7.6 LOWER MICHIGAN MCS CLIMATOLOGY: TRENDS, PATTERN TYPES, AND MARINE LAYER IMPACTS

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1. Introduction

One of the most significant summer forecast challenges downwind of a large lake (e.g., Lake Michigan) is the impact, if any, that the marine layer will have on existing convection as it crosses the body of water. One of the primary Mesoscale Convective System (MCS) activity corridors in the United States encompasses the southern Great Lakes region. Thus, forecasters in this region are frequently confronted with the potential impact of one of the Great Lakes on an existing MCS. Johns and Hirt (Johns 1987) identified that a major axis of derecho activity also stretches across the southern Great Lakes area (Figure 1) further demonstrating the potential importance of investigating convective interactions with marine layer processes.

The Great Lakes hold the world's largest supply of fresh water, containing about 18% of the global total and roughly 90% of the United States' total fresh water. Combined, the lakes cover an area of over 245,000 square kilometers (94,000 square miles) and contain 23,000 cubic kilometers (5,400 cubic miles) of water (information courtesy of the Great Lakes Environmental Research Lab). Given the enormity of the Great Lakes and the frequency of MCS events in this region, it seems necessary to investigate the impact of the Great Lakes on existing convection.

MCS events were chosen for investigation since they are a particularly organized form of convection and are frequently self-sustaining systems. If the marine layer impacts on MCSs can be identified, these lessons may be applied to less organized forms of convection as well. In particular, the study focuses on MCS events that cross Lake Michigan as the long axis of Lake Michigan is roughly perpendicular to the prevailing westerly flow and coincides with a primary axis of MCS occurrence in the United States.

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2. Methodology

Sixty-one MCS events that occurred over lower Michigan during the period from 1996 to 2001 were originally identified for potential inclusion into the study. Potential events were identified utilizing office records at the Grand Rapids National Weather Service Office, as well as through the utilization of NCDC's online radar archive and the SvrPlot software (John Hart, SPC). 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 100 km or more in horizontal scale in at least one direction.*" (AMS 2000)

In order to better assess the affect of Lake Michigan, the research is focused on MCSs that produce severe weather. Therefore, to be included in the final sample, the MCS had to be responsible for at least five severe weather reports upstream of Lake Michigan (typically this would be in eastern Wisconsin or northern Illinois). In addition, a portion of the MCS had to cross the waters of Lake Michigan. Some events were removed from the study as they did not meet the severe weather criteria (five reports upstream of the lake), while others were dropped because detailed data sets were unavailable. Of the identified events, thirty-seven have been analyzed through examination of radar, satellite, surface and lake temperature data as well as interrogation of upper air soundings and model 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 have been catalogued. In addition, composite analyses of common pattern types conducive to MCS occurrence across lower Michigan have been developed and composite values from upper air soundings across the Great Lakes region have been generated.

3. Climatological Information

Once the events were identified for inclusion in the study they were stratified by whether they maintained their intensity or weakened/dissipated as they crossed Lake Michigan. Additional parameters that were tracked included the location of MCS formation (and three hourly tracks of the centroid of the MCS), time of MCS initiation, time that the MCS reached the western edge of the lake, MCS residence time over the lake, 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" or "Dissipated" categories. 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 in the study that weakened or dissipated over the lake occurred in the months of June, July or August (Figure 2). 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 into 'Progressive' and 'Serial' types based on the classification of derecho events presented by Johns and Hirt (Johns 1987). Johns and Hirt identified progressive events as being characterized by a "short curved squall line oriented nearly perpendicular to the mean wind". Progressive events generally occur along and north of a warm frontal or quasi-stationary boundary. The serial type events are oriented in such a way that there exists only a small angle between the mean flow and the axis of the squall line. Serial events typically consist of a series of smaller bows and LEWPs (line echo wave pattern). While they often initially develop along and, in some cases, north of a warm front or quasi-stationary boundary they typically develop south into the warm sector ahead of a cold front (Johns 1987). Of the thirty-seven events in this study twenty-five were identified as being progressive in nature while twelve were serial. 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 3). Several concepts can be gleaned from the statistics. The progressive events tend to occur in more benign warm season environments and may be more likely to dissipate as they cross Lake Michigan due to lesser large scale "forcing". Also, the stable boundary layer in place over Lake Michigan is not as great in the summer months (weaker lake-land contrast). Conversely, serial events tend to be more "strongly forced" as they are typically associated with stronger upper level systems and their associated low level frontal 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., cold water temperatures overlain by 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 lower troposphere.

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 4). 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 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, or became increasingly elevated and less likely to produce wind damage east of the lake. 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 less than three hours. There were no identifiable trends with respect to residence time over the lake and the proclivity for an MCS to maintain its intensity or to weaken/dissipate.

4. Synoptic Analyses and Composite Pattern Types

In addition to the development of the MCS climatology, composite patterns were developed for the thirty-seven events. Delineation of synoptic pattern types can be a valuable tool in assisting forecasters with respect to the anticipation of potential severe MCS events. The ability to recognize patterns conducive to Great Lakes MCS initiation can be a first step in assessing the risk of severe weather downstream of the lake. Pattern types common to the thirty-seven Great Lakes MCSs were developed by comparing surface and upper air features for each event and then grouping those events which exhibited similar locations, amplitudes, and evolution of significant synoptic scale features. This synoptic pattern matching revealed consistencies that grouped the MCSs into eight pattern types.

In addition, data was collected for each of the events from fifteen upper sites stretching from North Platte, Nebraska to Buffalo, New York (Figure 5). Sounding information was collected for the three sounding cycles enveloping the occurrence of each 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 for each sounding including, 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 composite values were generated based on the pattern types previously identified. 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. Note that the objective sounding analyses only incorporated upper air sounding data. Therefore, these analyses are only useful for examining the large scale environment in which the MCS events initiated and evolved. Mesoscale detail is not possible at this scale of analysis. Additional detailed analysis utilizing RUC initialization data will likely be conducted to garner additional mesoscale trends.

4.1 Deep Southwest Flow Events

The Deep Southwest Flow pattern type contained seven events. Deep Southwest Flow MCS events were associated with vigorous upper level features and tended to be clustered in the spring or fall. Six of the seven events at least maintained their intensity as they crossed Lake Michigan. The initiation region for these events tended to be in the central plains (Figure 6) and they were all of the serial type.

This pattern type is characterized by moderate to strong mid-level flow and is most likely to occur during the early spring or fall months. Generally, Deep Southwest Flow cases exhibit a high amplitude longwave trough with its axis close to the western Great Lakes region and digging deep into the central U.S. (Figure 7). The majority of these 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 to upper level speed maxes (250 mb jet core 40-45 m/s) that are rounding the base of the trough. In general, strong flow and moderate to strong large-scale forcing (12 hour heights falls associated with the primary shortwave between 1200 UTC and 0000 UTC on the day event averaged 70 meters) characterize these events. Strong upper-level ridging is present over much of Ontario, Canada with most of the cases exhibiting a speed max rounding the apex of the ridge resulting in right entrance region upper level divergence and contributing to jet coupling over the western Great Lakes. The low-level response is that of a strong low-level jet (20-25 m/s) with its axis over the mid-Mississippi River Valley nosing northward into northern Illinois and southern Wisconsin. The convective systems are nearly always 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 Minnesota (Figure 8).

These cases exhibited the lowest MUCAPE values on average of all of the pattern types in the study. This is to be expected as they 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 9). A sharp gradient in MUCAPE exists in these events with values dropping to 300-750 J/kg across lower Michigan. Equilibrium Heights are low in these events, typically in the 6-9 km AGL (20,000 to 30,000 ft) range. This is fitting in that these cases tend to be serial MCSs consisting of relatively low topped convection. Max Theta-E Difference values (between the near surface layer and the mid levels), which are a measure of downdraft potential, are in the 15 to 20 degree Kelvin (K) range. This is comparatively low when looking at some of the other pattern types. These events are more dynamic in nature and tend to rely less on the ingestion of dry mid level air for the maintenance of strong downdrafts than do some of the other pattern types.

