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Diagnosing the Impacts of the Great Lakes on an Alberta Clipper

G.E. MANN[1]

ABSTRACT

The impacts of the Great Lakes upon the regional weather extend much further than the lake-effect snow bands generated by an individual lake. The Lakes also can collectively impact the regional weather. This lake-aggregate effect can attract weak sub-synoptic scale cyclones, such as Alberta Clippers, passing near or through the region. What is more important is that the modification of the wind field is significant, such that a place that would not have seen lake-effect snow receives a large amount of snow. In fact, it is not uncommon to see these weak cyclones linger in the region for 1-2 days enhancing snowfall amounts even more.

An investigation of this phenomenon focuses on a characteristic case that occurred from 13 Dec. 1989 to 16 Dec. 1989. This particular cyclone was an Alberta Clipper passing to the south of the Lakes Region. Precipitation amounts associated with the sub-synoptic cyclone were substantial in some areas. The enhanced precipitation may be a result of a number of factors. For instance, the modification of the path and intensity of the system may play a vital role in the distribution of precipitation. Other factors involved include the enhanced convergence forced by the lake-aggregate circulation and placement of lake effect snow bands with relation to the aggregate circulation.

This study examined the salient features of these "trapped" systems. The case presented demonstrates that these types of systems have the capability of producing large amounts of snow in short periods of time. However, due to the lack of resolution of numerical weather prediction models, the improvement in forecasting will be a result of the forecaster's knowledge of such events. Consequently, a rather simple but effective diagnostic technique to examine the lake-aggregate phenomenon is demonstrated. As a result, this investigation is a first step toward improving our knowledge of the evolution and features of these events.

Key words: lake effect, lake aggregate, Alberta Clipper

1. INTRODUCTION

The impact of the Great Lakes upon the regional weather and climate during the winter season has been recognized for decades (Cox, 1917; Petterssen and Calabrese, 1959). The primary mechanism responsible for Great Lakes' impact is that during cold air outbreaks the lake surface is often significantly warmer than the overlying air. It is this temperature difference between the lake and the atmosphere that produces the convectively unstable environment favorable for the development of the well-known lake-effect snow squalls (Niziol, 1987). These snow squalls impact the lee side of an individual Great Lake (Eichenlaub, 1979). However, the snow squalls are small, localized phenomena forced by a single lake and have little direct impact away from the immediate shoreline region (Norton and Bolsenga, 1993).

Moreover, the Great Lakes can have an influence away from the lake shore region. The result of this influence is that the lower atmosphere in the Great Lakes Region (GLR) is often warmed and moistened by a combination of all the Great Lakes during a cold air outbreak (Petterssen and Calabrese, 1959, Fritsch et al., 1989). This collective contribution can lead to the formation of several lake-aggregate effects (LAEs) (Sousounis and Fritsch, 1994 [hereafter

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[1] Western Michigan Family Broadcasting, Inc.; P.O. Box 907; Jenison, Michigan 49429-0907 (Formerly of Department of Atmospheric, Oceanic and Space Sciences; The University of Michigan; Ann Arbor, Michigan)

referred to as SF94]). One such effect is a meso-α scale circulation that develops over the region in response to the aggregate heating (SF94). In contrast to the lake-effect snow squalls that are on the scale of a single Great Lake, the LAE is on the scale of the entire GLR or possibly larger (SF94). Consequently, the lake aggregation can have an impact on the synoptic scale pattern in and around the GLR (Boudra, 1981).

Previous observational studies (Fritsch et al., 1989; Silberberg, 1990) have demonstrated qualitatively the impacts of the lake-aggregate during cold air situations on synoptic-scale extratropical cyclones (SEC). Numerical studies (Danard and Rao, 1972; Boudra, 1981; and SF94) have demonstrated the impacts quantitatively. While these numerical studies relied on sophisticated high-resolution numerical models to quantitatively assess the lake-aggregate effects, it is possible to do so observationally. In this study the lake-aggregate effects on an Alberta Clipper, a sub-synoptic scale cyclone (SSC), will be quantified using a developed diagnostic technique on existing observational data.

