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How Super Cell Thunderstorms Interact With the Great Lakes

Introduction:

It has long been known that large bodies of water (e.g., Cox 1917) - such as the Great Lakes can affect local weather phenomena ranging from lake breezes, to lake effect snow in winter, to altered cloud cover. The majority of previous research has focused on the Great Lakes as initiators of weather. It is also important to consider the role of lakes as modulators of active weather. This has been studied in some detail for fall and spring baroclinic systems. However, relatively minute attention has been paid to the role of the Great Lakes on active severe weather. The Great Lakes create variable and complex micro environments, which can modify existing supercell thunderstorms. A supercell thunderstorm is one that is associated with a mesocyclone and has a deep and intense updraft. In other words, supercell thunderstorms have the characteristics that could lead to tornadic development. Here we examine how pre-existing supercell thunderstorms interact with the Great Lakes to gain a better understanding of how the Great Lakes influence pre-existing severe weather through the examination of small-scale variability dealing with temperature, wind, and stability.

Despite the lack of research on the influence of Great Lakes on supercell thunderstorms, some guidance can be gleaned from examinations of the influence of the urban heat island on convective activity. Rozoff et al. (2003) and Niyogi et al. (2011) show that the urban heat island can have a dramatic impact on the timing and intensity of rain events. Niyogi et al. (2011) found that within the Indianapolis area, 60% of the storms examined changed their structure through splitting, initiation, intensification, and dissipation, as compared to only 25% in the rural comparatives. This is likely due to the fact that large metropolitan cities have the ability to alter daytime convection and provide extra atmospheric lift within the warmer city bounds. By preforming a model based case study of a specific thunderstorm event occurring on June, 13 2005, Niyogi et al. (2011) found that without the urban heat island provided by the city of Indianapolis, the storm could not be simulated correctly.

Niyogi et al. (2011) demonstrated that the presence of Indianapolis modifies the regional buoyancy and winds. Removing Indianapolis from the model caused changes in simulated base reflectivity, surface energy balance (through sensible heat flux, latent heat flux, and virtual potential temperature changes), and boundary layer structure. Large bodies of water, such as the Great Lakes region, also provide anomalous small-scale environments, as compared to their land surroundings. Therefore, it is expected that large water masses such as the Great Lakes will alter and interact with thunderstorms that pass over them (e.g., Changnon and Jones 1972). Changnon and Jones (1972) showed that the Great Lakes extract heat from the air in warmer seasons, which stabilizes the air above the water as opposed to the air over land. It was also shown that in summer lakes provide a low level air mass of cold air domes reaching 100-1,500 meters above the lake.

Cold air domes over the Great Lakes are not ideal for thunderstorm development and strength because they stabilize the atmosphere. It is known that supercell thunderstorms are favored when steep lapse rates and weak inversions persist (e.g., Lemon 1980, Klemp 1987). Thus it is expected that lakes will negatively impact supercell thunderstorms. In addition to modifying stability, Changnon and Jones (1972) also stated that the Great Lakes alter central pressure of cyclones. A study on a cyclone that moved into the Great Lakes region from the west was seen to split into two distinct low-pressure centers as it interacted with the Great Lakes region. This is significant in that it shows that the Great Lakes do have the ability to alter weather that moves toward them and not just serve as an initiator of weather phenomena. Changnon and Jones (1972) found that the Great Lakes promoted an amplification of lows (highs) in the winter (summer). This suggested that the impact of the Great Lakes on preexisting severe weather will vary seasonally. Angel and Isard (1996) showed similar outcomes on the interaction of the Great Lakes on mid-latitude cyclones. It was found that in the winter, cyclones or low-pressure systems would accelerate as they neared the lake as well as intensify upon entering the Great Lakes region. These mid-latitude cyclones also tended to linger within the Great Lakes region and then weaken upon their departure. In the summer, cyclones accelerated as they neared the Great Lakes, but only intensified with about half the magnitude of their winter cyclone comparables. Cyclones in the summertime also did not linger within the Great Lakes Region, nor was there any change in speed or strength upon their departure (Angel and Isard, 1996).