4.2 Southwest Flow Events

Five events fit into the Southwest Flow pattern type and all of these survived across Lake Michigan. These events all occurred in the late spring or early fall (May or September) and all but one was progressive in nature. Wisconsin was the initiation region for all of the Southwest Flow events which tend to reach Lake Michigan in the evening or overnight hours (Figure 10).

Southwest Flow events have a propensity toward positively tilted longwave troughs. The trough axes are displaced much farther west into the Inter-mountain region than in the Deep Southwest Flow cases promoting broad, and often weak, diffluence over the northern Plains and Great Lakes. Ridging downstream of the trough over the central and eastern Great Lakes is generally weaker in these cases (Figure

11). Initiation is often beneath a 40-45 m/s 250 mb jet streak over the western Great Lakes. The low level jet (15-20 m/s) is oriented southwest to northeast over Illinois and Missouri with parcel trajectories originating from a warm sector that is warmer and moister than for Deep Southwest Flow events. Forcing for initiation and maintenance of convection appears to be dependent on low-level convergence on the terminus of the low level jet. Drier air is available at 500 mb when compared to the Deep Southwest Flow cases with dewpoint depressions generally 10-20 C in the Great Lakes region. An area of surface low pressure is more likely to be centered in the central and northern Plains with a warm front extending eastward into the Great Lakes region and across Lake Michigan (Figure 12). In these cases, MCSs tend to propagate along and north of the front before traversing Lake Michigan.

Southwest flow cases exhibit a corridor of 1000-2000 J/kg MUCAPE values stretching from Kansas into southwest Wisconsin at 0000 UTC on the day of the event (Figure 13). There is a gradient in the MUCAPE field 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 9-10.5 km agl (30,000-35,000 ft) 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 Max Theta-E difference (near surface to mid levels) values are not as high as some of the other patterns with values of 15-20 K stretching from the Northern Plains into the Ohio Valley. MCSs generally initiate in the vicinity of a warm front or quasi-stationary boundary with this pattern. Initiation occurs in Wisconsin along a relatively tight gradient in the MUCAPE field and northwest of a region of relatively strong low level inhibition across the Ohio Valley.

4.3 Northern Plains Trough Events

There were six Northern Plains Trough Events that were identified in the data set. Northern Plains trough events all initiated in Wisconsin or Minnesota before tracking southeast into lower Michigan (Figure 14). These events occurred between the months of July and September and tended to be somewhat of a hybrid between the serial and progressive echo types. Five of the six Northern Plains Trough events at least maintained their intensity as they crossed the lake.

These events occur within weak to moderate mid-level flow scenarios. A speed max typically rounds the base of a northern Plains trough that triggers an evolution toward more of a negative tilt configuration and strengthening of the mid-level low. Mid and upper tropospheric westerlies are shifted well into Canada and the northern tier of the U.S. (Figure 15). 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 low level jet development is north of the initiation region and is, typically, not a factor in MCS development (Figure 16). Very moist conditions characterize the mid levels. The 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 a southwest U.S. subtropical ridge into the initiation region just west of Lake Michigan.

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 17). To the north of this region of high MUCAPE values 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) to lower Michigan (<1000 J/kg). It is in this gradient (and upstream of the lake) where the MCS events in this pattern type tend to initiate. Maximum Theta-E Difference values are not particularly impressive with values of 15 to 20 K from the northern Plains through the Ohio Valley. An area of higher Maximum Theta-E Difference values (20 to 25) stretched from eastern Kansas and all of Missouri into extreme southern Wisconsin near the source region of the MCS events. This source of dry mid level air in the MCS inflow region may contribute to the development and maintenance of intense downdrafts. MCSs tend to initiate in a region of low level convergence in the gradient of high MUCAPE values in the western Great Lakes.

4.4 Ridge Rider Events

Ridge Rider MCS cases accounted for seven of the events in the data set. These events tend to initiate in the western Great Lakes region from Minnesota and Wisconsin to as far south as northern Iowa (Figure 18). They generally reached Lake Michigan in the late evening and overnight hours with over half (4 out of 7) weakening or dissipating as they traversed the lake. These events were all progressive mid-summer events occurring in June, July, or August.

In Ridge Rider events, shortwave toughs within weak mid-level flow eject out of the Intermountain region and propagate along the northern periphery of a large subtropical ridge centered over the southern plains (Figure 19). As the shortwave trough and associated speed max shift into the northern Plains/Upper Midwest, the exit region places much of northern Minnesota beneath ascent forced by upper level divergence. Forcing is typically strongest well west of Lake Michigan. Many of the events exhibit shortwave ridging over the eastern Great Lakes and southeast Canada. The Upper level speed max (33-36 m/s) rotating around this ridge combines with a speed max (33-36 m/s) associated with the primary trough in the northern plains contributing to enhanced vertical motion through jet streak coupling over the western Great Lakes region. The low-level response is a low level jet (10-15 m/s) situated west of Lake Michigan with its terminus over central and western Wisconsin. This low level jet position is farther west than with most other patterns identified in the study. Initiation of the MCS occurs north of a surface quasi-stationary front extending from low pressure in the northern Plains (Figure 20). MCSs are sustained along the surface boundary and encounter the lake later in their life cycles. Due to the limited large scale ascent aiding their maintenance, they are much more vulnerable to lake processes in their evolution.

Ridge Rider 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 21). Similar to the Northern Plains Trough events, there was a MUCAPE gradient across lower Michigan. MUCAPE values of 2000 J/kg west of Lake Michigan decreased to less than 500 J/kg across northern lower Michigan and around 1000 J/kg across southeastern lower Michigan. These cases exhibited decent 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 ingestion of dry mid level air. Maximum Theta-E Difference values (Figure 22) were in the 25 to 30 K range from Kansas to southern Minnesota and east into southern lower Michigan and eastern Ohio.

4.5 Zonal Flow Events

Three Zonal Flow events, all initiating in southern Wisconsin or Northern Illinois, were included in the study (Figure 23). The occurrence of the Zonal Flow events was spread through the late spring and summer months (May-August). All were progressive in nature and two of the three maintained their intensity as they crossed Lake Michigan.

Zonal Flow events, as the name implies, exhibited very little meridional component to the flow which was characterized by the presence of a 40-45 m/s speed maxima across the northern plains. The speed max coincided with the base of a progressive, neutral to positive tilt shortwave within the zonal flow (Figure 24). MCS development occurs just west of Lake Michigan near or beneath an upper level jet streak and in the vicinity of a weak east-west oriented surface frontal boundary (Figure 25). Upper divergence induced a strong low level jet, which nosed into extreme southern Lake Michigan and northern Indiana with its axis extending back into central Missouri. The low level jet is characterized by 13-18 m/s flow and it is a primary source of buoyant return flow on the back side of Southeastern U.S. ridging. This sloped flow appears to result in rapid elevated destabilization and, typically, nocturnal convective initiation along and north of the boundary.

In the Zonal Flow events, there was a MUCAPE gradient that ran from Eastern South Dakota into eastern Ohio (Figure 26). 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. As is frequently the case, MCSs in this pattern type tended to propagate along the MUCAPE gradient. Little convective inhibition is noted in these cases with the majority of the domain exhibiting CINH values of zero to -50 J/kg. Maximum Theta-E Difference values were relatively low in these cases with values largely in the 15 to 20 K range from Minnesota into the Ohio Valley. 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 15-20 m/s across the domain.

4.6 Wave in Zonal Flow Events

There were three Wave in Zonal Flow events which occurred during the time frame of the study. These events tended to be small and were associated with a limited number of severe weather reports. The initiation region for all three events was in either Wisconsin or Minnesota with the MCS tracking over southern Lake Michigan (Figure 27). The MCS events all initiated in the evening hours (00-02Z) and occurred in the summer through early fall (June through September). The events exhibited both progressive and serial characteristics, but tended to be more serial in nature. Two of the three MCSs maintained their intensity as they crossed the lake

In some respects, this pattern is similar to the Ridge Rider events (see section 4.4) in that strong ridging persists over the south/central U.S., typically, centered over the lower Mississippi River valley (Figure 28). The subtropical ridge is less expansive for this pattern type than for other warm-season, weak flow situations, but equally intense. One anomaly from the other pattern types is the mid-level cold-core closed low near Vancouver, British Columbia, with slight downstream ridging over the northern Rockies. These cases exhibit largely zonal flow over the northern tier of the U.S. with vigorous shortwave troughs progressing into the Great Lakes region. This promotes locally enhanced mid-level diffluence and speed divergence over the initiation region in central Minnesota and Wisconsin. A 10-15 m/s low level jet develops in response to the upper disturbance, and stretches from Missouri into southern Lake Michigan which may focus convection over Lake Michigan. At the surface, weak low pressure develops near the Wisconsin/Minnesota border with an attendant cold front trailing back into the southern Plains and a weak warm front draped across central lower Michigan. Initiation of convection occurs along the cold front and the MCS evolves along and south of the warm front while convergence is enhanced by the low level jet within the warm sector (Figure 29).