A conceptual model of LAE on SSCs is presented in section 2. A case study of the Alberta Clipper from December 1989 is presented in section 3. The extraction analysis is presented in section 4. Finally, the summary and conclusions are presented in section 5.

2. A CONCEPTUAL MODEL OF THE LAKE-AGGREGATE EFFECT

Sousounis and Shirer (1992) along with SF94 have focused upon the quantitative aspects of the meso-α scale LAE from an analytical and or numerical model perspective. However, the purpose of this section is to present a qualitative, conceptual model of the LAE. This will aid the interpretation of observational results in the case study presented in section 3 and the extraction method presented in section 4.

a. Conceptual development of the lake-aggregate effect

During the winter season, frequently the planetary boundary layer air (PBL) is colder than the lake surface. Typically this is a result of cold air being advected over the relatively warm lake surface behind an Arctic front. The resultant thermodynamic configuration in the PBL is unstable and convective cells develop (Sousounis et al., 1989). The convective cells transfer sensible heat and moisture from the lake surface into the lower troposphere (Fig. 1a) (Boudra, 1977). The instability may result in lake-effect snow band development (Braham and Kelly, 1982; Sousounis, 1993). However, the added heat and moisture in the PBL do not remain concentrated over the lake. Some residual heat and moisture is advected into the region downwind of the lake by the basic state flow (Fig. 1b). This process is common to all the Great Lakes when the surface is ice-free. The plumes of warmth and moisture from the individual lakes eventually merge with one another (Fig 1c). The corresponding merging (advecting) time scale is typically about a day (SF94). Consequently, the entire region is warmed and moistened.

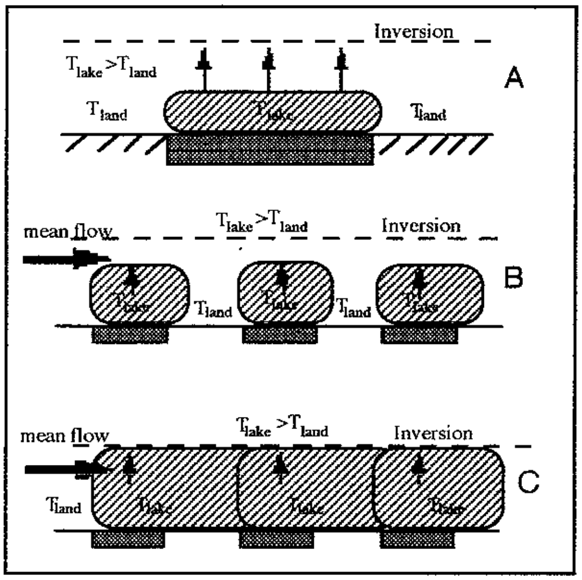


Figure 1: Schematic illustrating the evolution of sensible heat transport over the lake-aggregate. T_{lake} and T_{land} are the characteristic temperatures over the Lakes and over the land surface respectively. (A) Initial stage. (B) Development stage. (C) Mature stage.

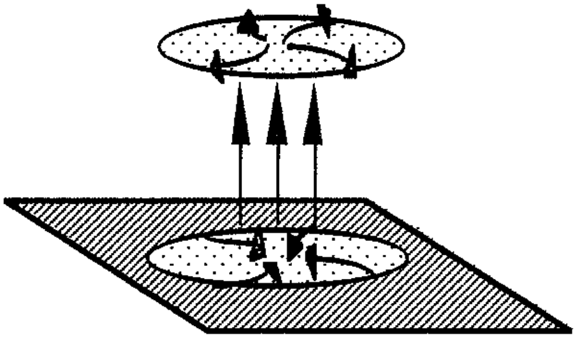


Figure 2: Schematic illustrating the hypothetical lake-aggregate circulation over the Great Lakes.