Many studies have been conducted on how the Great Lakes impact winter weather. It is known that the Great Lakes can induce heavy lake effect snow events and create other weather such as clouds, fog, and lake breezes. The Great Lakes have been seen to be capable of producing upwards of three times more precipitation annually as compared to their surrounding areas (Scott and Huff 1996). The Great Lakes can release a large amount of energy known as latent heat. Latent heat is the energy resulting from water evaporating at the surface, which then releases heat into the atmosphere. It is believed that through this process, the Great Lakes induce cloud formation through microphysical processes that ultimately leads to enhanced observed snowfall rates within meso -ß- scale convection (Hjelmfelt 1990). These findings may help to explain the lake effect snow event that impacted areas of northeastern Ohio and northwest Pennsylvania during the year of 1996 from the 9-14 of November. This particular event resulted in over $3 million dollar's worth of insured damage claims, hundreds of injuries, and 8 deaths (Schmidlin and Kosarik 1999). Since it is to be expected that the Great Lakes enhance precipitation, it is not surprising that Changnon and Jones (1972) discovered that areas downwind of Lake Michigan observed an average of 72 cloudy days as compared to 19 days observed upwind from the lake. When colder air moves over warmer water, the water heats up the bottom layer of the air causing the lake water to evaporate. This increases the buoyancy of surface air, which induces lift. As the air rises, it cools and condenses forming clouds and eventually precipitation, given an adequate supply of cloud condensation nuclei.

Apart from cloud formation, the Great Lakes can also have a significant impact on area temperature. It was found that the eastern side of Lake Michigan experienced more frequent lake breezes than the western side and that on average; both sides of the lake saw the highest number of lake breeze occurrences in August (Laird et al. 2001). The change in temperature from water to land surface is crucial to the strength and frequency of lake breezes. Higher pressure forms over the lake due to the cooler air above the lake relative to the land and lower pressure over the land, thus inducing a lake breeze. As stated earlier, supercell thunderstorms do not thrive under high pressure conditions so it is to be expected that when a lake breeze forms, high pressure exists over the lakes which should act to weaken existing supercell thunderstorms propagating toward them. These lake breezes can be quite influential on local observed conditions. For example, it was found that Lake Michigan causes a net cooling of average summer temperatures by as much as 2°C within 80 km of the shore (Scott and Huff 1996). Temperature differences of this magnitude greatly impact societies, economies, and climatology of communities near shore to the Great Lakes.

The primary goal of this study was to understand what sets the storm environment near Lake Michigan. Physical intuition suggests that the Great Lakes will always attempt to reduce the intensity of active convection. However, there may be a few situations in which the lake actually increases the severity of convection (as discussed in the results). Section 1 will discuss the hypotheses associated with this goal. Section 2 will discuss the methodology, including the data types and analysis conducted. Moving into section 3, results will be presented followed by a discussion section with conclusions and remaining questions.

1. Hypotheses:

The Great Lakes can create microenvironments that can alter storm structure and therefore storm magnitude, as can be seen by comparing land and water radar returns. Depending on what angle the storm approaches the lake-induced microenvironment may alter storm structure and magnitude in different ways. The ultimate goal would be to define a set distance from the lakeshore that the lakes microenvironments can be seen to affect storms. This is important so that it is understood as to what distance it begins to become important to start applying the rules of what happens to storms when they interact with the Great Lakes and adjust forecasts and warnings accordingly. The variables assessed for changes within the lake induced micro environments included surface heat fluxes, lapse rates, wind speeds, and pressure gradients.