These events tend to exhibit a large degree 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 MUCAPE stretches from near Topeka, KS to Green Bay, WI (Figure 30). 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 Great Lakes region. 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. Also, an area of 25-30 K Max Theta-E

Difference values stretches from the central Plains to Michigan's Upper Peninsula. This is an indication that relative to surface values there is cool dry air in the mid levels available for the maintenance of strong downdrafts in this pattern type.

4.7 Weak Northwest Flow Events

Only 2 events in the study fell under the Weak Northwest Flow pattern type. Both of these events initiated near the western shore of Lake Michigan and were progressive in nature (Figure 31). Both events also occurred in the mid-summer months (July), and one maintained its intensity while the other dissipated rapidly over the lake.

The cases exhibit weak anticyclonic curvature around a large ridge over the intermountain region which promotes northwest mid and upper level flow over the northern tier of the U.S. including the Great Lakes region (Figure 32). In addition, strong ridging extends northwestward into British Columbia, Canada enhancing the meridional component of the upper flow. Upper level speed maxes of 35-40 m/s propagate around the ridge and dive southeastward toward the Great Lakes region. 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 which contributes 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. A low level jet of 13-18 m/s develops from the central Plains into southern Wisconsin near the initiation region of the events. Deep convergence and lift occurs along the cold front moving into very moist and unstable air just west of Lake Michigan and near the terminus of the low level jet in the late afternoon and evening hours (Figure 33).

A maximum 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 (Figure 34). One parameter that stands out in the Weak Northwest Flow events is the Maximum Theta-E Difference values. Differences of 25 to 40 K run from Minneapolis and Green Bay southwest through Kansas (Figure 35). This suggests that there is likely a wedge of cool dry air in the mid levels overlaying a very warm moist airmass in the low levels in these cases.

4.8 May 98 Events

Two significant MCS events occurred across the Great Lakes region in May 1998. These two events, one of which was the May 31st, 1998 derecho event, were unusual in many respects and hence are grouped in their own category. Both events initiated in the late afternoon and evening hours and survived the trip across Lake Michigan. The initiation region for these two MCSs was in northern Iowa and southern Minnesota (Figure 36) and both were progressive in nature.

Two mid-level longwave trough features within this pattern contribute to large-scale forcing for ascent over the upper Midwest and Great Lakes region (Figure 37). A large west coast cold-core low established off the coast of California ejected smaller-scale southern stream shortwave troughs and speed maximums northeastward toward the northern tier U.S. In south central Canada, shortwave troughs rotated around a larger, positively tiled upper level 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. Of particular note is the upper level divergence associated with the right entrance region of a 45-55 m/s upper level jet over the initiation region of the MCS events. A 13-17 m/s low level jet oriented perpendicular to an east/west oriented surface front, which bisects the upper Midwest and lower Lake Michigan, transported ample unstable air into the pre-convective environment over northern Iowa, southern Minnesota, and Wisconsin (Figure 38). The circulation with this low level jet coupled with the thermally direct circulation in the right entrance region of the upper level jet. Surface low pressure is present over the central Plains, and MCS initiation occurs just to the northeast of the low's center.

A strong MUCAPE gradient stretches from South Dakota into the southern Great Lakes. MUCAPE values from North Dakota to Michigan's Upper Peninsula range from 500-1500 j/kg while 2000-4000 j/kg MUCAPE values stretch from Nebraska into the Ohio Valley (Figure 39). These cases exhibited steep mid level lapse with 700-500mb Lapse Rates in excess of 7.5 C/km from South Dakota into Indiana. Maximum Theta-E Difference values were generally in the 20s K across most of the domain. The 0-6km mean wind speeds were amongst the highest of all the pattern types with 20-25 m/s values stretching from Minnesota into lower Michigan.

5. Marine Layer Considerations

One of the primary goals of this research was to investigate the impact that the Lake Michigan marine layer imposed upon severe MCSs as they traversed the lake. This analysis was conducted in order to delineate temporal consistencies in MCS evolution due to changing lake surface temperatures and the potential for ingestion of stable marine layer air into the MCS. Initial evidence suggests that the difference between the buoy air temperature and the buoy water temperature may be a useful tool in helping to determine whether an MCS will maintain its intensity as it crosses the lake or whether it will weaken or dissipate over the lake.

Detailed analyses of water temperature, buoy air temperature (approximately 12 feet above the water surface), and temperatures from land based sites outside of any lake breeze have been conducted for a subset of the events in the study. Two National Data Buoy Center (NDBC) buoys are located near the mid point of Lake Michigan (Figure 40). One buoy is located across the northern portion (NDBC Station 45002) of the lake while the second is located in the lake's southern bowl (NDBC Station 45007). For each event, the water temperature and air temperature data were collected for the buoy which was closest to the location of the MCS as it crossed the lake. Then the events were categorized by whether they maintained their intensity or whether they weakened or dissipated as they crossed the lake. Detailed analysis revealed that the temperature difference between the lake water and buoy air (ΔT_b) was more strongly correlated with respect to the MCS intensity trend as it crossed Lake Michigan, than the temperature difference between the lake water and land temperature. ΔT_b was found to be is a reasonable proxy for the intensity of the marine stable layer (or even unstable layer during the fall months when the water temperature is warmer than the surrounding land mass)

Further investigation of ΔT_b may be useful for forecasters. When the buoy water temperature is subtracted from the buoy air temperature positive values indicate a stable layer (i.e. inversion) near the surface while negative values are indicative of an unstable layer near the surface. For example, a buoy air temperature of 15C over a water temperature of 10C would be indicative of a strong stable layer near the surface of the lake. This comparison when conducted on a subset of the cases in the study revealed that a stronger stable layer, represented by the buoy air temperature being at least 2.5 C warmer than the water temperature, was evident in many events that maintained their intensity as they crossed Lake Michigan. Conversely, many of the weakened and dissipated cases exhibited very weak stable layers (represented by the buoy air temperature being less than or equal to 1C warmer than the water temperature). It is believed that a very stable marine boundary layer (MBL) is sharply decoupled and, therefore, allows convection to become elevated as it crosses the lake while it continues to ingest elevated unstable air. It is believed that the cold pool circulation associated with MCS events that encountered a weak stable marine boundary layer were more likely to be able to overturn the marine layer and therefore ingest stable marine layer air, making it more difficult for them to maintain their intensity. However, events in the late summer season, which encountered lake waters in excess of 19C, were more likely to maintain their intensity as they crossed the lake even if ΔT_b indicated a weak stable layer could be ingested into the MCS.

It should be noted that this analysis has only been conducted on roughly half of the cases in the study and is only a piece of the puzzle when determining whether or not an MCS will sustain itself as it crosses Lake Michigan. In addition to the intensity of the marine stable layer, other factors must be considered when determining whether an MCS will survive across the lake including the strength of the forcing associated with the MCS, stage of the MCS life cycle, and downstream environment to name a few.

6. Conclusions

Thirty-seven MCS events which occurred over lower Michigan during the period from 1996 to 2001 were investigated. To be included in the final sample, the MCS had to be responsible for at least five severe weather reports upstream of Lake Michigan (typically in eastern Wisconsin or northern Illinois). In addition, a portion of the MCS had to cross the waters of Lake Michigan.