The warming of the PBL causes the pressure at the surface to lower and the heights at pressure levels above the PBL to rise maintaining a hydrostatic balance. This adjustment in the mass field eventually induces a change in the momentum field throughout the PBL. Namely, the lower pressure at the surface produces a cyclonic circulation; and the higher heights above the warmed layer produce an anti-cyclonic circulation (Fig. 2). The circulation configuration is consistent with convergence near the surface and divergence aloft which satisfies continuity (Fig. 3a). The length scales of the lake-induced circulations (Fig. 3b) are initially meso-β scale (L~100 km) and are associated with the individual Great Lakes. These meso-β circulations eventually expand to produce a meso-α scale circulation (Fig. 3c), as the warmth and moisture are advected over the entire region by the basic state flow.

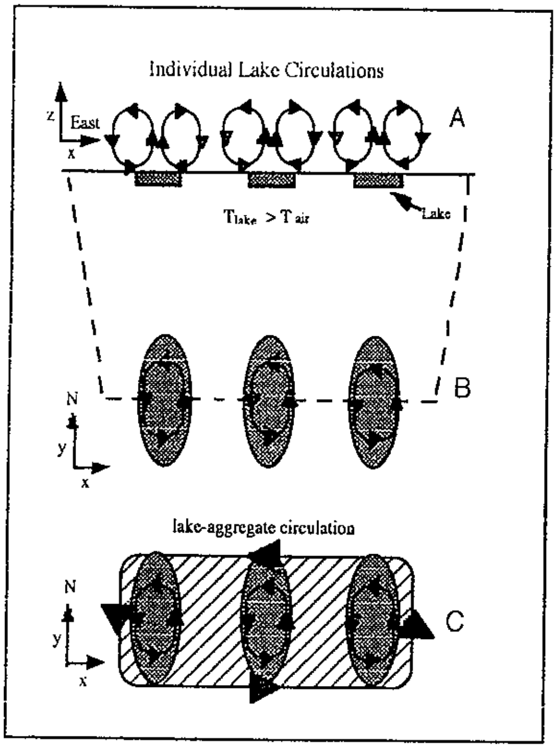


Figure 3: Schematic illustrating the formation of the lake-aggregate circulation. (A) vertical cross-section of the basic flow pattern. (B) horizontal meso-β circulations associated with individual lakes. (C) lake-aggregate circulation.

Due to the convergence near the surface forced by the LAE cyclonic circulation, large-scale ascent occurs over the GLR (Fig. 3c). The increased ascent combined with the added moisture can lead to an enhancement of clouds and precipitation. The increase in cloud cover and precipitation depends upon the vertical depth of the lake-aggregate disturbance. Typically, the top of the LAE is below the 600 mb level during the peak of an event (SF94). However, as a result, the LAE may have a significant impact on SSCs that typically are weakly forced thermodynamically and dynamically.

b. Conceptual impact of the lake-aggregate effect on sub-synoptic scale systems

The modification of the thermodynamic and dynamic structure of the lower atmosphere by the LAE can change the path and/or intensity of SSC. The enhanced cyclonic flow at the surface corresponds to higher amounts of vorticity near the surface (e.g., Petterssen and Calabrese, 1959). This enhanced vorticity coupled with the diabatic heat source from the lakes produces a cyclogenetic environment near the surface. In this sense, the lake-aggregate can act as a thermodynamic and dynamic magnet for weakly forced systems, e.g., SSCs.