2. Methodology:

The necessary storm report data was gathered from the NCDC (National Climatic Data Center), storm reports archive. A 30 year time frame was chosen, as this is the standard time frame for climatology, of storm reports across southern Wisconsin was collected. The region of study coordinates, (latitude and longitude), starting from the southwest corner moving in a clockwise fashion form a square area as follows: (42, -90), (44, -90), (44, -87), (42, -87). This subject area was chosen because it lies adjacent to the southernmost extent of the Great Lakes, Michigan, therefore having the best chance at seeing prominent and more frequent severe weather outbreaks as gulf moisture, heat, and instability are more readily available in this region as compared to the other Great Lakes. Also, the land to water temperature gradient of Lake Michigan is great enough to create a sufficiently different heat flux as a storm moves over the lake. Heat flux is a major component to supercell thunderstorm development because heat fluxes can destabilize the atmosphere, which promotes supercell development. The greater the differences in surface to atmosphere heat flux over land versus water, the more likely the storms are to respond to the lake in some way. This region was also chosen because to the west, there are no large bodies of water to speak of and typically storm movement is from West to East or Southwest to Northeast. This made southern Wisconsin a prime subject area for this study because geographically speaking it provides a means of comparing land environmental parameters to a large body of waters parameters, and then comparing how supercell thunderstorms behaved over each by looking into storm reports and radar data archives.

Significant storm events were chosen for each year based on the number of reports being issued for the event, the magnitude of the storm reports, defined by both aerial coverage (area of land subject to damage) and strength (the magnitude of the winds or hail size reached and extent of associated damage in monetary value), and specifically storm reports that had more damage reported away from the like as compared to near the lake. This was done in order to compare what sort of storm reports were observed inland from the lake and near the lake shore, and then analyzed with radar data and data from North American Regional Reanalysis (NARR; Mesinger, and Coauthors 1996), to check for statistically significant parameters that altered storm behavior and thus the observed storm reports. Comparing the storm reports to radar and NARR data gave us an idea of what the environment over the land and water was like at the time of the report and made analyzing the influence of the lake possible.

Data retrieved before 1995 had to be omitted as archived radar data can only be accessed as far back as that year and also because the validity and amount of the storm reports available before 1995 are low. Radar data was collected through NOAA's NCDC radar archive for the Milwaukee/Sullivan site.

After collecting all the storm reports from 1995- present, they were filtered out under the criteria listed previously. High wind events exceeding the common 55-mph threshold and hail greater than the 1-inch diameter threshold to become severe were chosen. These thresholds were chosen so that the sample size would be statistically significant. Special interest was given to events that had many damage reports issued while they were far inland from the lake, and decreased as they reached the lake shore. Another set of reports reviewed were those that the storm reports did not seem to follow a downward trend in strength or occurrence as they moved toward the lake shore. Events classified as strengthening were those in which the maximum reflectivity of radar returns increased as storms propagated toward the lake and exhibited an increase in strength or frequency of the associated storm reports.

3. Results:

Lakes primarily influence the atmosphere via surface and latent heat fluxes. These fluxes in turn can influence the low-level stability, and surface pressure gradient. This suggested a consideration of: sensible heat, dew point, winds, and lapse rates. Initial evaluation of NARR data divided into three categories (strengthening, weakening, and maintaining intensity) revealed no statistically significant results. To increase the sample size the number of categories was reduced. The category that the storm events ultimately displayed no changes as they propagated toward that lake was combined with the events in which showed strengthening. Here strengthening was defined as radar returns DBZ values increasing as the storms propagated toward Lake Michigan and associated storm reports increasing in intensity with the same fashion. This was done in light of the original question posed: How do supercell thunderstorms interact with the Great Lakes?

Our results suggested that when the land-water temperature gradient exceeds 10^{o}C, Lake Michigan modifies storm strength. Figure 1 displays a sample of one such event when a storm weakens.