MCS events were divided into those that maintained their intensity and those that weakened or dissipated as they crossed Lake Michigan. 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. The majority of the MCS events were progressive, as defined by Johns and Hirt (Johns 1987). Progressive MCS events were more likely to occur during the summer months (June-August) while serial events were more common in the spring (April-May) and fall (September-November). It is hypothesized that since progressive events occur in more benign warm season environments they may be more likely to dissipate as they cross Lake Michigan due to lesser large scale "forcing", which makes them more susceptible to lake processes. Also, the stable boundary layer in place over Lake Michigan is not as great in the summer months (weaker lake-land contrast). Serial events tend to be more "strongly forced" and those that occur in the spring months are more likely to encounter a very stable marine layer (i.e., cold water temperatures overlain by 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 lower troposphere.

Pattern types common to the thirty-seven Great Lakes MCSs were developed by comparing surface and upper air features for each event and then grouping those events which exhibited similar locations, amplitudes, and evolution of significant synoptic scale features. This synoptic pattern matching revealed consistencies that grouped the MCSs into eight pattern types. The most common pattern types were Deep Southwest Flow, Southwest Flow, Northern Plains Trough, and Ridge Rider events. These four pattern types accounted for approximately 70% (25 of 37) of the cases in the study.

It was revealed that the temperature difference between the lake water and buoy air temperature (ΔT_b) exhibited some correlation with respect to the MCS intensity trend as they crossed Lake Michigan. ΔT_b was found to be is a reasonable proxy for the intensity of the marine stable layer (or even unstable layer during the fall months when the water temperature is warmer than the surrounding land mass). When this proxy was examined for a subset of cases it was found that a stronger stable layer, represented by the buoy air temperature being at least 2.5 C warmer than the water temperature, was evident in many events that maintained their intensity as they crossed Lake Michigan. Conversely, many of the weakened and dissipated cases exhibited very weak stable layers (represented by the buoy air temperature being less than or equal to 1C warmer than the water temperature).

7. Acknowledgements

Partial funding for this research came from a COMET Partners Project. Special thanks to Dolores Kiessling at COMET for her assistance in gathering data sets utilized in the study. High resolution RUC data sets were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Environmental Sciences Division.

8. References

American Meteorological Society, 2000: Glossary of Meteorology. Second Edition, pp 486.

Johns, R. H. and Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Weather and Forecasting*, **2**, 32-49.

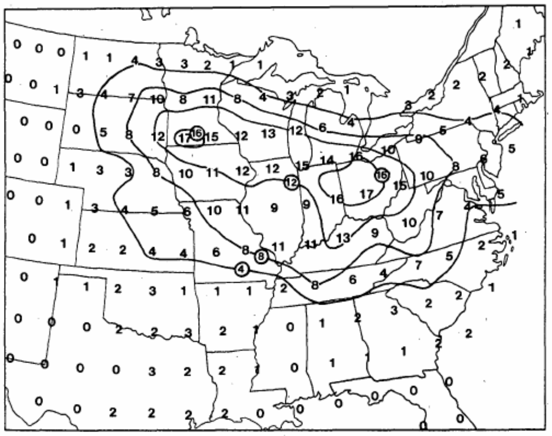

Figure 1 – Total number of derechos occurring in 2 degree latitude by 2 degree longitude squares during the months of May through August for the period 1980-1983. Image from Johns and Hirt 1987.

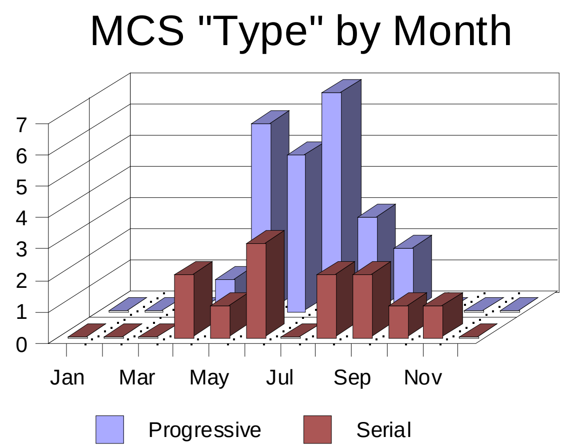

Figure 3 – MCS echo type (Progressive or Serial) distribution by month.

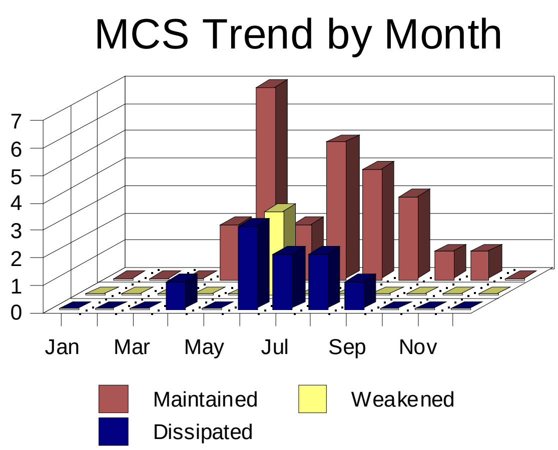

Figure 2 – Trend of MCS events by month

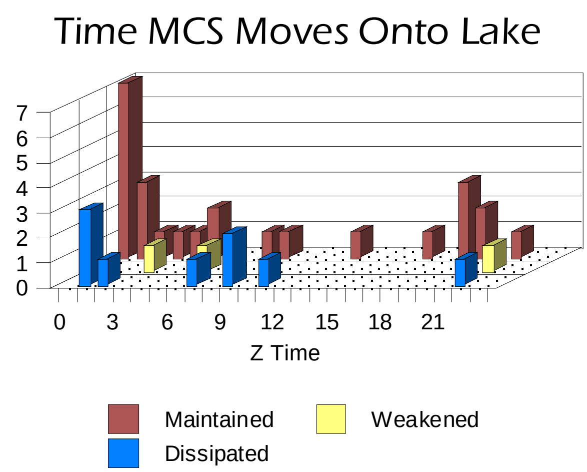

Figure 4 – Time (UTC) at which leading edge of MCS moved over Lake Michigan. Times are stratified by trend of the MCS events (Maintained, Weakened, Dissipated)

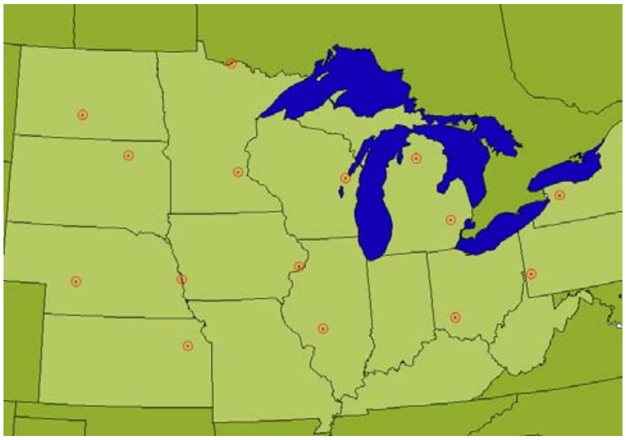

Figure 5 – Location of upper air sounding sites utilized in sounding analysis.

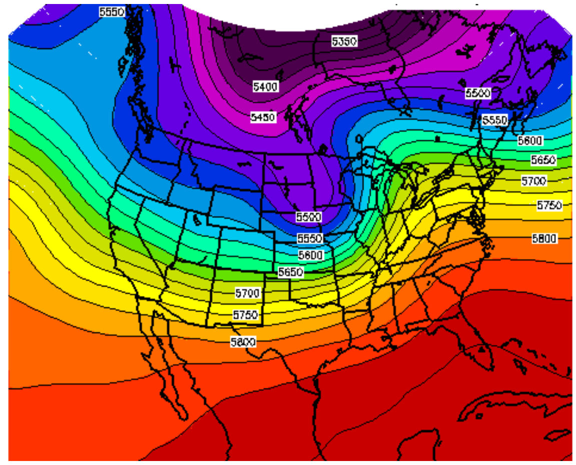

Figure 7 – Deep Southwest Flow Mean 500 mb heights. Composite image is from 00Z the evening of the MCS event(s)

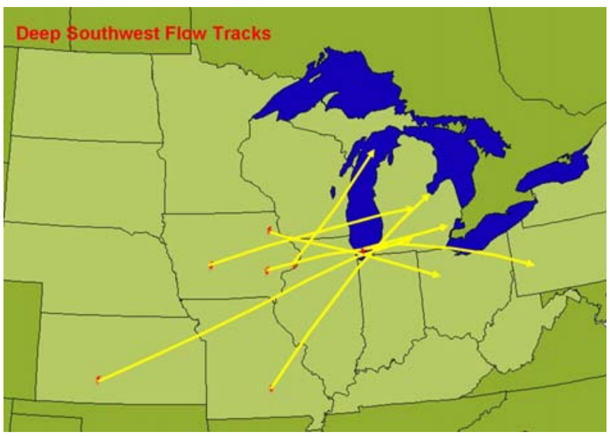

Figure 6 - Initiation locations and centroid tracks of Deep Southwest Flow events.