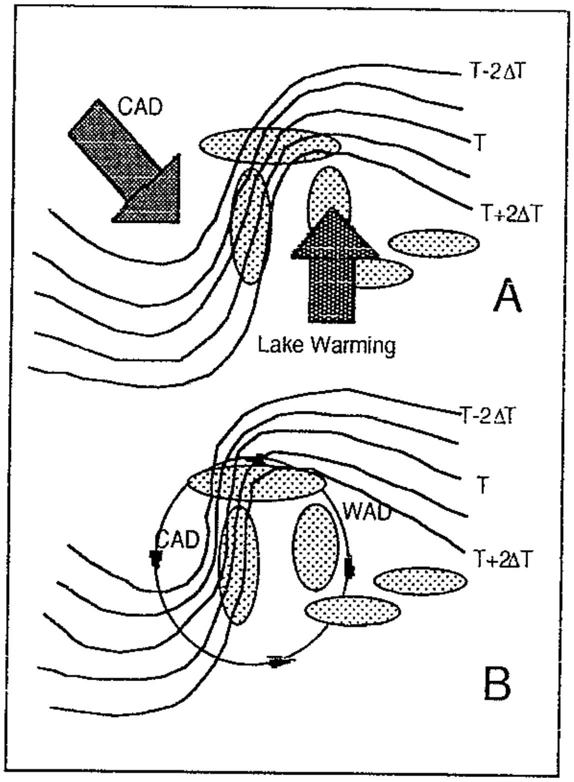


Figure 4: Schematic illustrating the impact of the thermal (A) and dynamic (B) aspects of the lake-aggregate upon the synoptic-scale temperature pattern.

The heating from the Lakes in conjunction with the continuing cold air advection (CAD) over the region increases the baroclinic zone at the surface and at the 850 mb level as shown in Fig. 4a. As a result, the enhanced cyclonic circulation from the lake-aggregate heating near the surface may intensify the warm air advection (WAD) on the east side of the surface feature (Fig. 4b). In the same manner, the lake-aggregate circulation may intensify the CAD behind the system (Fig. 4b). Due to the constant heating from the Lakes, the baroclinic zone remains quasi-stationary over the GLR (e.g., Fig. 5b-f). Therefore, the enhanced CAD and WAD continue over the same regions for extended periods of time. This may further enhance the baroclinic zone via shear deformation of the isotherms and the cyclogenetic environment over the GLR. If the thermodynamic forcing and consequent dynamic response becomes significant, then the initial large-scale forcing of the weak SSC is over-shadowed by the lake-aggregate scale forcing.

The LAE can impact the SSC in several ways as noted in SF94. For instance, the path of the system may deviate significantly from the mean steering flow. This is primarily in response to the thermodynamic forcing of the LAE. The SSC may also intensify in response the to forcing. The intensification may be distinctly visible as a sea-level pressure deepening rate or masked as a slower sea-level pressure filling rate in a cyclolytic environment. The amount of precipitation may also be greatly enhanced as a result of two processes: (1) the LAE produces enhanced large-scale ascent which leads to more clouds and precipitation; and (2) the small-scale lake-effect snow storms may persist for longer periods of time because of the destabilized environment causing large amounts of snow to fall in some lake shore areas (cf. Sousounis and Mann, 1994). All the features from the LAE's impact on the SSC can pose problems for the forecaster. Hence, many of these features may not be forecasted.

3. CASE STUDY

To demonstrate the lake-aggregate scale impact on SSCs, an observational investigation of a case is presented. This case occurred during the period 00GMT 13 Dec. to 12GMT 16 Dec., 1989 and the surface feature progression is shown in figure 5. The horizontal length was on the order of 500 km (meso-α scale), a characteristic Alberta Clipper; hence, it can be classified as a SSC. The system was forced by a weak vorticity maximum at 500 mb imbedded in the flow around a cut-off low . It was also associated with a weak surface baroclinic zone located in the cold air mass. This investigation outlines the evolution of the SSC as it enters the GLR.

This cyclone was associated with a large cold air mass that affected the Eastern two-thirds of the United States in December 1989. The surface analysis (Fig. 5) depicts the evolution of the sea-level pressure field (every 2 mb). The 850 mb and 700 mb panels (Fig. 6, 7 respectively) are from the initialization of the LFM and depict heights (every 30 m) and temperatures (every 2 ^{0}C). Similarly, the 500 mb panels (Fig. 8) are also from the initialization of the LFM and depict heights (every 60 m) and vorticity (every $2x10^{-5}\ s^{-1}$=2 VU, vorticity unit).