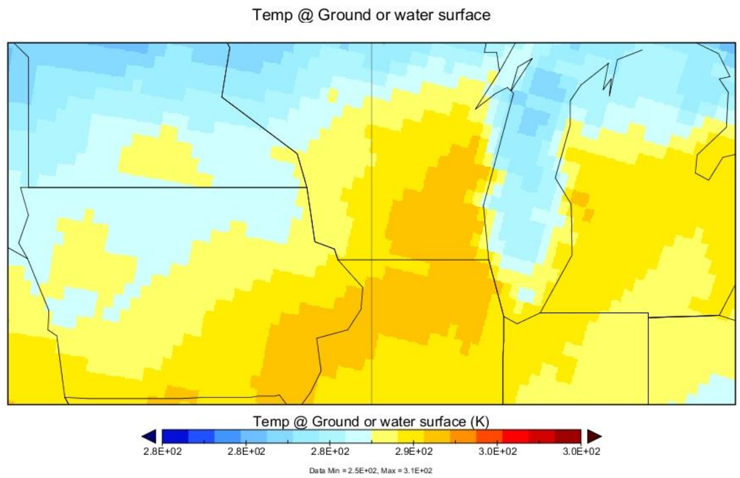

Figure 1) land and water surface temperature NARR data from 3z on 6-24-2004

As can be seen in figure 1 the land-lake temperature differs by about 15˚ Celsius which is above the 10˚ Celsius threshold for when the Great Lakes have been seen to become capable of altering pre-existing supercell thunderstorms. In this particular case, since the gradient differed by over 10˚ Celsius, the storms weakened and can be seen to do so in figure 2 of associated radar returns for the event.

a.) b.) c.)

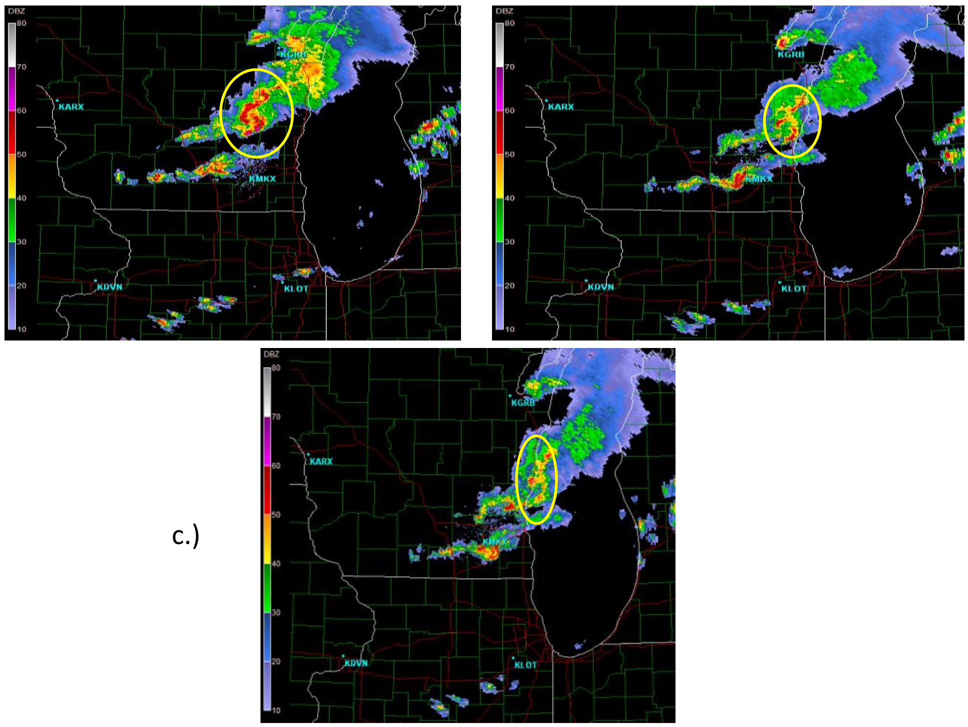

Figure 2 base reflectivity from 6-24-2004 at a.) 2:00:30z, b.) 2:30:29z, and c.) 2:45:29z respectively, with area of interest within yellow ovals to show weakening progression over time.