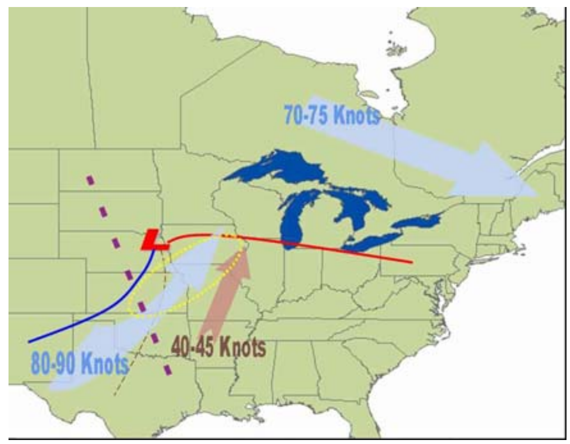

Figure 8 – Deep Southwest Flow Composites image near time of MCS initiation. Warm and cold fronts are noted by solid red and blue lines, respectively. Purple dashed line denotes location of 500 mb trough axis. Pale blue arrows highlight 250 mb jet cores. Pale red arrow indicate 850 mb jet core. Dashed yellow line encompasses area of MCS generation.

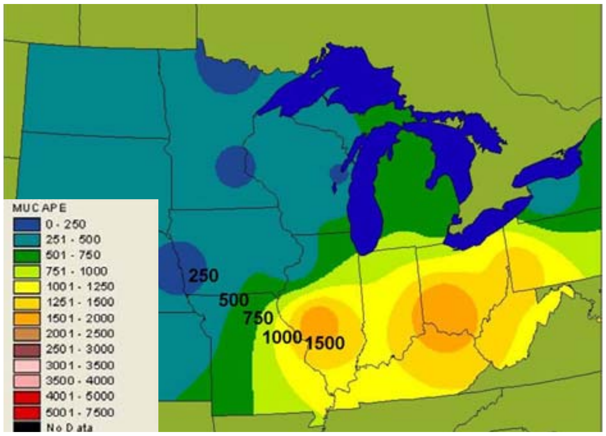

Figure 9 - Deep Southwest Flow events composite MUCAPE field 00Z evening of the event.

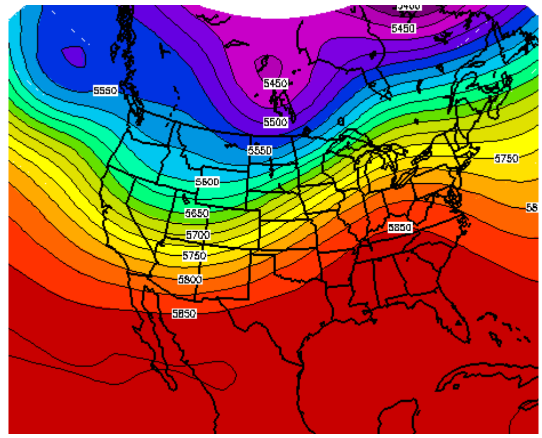

Figure 11 – 500 mb heights for Southwest Flow events. Composite image is from 00Z the evening of the MCS event(s).

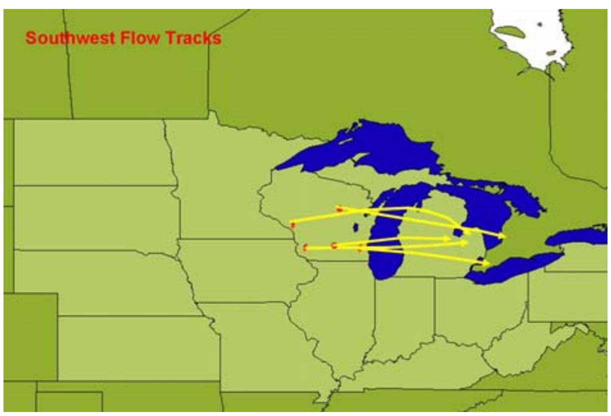

Figure 10 - Initiation locations and centroid tracks of Southwest Flow events.

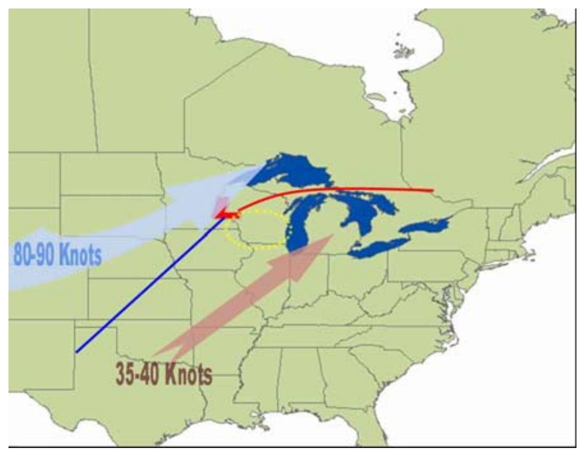

Figure 12 – Southwest Flow events. Details are the same as in Figure 8.

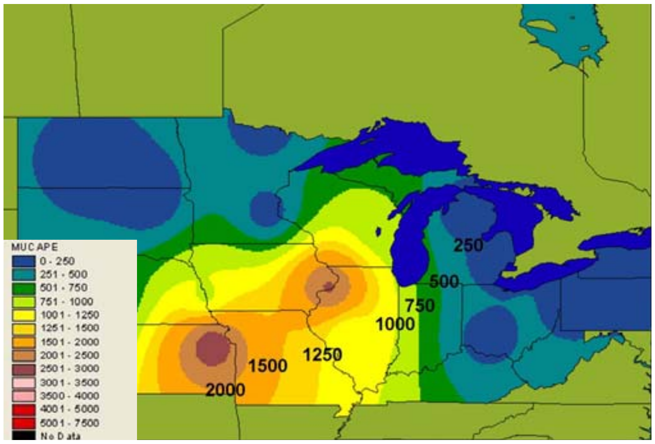

Figure 13 - Southwest Flow events composite MUCAPE field 00Z evening of the event.

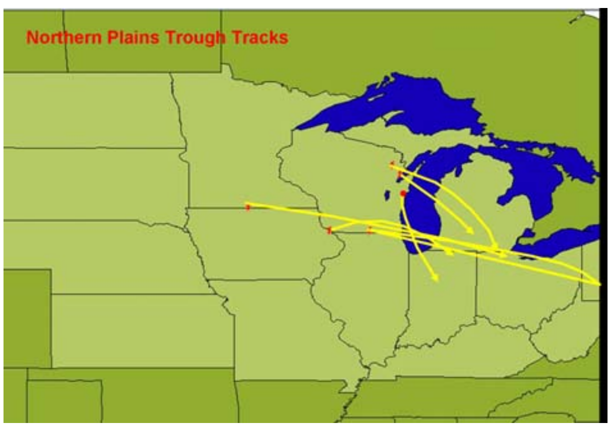

Figure 14 - Initiation locations and centroid tracks of Northern Plains Trough events.

