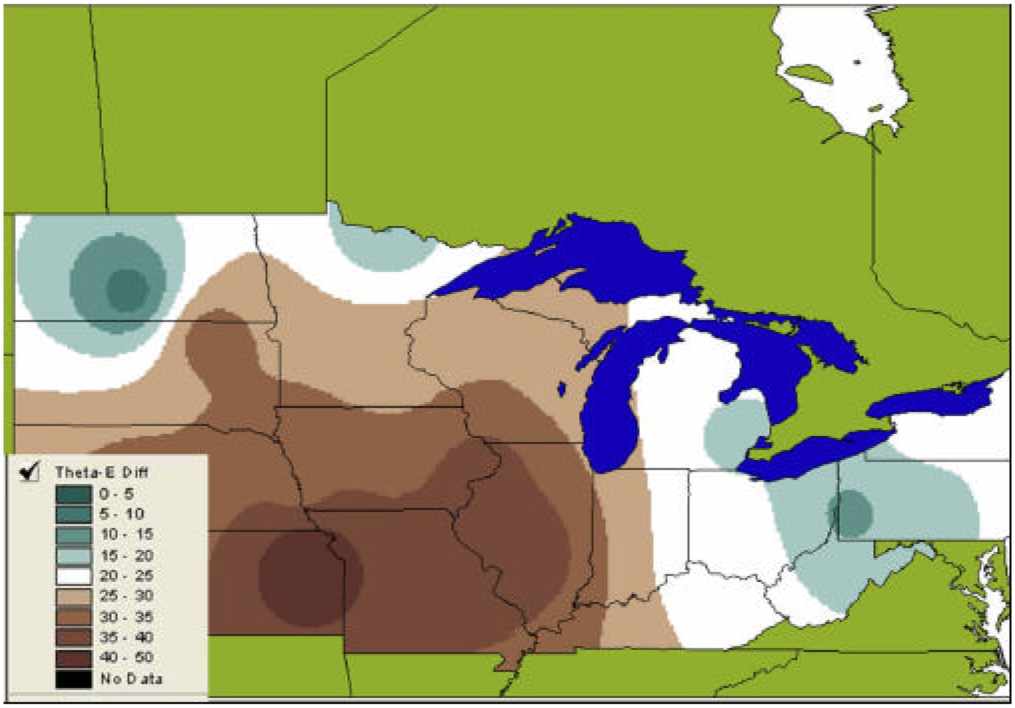

Figure 29 – Maximum Theta-E difference (K) for Weak Northwest Flow events.

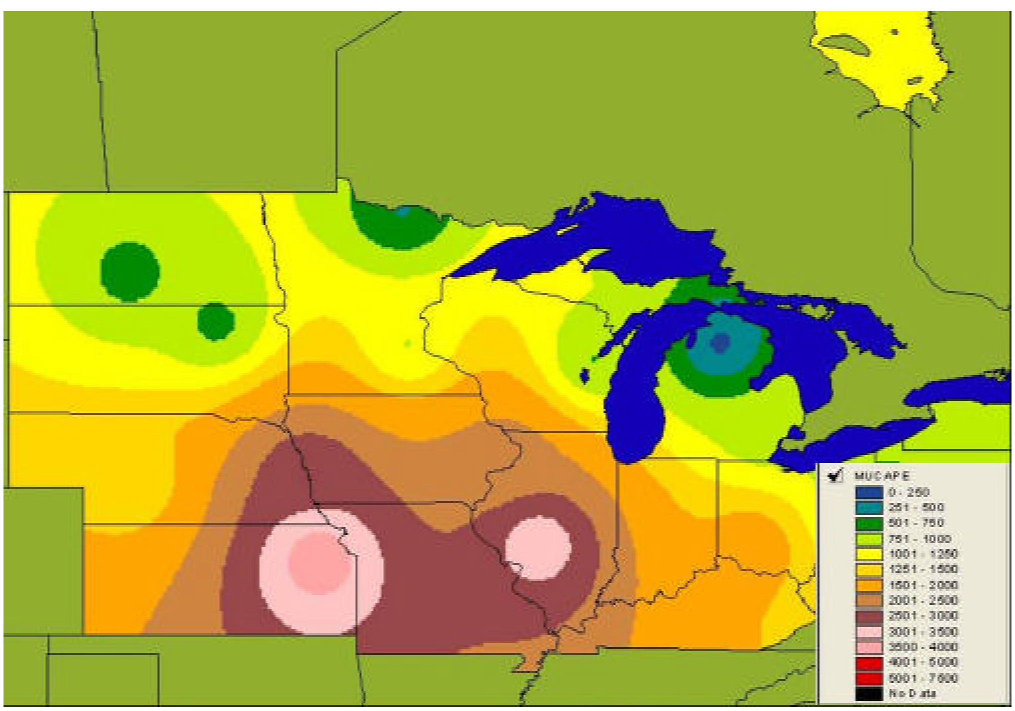

Figure 30 – MUCAPE (J/kg) values for Zonal events.