As can be seen in figure 2, the storms weakened as they propagated eastward toward the lake as expected by the land to water temperature gradient. The associated radar returns show a general downward trend in the storms eastward propagation.

If the temperature gradient between land and water is less than 10^{o}C, the lake did not impact existing supercell thunderstorms. When this temperature gradient increased to above 10°C, storm strength and structure was modified and existing supercell thunderstorms were weakened in their associated storm report damage data. An event that displays this land to water temperature gradient of being less than 10°C and the storms were allowed to strengthen occurred on 8-1-2003. This event's land and water temperature gradient aspects serve to portray what holds true across all of the non-weakening events. In this particular event, a storm initiates inland around the Waukesha county area and propagates NE toward Lake Michigan. Figure 3 shows a reference of Waukesha County on a Wisconsin map.

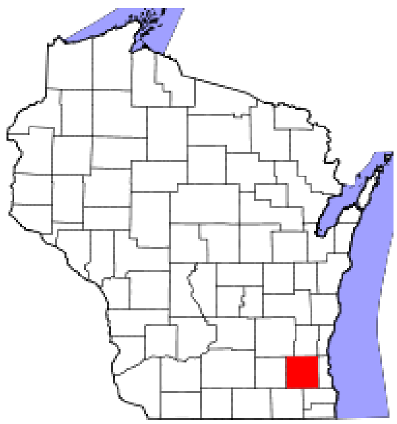

Figure 3) Waukesha county of southeastern Wisconsin in red.

As it approaches the lake, the storm either begins to stall out and better organize itself, or it begins to back build. It then merges with storms coming into the region from the NW and was ultimately able to drop one inch diameter hail damaging fruit farms in the community of Mequon, and wind gust to 56mph in Port Washington, which was among the hardest hit communities. Figure 4 displays the observed land and water surface temperatures for the time of the event.

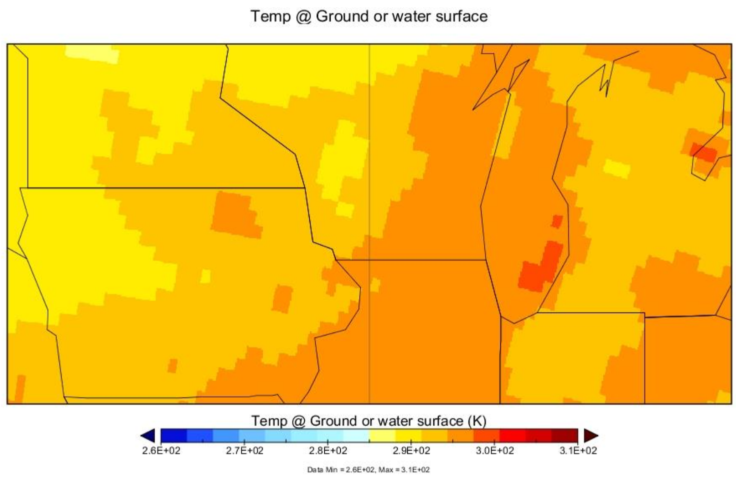

Figure 4) land and water surface temperature NARR data from 9z on 8-1-03

In figure 4, the land to lake temperature gradient is minimal and well below the 10 degree Celsius threshold. However, what makes this event especially unique is the convergence that is occurring along the lakeshore where the storm stalled and developed further. In analyzing the wind field and looking at local surface station reports, it appears that a localized lake breeze provides a pocket of low level moisture convergence. Supercell thunderstorms thrive off of surface convergence so storms that propagate into this region should strengthen upon interacting with the lake breeze coupled with an interaction with an advancing cold front from the west. This interaction can be seen in figure 5.