The SSC origins were in the Northern Portions of Alberta and Manitoba (not shown). The primary source of energy was a small enhanced vorticity lobe associated with a strong 500 mb low situated over the Hudson Bay Region of Ontario (Fig. 8a). It was imbedded in the swift flow around the cut-off low. The system also had a weak baroclinic zone associated with it (Fig. 6a). There was also a small area of light snow in advance of the surface low (Fig. 5a). with snowfall amounts around an inch. However, a few locations throughout the Northern Plains States reported higher totals (Fig. 9).

The surface feature took a track from North Dakota into Southern Iowa in the 12 hours ending 12GMT 13 Dec. (Fig. 5b). The system filled 1 mb in 12 hours. The area of light snow was confined to Northern Missouri northward into Central Wisconsin. By this time, circulations had developed over the individual Great Lakes. These meso-β disturbances were common to all the Great Lakes. As a result, areas over Lower Michigan were experiencing some cloudiness and lake-effect snow showers. Liquid equivalent precipitation totals were generally light across the Western GLR. A few locations received more than 0.2 cm.

By 00GMT 14 Dec. the surface low had moved to North Central Illinois with a central sea-level pressure of 1014 mb (Fig. 5c). The corresponding vorticity maximum at 500 mb was weak with a value of 14 VU (Fig. 8c). At this time, the vorticity lobe was in the process of being absorbed into the larger scale vorticity associated with the cut-off low. At 850 mb, the baroclinic zone was beginning to intensify (Fig. 6c). This is likely a result of the sensible heat flux from the LAE. Also, a larger area of light snow existed with the SSC as compared to 12 hours prior (Fig. 5c). At upper levels, the flow at both 500 mb and 700 mb was diffluent or divergent over the Lakes Region (Fig. 7c, 8c). Meanwhile, the flow was convergent near the surface. This is consistent with the conceptual model presented in section 2. The motion of the 850 mb low slowed and became almost stationary during the period 12GMT 13 - 12GMT 14 Dec. (Fig. 6b-d). However, the low at 700 mb continued to progress eastward (Fig. 7b-d). The quasi-stationary pattern at 850 mb is most likely an indication that the LAE was influencing the flow there.

The impact of the LAE became more evident by 12GMT 14 Dec. At this point, the surface low was diverted to the north into the Southern Lakes Region (Fig. 5d). The SSC deepened from 1014 mb to 1012 mb, as well. This is likely due to the cyclogenetic environment that the LAE produces. As a result, areas of moderate snow were occurring because of the combination of the SSC and lake-effect snow