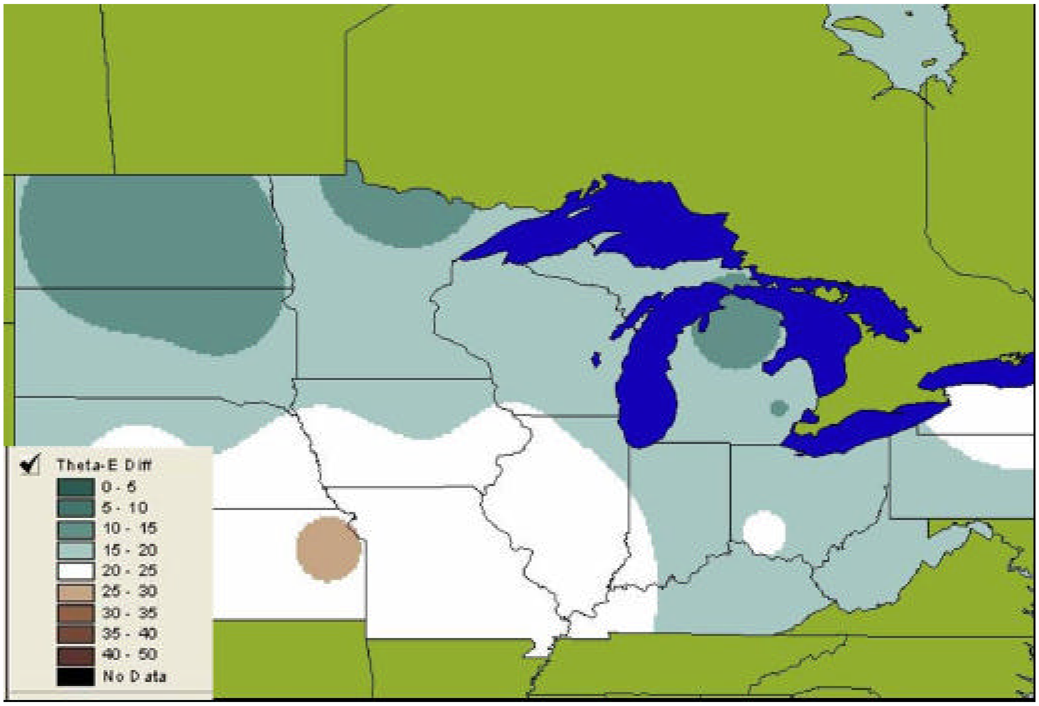

Figure 31 – Maximum Theta-E difference (K) for Zonal events.

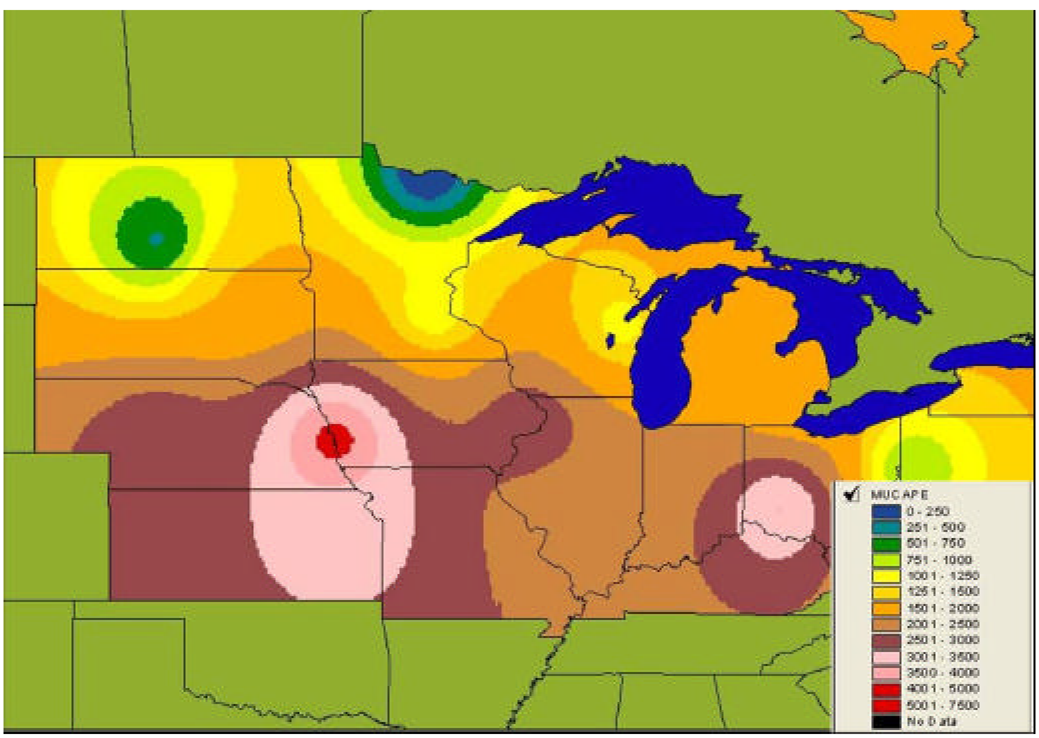

Figure 32 – MUCAPE (J/kg) values for May98 events.