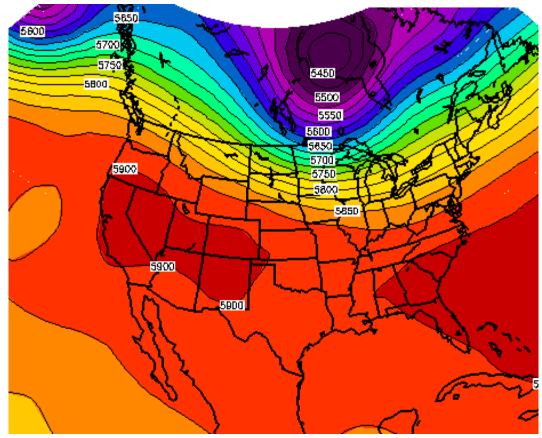

Figure 15 – 500 mb heights for Northern Plains Trough events. Composite image is from 00Z the evening of the MCS event(s).

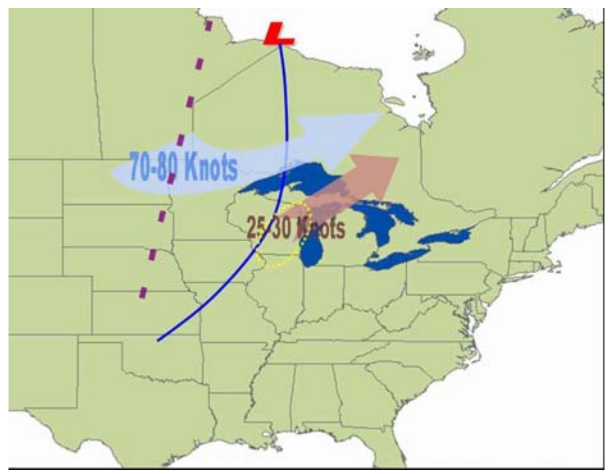

Figure 16 – Northern Plains Trough events. Details are the same as in Figure 8.

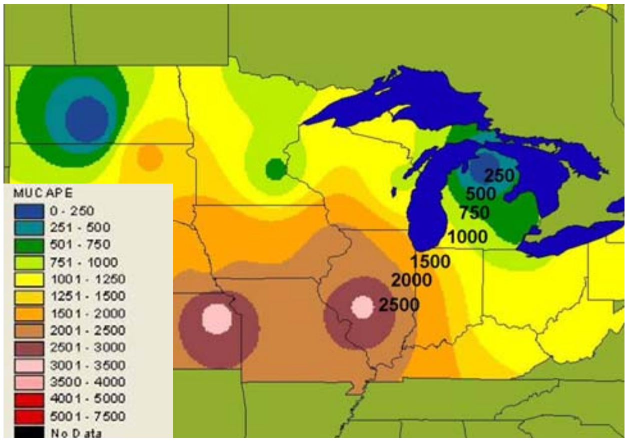

Figure 17 – Northern Plains Trough 00Z MUCAPE values.

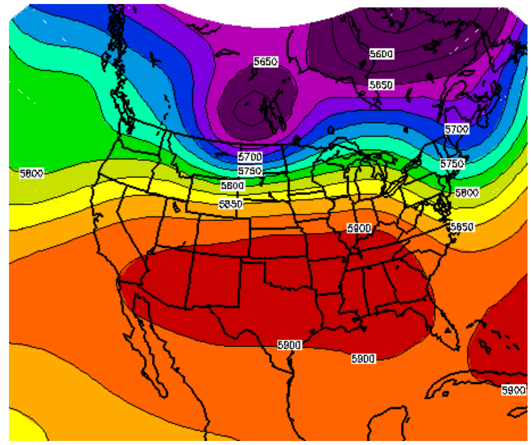

Figure 19 – 500 mb Heights for Ridge Rider events. Composite image is from 00Z the evening of the MCS event(s).

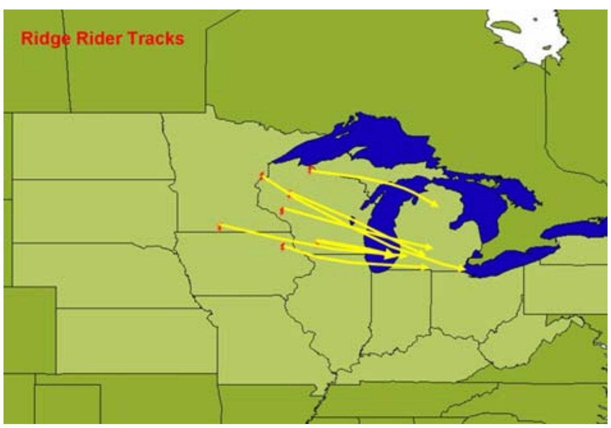

Figure 18 - Initiation locations and centroid tracks of Ridge Rider events.

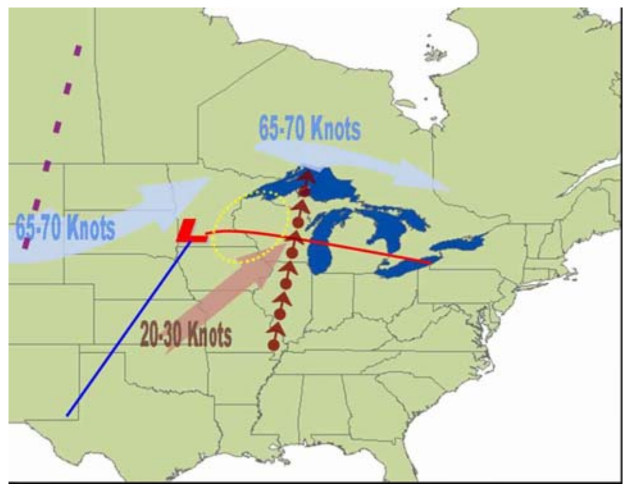

Figure 20 –Ridge Rider events. Details are the same as in Figure 8. Note: Short maroon arrows mark location of 500 mb ridge axis.

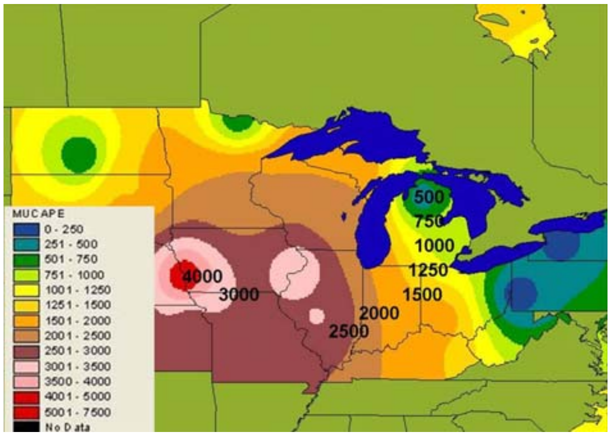

Figure 21 – Ridge Rider events 00Z MUCAPE values.

Figure 23 - Initiation locations and centroid tracks of Zonal Flow events.

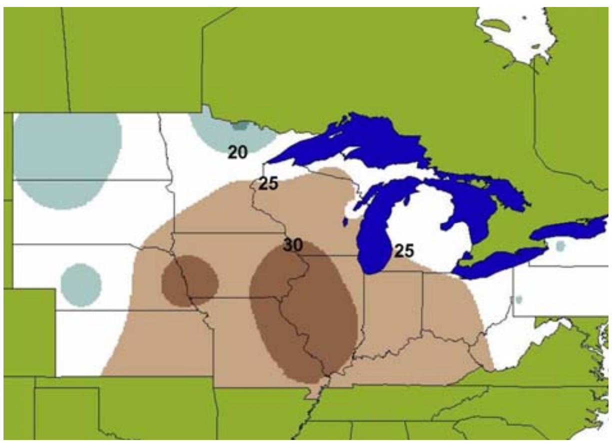

Figure 22 – Ridge Rider Max Theta-E Difference (K) values 00Z evening of the event.