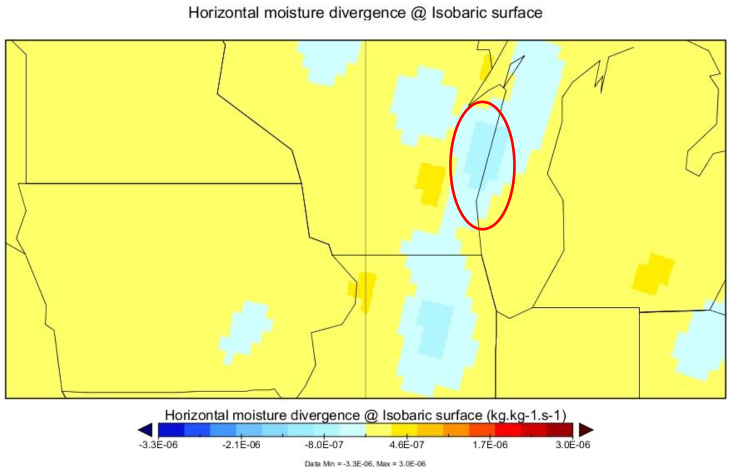

Figure 5) horizontal moisture divergence at isobaric surface NARR data from 9z 8-1-03 with red oval around subject area of interest.

Figure 5 shows that as the storm propagated NE toward the lake it was entering a region of more negative horizontal moisture divergence at the isobaric surface, (within the red oval), or moisture convergence provided through a localized lake breeze over that area at the time. Without running a model simulation to see if the storm reacts the same with and without the lake breeze it cannot be determined if the lake breeze is a controlling parameter involved within the storm strengthening but we believe this to be the case. Another variable found to be significant in altering supercell thunderstorms ability to strengthen or weaken as they propagate toward the Great Lakes is surface fluxes.

It was found that when the storm events analyzed were allowed to maintain their intensity or strengthen the vertical temperature gradient between the water and low-level atmosphere (30 m) was less than .28˚ C/m and in times when supercell thunderstorms were weakened by the Great Lakes this value was greater than .28˚ C/m. This implied that weakening storms experience a strong sensible heat flux into the lake. Figure 6 shows the temperature difference between 30m above the ground and the surface for the strengthening event on 8-1-03.

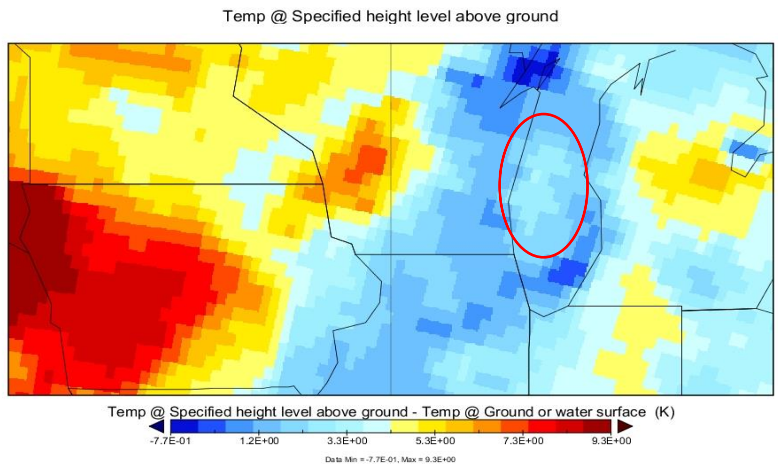

Figure 6) temperature at specified height level above ground NARR data from 9z 8-1-03 with red oval around subject area.

As seen in figure 6, the over the lake threshold of .28˚ C/m is not met and in fact, as the storm propagated to the NE it entered an area where the atmosphere was giving up less heat to the lake as seen within the red oval. This meant that the supercell environment was more favorable in this region because there was more heat to work with in the atmosphere.

By analyzing the severe weather event that occurred on 8-1-03 it appears that in some scenarios, when the right variables comes together the lake is capable of serving as a strengthening mechanism for supercell thunderstorms that propagate toward it. In this scenario, the land to water surface temperature difference was less than 10^{o}C, the low level moisture convergence generated by the lake breeze, and the pocket of higher heat available in the atmosphere, allowed this storm to strengthen. As expected and alluded to, the Great Lakes can also frequently serve as a weakening mechanism through these parameters.