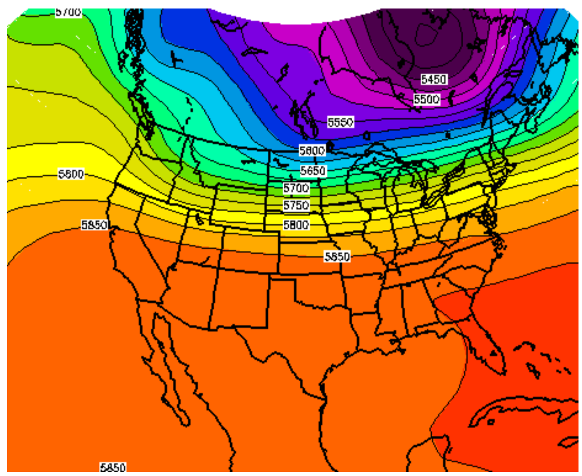

Figure 24 – 500 mb Heights for Zonal Flow events. Composite image is from 00Z the evening of the MCS event(s).

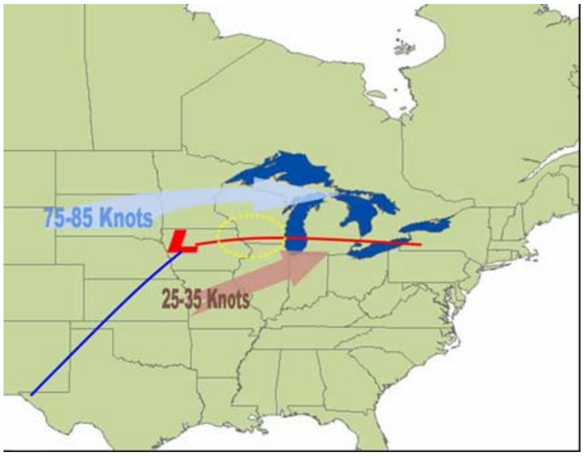

Figure 25 – Zonal Flow events. Details are the same as in Figure 8.

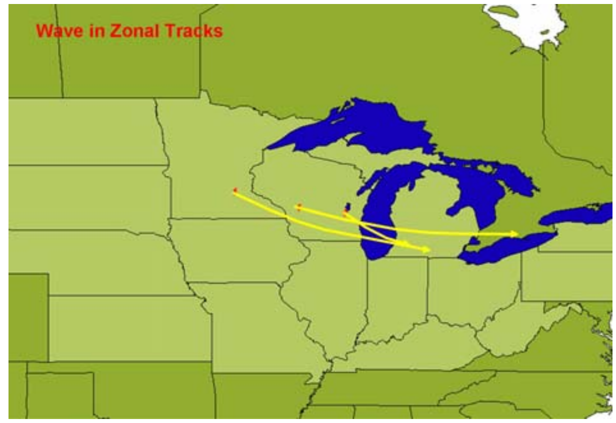

Figure 27 - Initiation locations and centroid tracks of Wave in Zonal flow events.

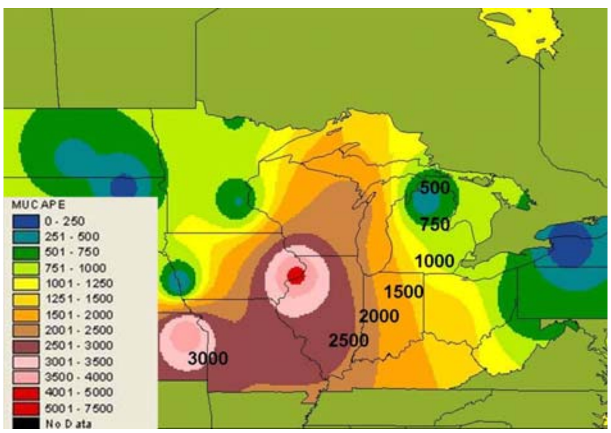

Figure 26 – Zonal Flow events 00Z MUCAPE values.

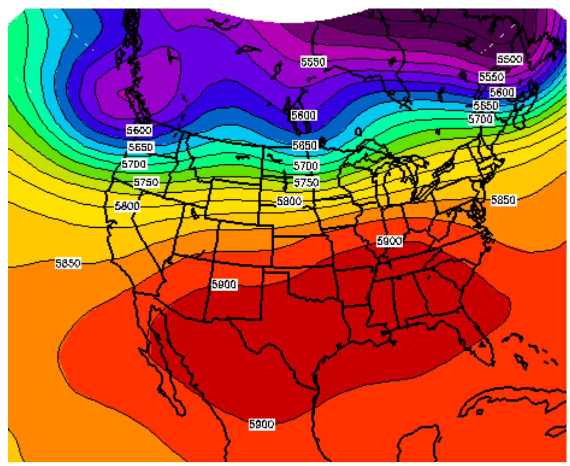

Figure 28 – 500 mb Heights for Wave in Zonal Flow events. Composite image is from 00Z the evening of the MCS event(s).

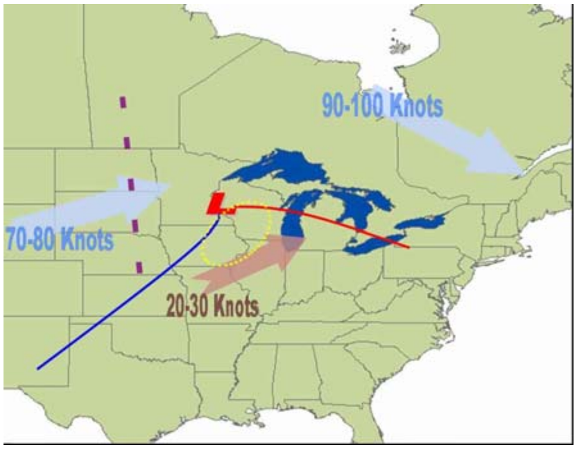

Figure 29 - Wave in Zonal events. Details are the same as in Figure 8.

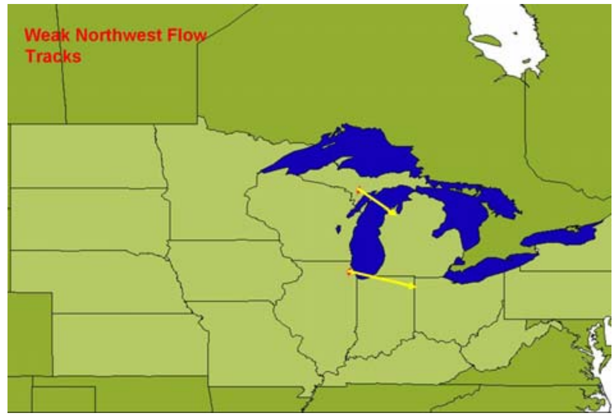

Figure 31 - Initiation locations and centroid tracks of Weak Northwest Flow events.

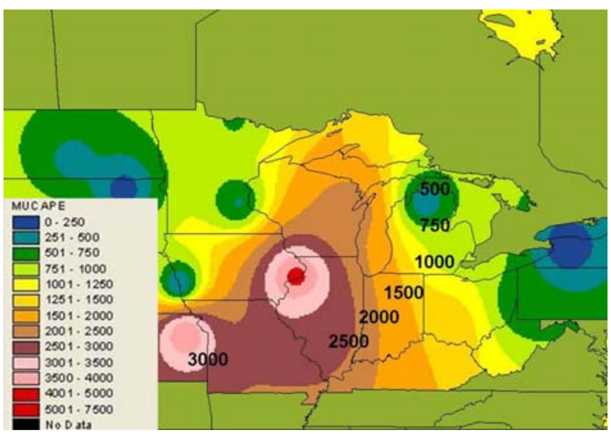

Figure 30 – Wave in Zonal flow events 00Z MUCAPE values.

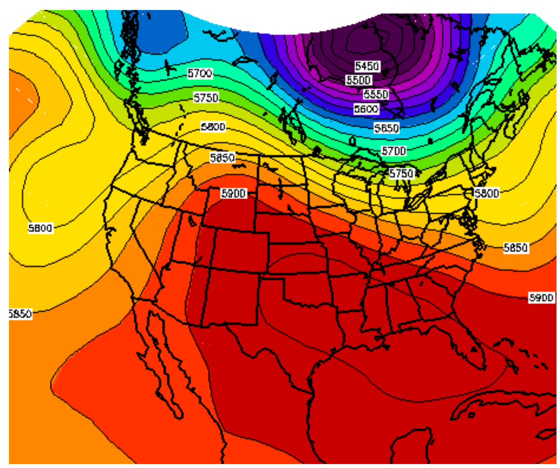

Figure 32 – 500 mb Heights for Weak Northwest Flow events. Composite image is from 00Z the evening of the MCS event(s).