When the land to water temperature gradient differs by more than 10˚C, supercell thunderstorms weaken. A severe weather event on 6-6-1999 will serve as a representative of all weakening events. In this particular event two tornadoes, 10 gustnadoes, golf ball sized hail, and 80-mph straight line winds were observed. All of these counties are inland from the lake. The eastern and northernmost report is from Cedar Grove on the Sheboygan and Ozaukee county line at a weak 55-mph gust. It is clear on both the storm reports and radar that this event weakened at it propagated NE toward the lake. When looking at the surface temperatures for the time of the event, we can see that they differ by more than the 10 degree Celsius threshold (Figure 7).

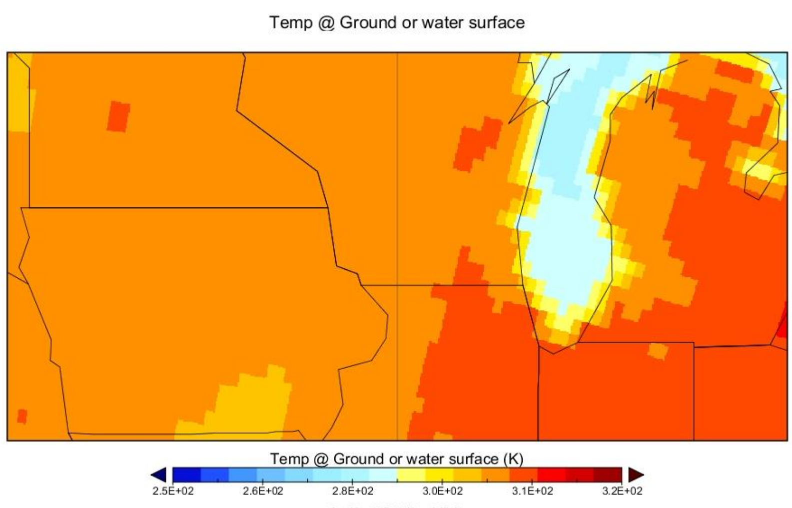

Figure 7) land and water surface temperature NARR data from 21z 6-6-1999

Figure 7 shows us that on 6-6-1999 the land to water temperature gradient is approaching 20°C. It is to be expected that this storm event would weaken as it propagated NE toward the cooler lake waters. Not only does the surface temperature of the land versus the water support weakening by breaching the threshold, but the lake heat absorption values do as well, as shown in Figure 8.

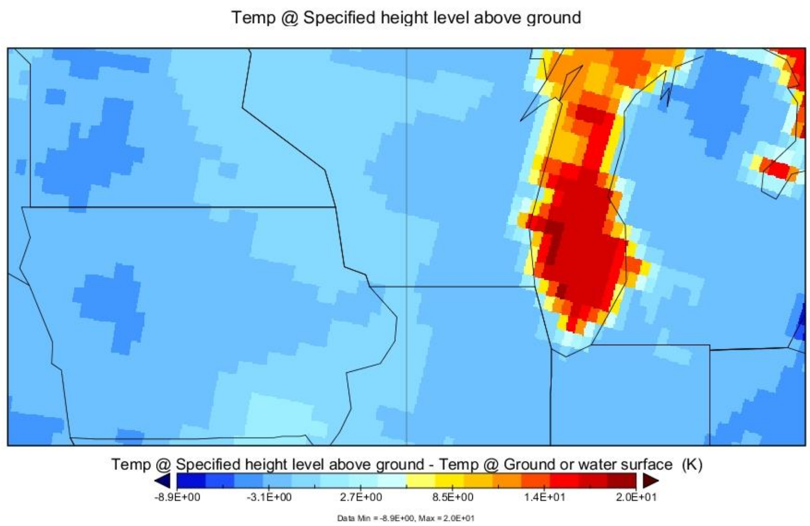

Figure 8) temperature at specified height level above ground NARR data from 21z 6-6-1999

As you can see Figure 8 is implying that the sensible heat flux will be largely negative leading to storm weakening. This in combination with the land water temperature gradient threshold explains why the storms on 6-6-1999 weakened.

<u>Discussion:</u>

It can be said that land and water surface temperature and the gradient between the two is very important to supercell interaction with the Great Lakes. It was found that a 10 degree Celsius land to water surface temperature gradient is crucial to supercell storms weakening or strengthening when toward the Great Lakes. When the gradient is less than 10^{o}C, the lake does not have an effect on supercell storms. When the gradient is more than 10^{o}C, the lake begins to alter supercell thunderstorms. Another variable determined to be important in how supercell thunderstorms interact with the Great Lakes deals with how much heat the atmosphere gives up to the lakes. Here it was found that the critical vertical temperature gradient threshold is .28˚ C/m. When the lake has a vertical temperature gradient compared with the atmosphere on the order of .28˚ C/m or less, storms are allowed to strengthen. When the lake is absorbing heat from the atmosphere greater than .28˚ C/m, supercell thunderstorms weaken. While the results relating to the vertical temperature gradient are not surprising, knowledge on vertical and horizontal temperature gradients interactions with existing supercell thunderstorms is slim and needs to be analyzed further. These gradients could be important to supercell thunderstorm strength prediction as they move among differing vertical and horizontal gradients.

Many other questions remain as to what variables and related thresholds control supercell thunderstorms. Ways to build upon and improve this research deals with gathering a larger sample size of supercell thunderstorm events to analyze so that the results can become more coherent and significant. With the current sample size, a complete story was not able to be painted, but a coherent one was able to be established in that two specific thresholds were found to be significant in lake supercell thunderstorm modification. These thresholds include the land to lake temperature gradient of 10˚C and the .28˚ C/m vertical temperature lake heat absorption. Model simulations could assess whether or not the thresholds determined here are critical to supercell intensity. Simulations could also help assess the role of lake breezes in thunderstorm structure and initiation. Further questions to look into include how do we predict and forecast lake breezes, as the one case study on 8-1-03 proved to be quite a significant factor in storm strength and outcome. Another interesting aspect to pursue in the future would be to look at the reflectivity of storms along the lakeshore counties and see how the reflectivity changes as the storms move out over the water. Once that is done, it would be interesting to see if there are any critical values to DBZ reflectivity in relation to the land to water temperature gradient and the amount of heat the lake is absorbing. For example, it would be a great improvement to forecasting supercell thunderstorms impacts to lake shore counties if a relationship being observed DBZ reflectivity values inland were correlated to lake surface temperature and heat absorption, and in turn forecast if that storm will weaken or strengthen as it propagates toward the Great Lakes.

Another area of further inquiry lies within storm angle of propagation. It does appear that angle of propagation could have vastly different impacts on storm strength and structure, in that head on collisions with the lake appear to allow storms to hold their strength whereas coming in at any sort of angle has other affects dealing with weakening or strengthening. We cannot conclude why this is but we imagine that when coming in at an angle the lake can more readily alter supercell structure as compared to a head on collision based on the amount of time that lake has to interact with the storm. Moving in on the lake in an angled fashion leads to the storm being within close bounds to the lake for a longer amount of time. Thus, it may be expected that for this longer time association, the lake is able to interact with the storms further and alter them more so than the less time available in a head on collision.

Many interesting pursuits in researching how the Great Lakes can alter pre-existing weather phenomena such as supercell thunderstorms remain. The results found in this study set the stage for further inquiry and lay out that surface temperature and lake heat absorption play a key role in the interactions supercell thunderstorms have with the Great Lakes. These variables set the stage for improved forecasting techniques, especially in areas bordering large bodies of water such as the Great Lakes that have the ability to create micro environments.

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