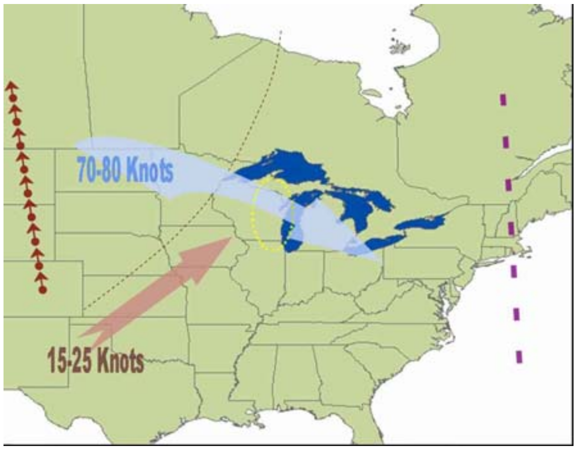

Figure 33 – Weak Northwest Flow events. Details are the same as in Figure 8. Note: Short maroon arrows mark location of 500 mb ridge axis.

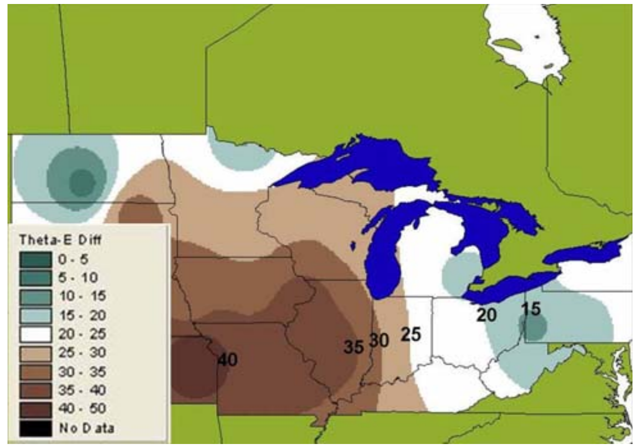

Figure 35 – Weak Northwest Flow events Max Theta-E Difference (K) values 00Z evening of the event.

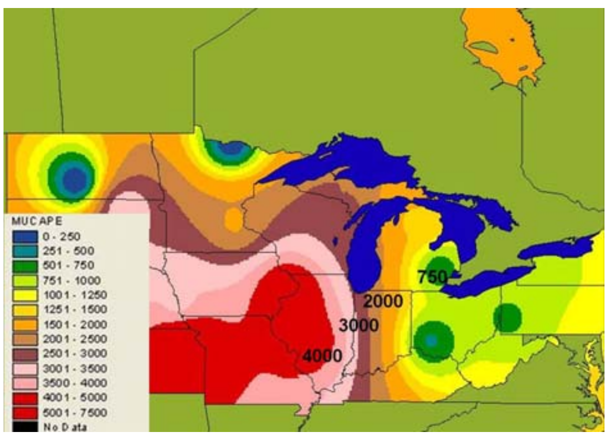

Figure 34 – Weak Northwest Flow events 00Z MUCAPE values.

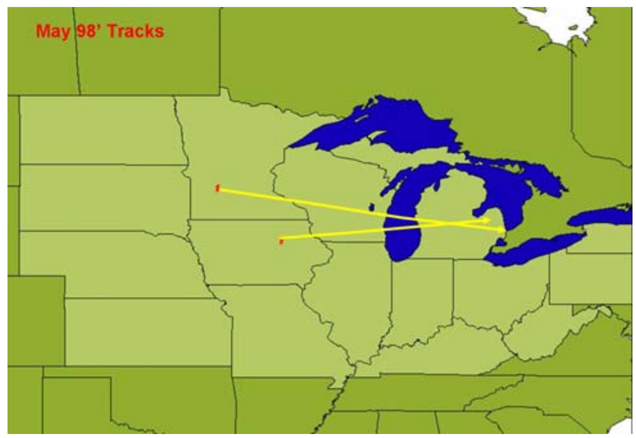

Figure 36 - Initiation locations and centroid tracks of May98 events.

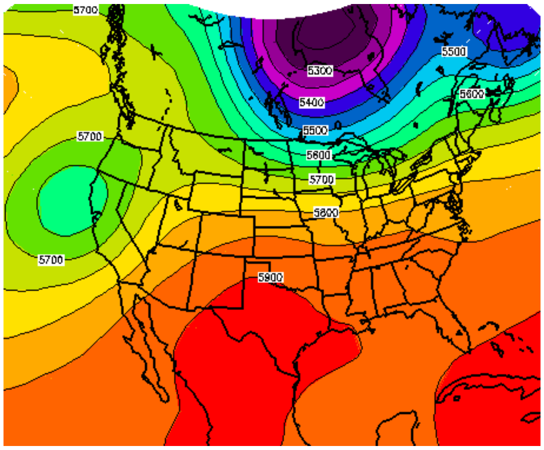

Figure 37 – 500 mb Heights for May98 events. Composite image is from 00Z the evening of the MCS event(s).

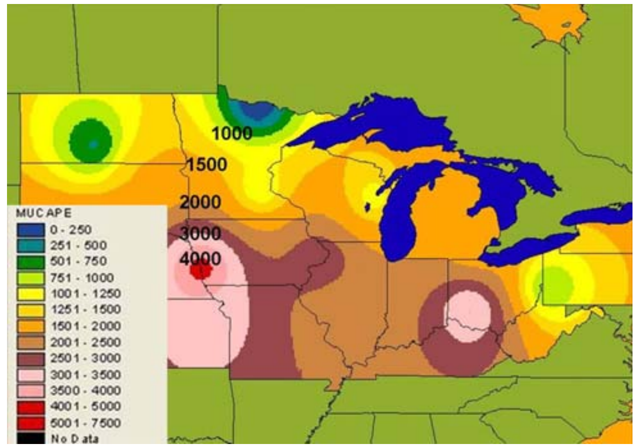

Figure 39 – May98 events 00Z MUCAPE values.

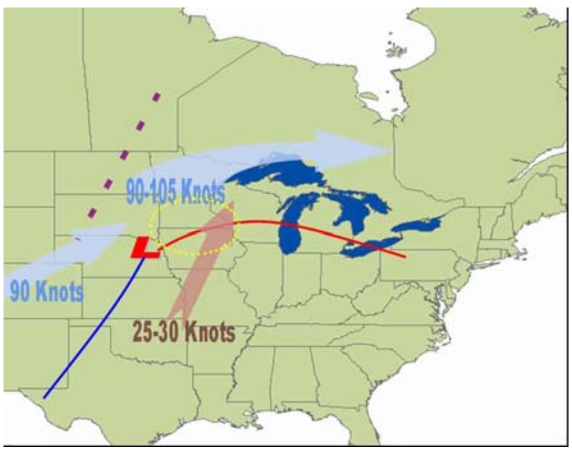

Figure 38 - May98 Events. Details are the same as in Figure 8.

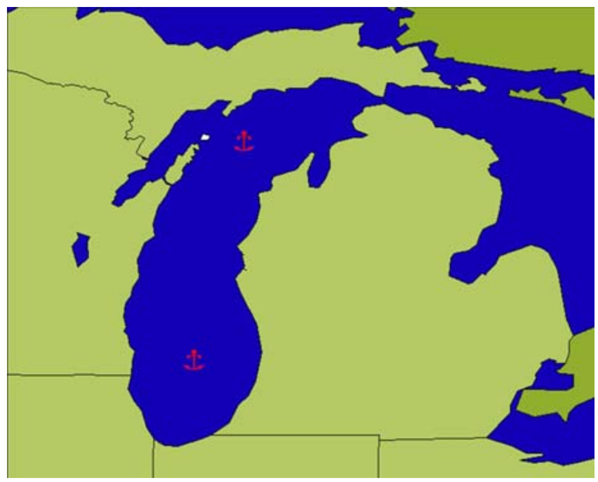

Figure 40 – Locations of Lake Michigan Buoys.