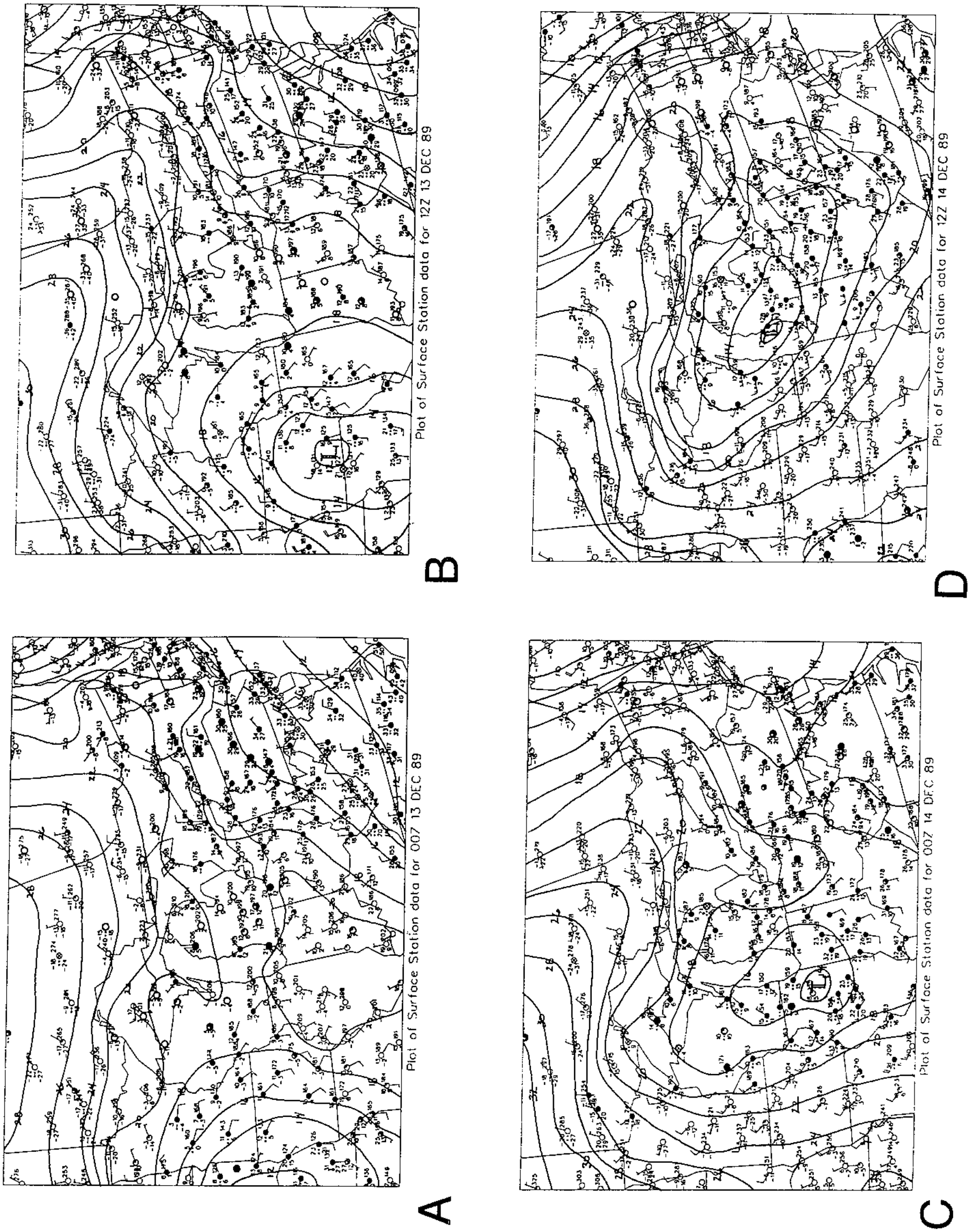
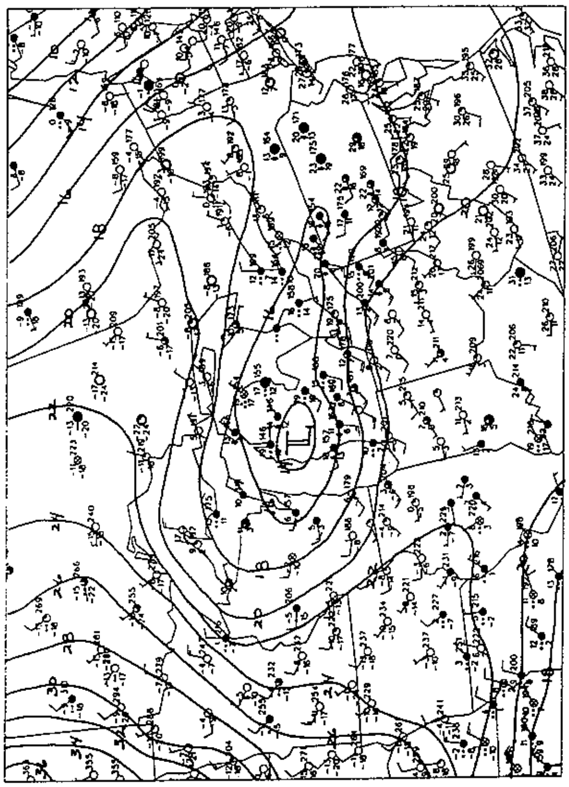


Figure 5: Surface analysis with sea-level pressure analysis for the period 00GMT 13 Dec. 1989 to 12GMT 16 Dec. 1989 at 12 hour intervals. The sea-level pressure contours are displayed at 2 mb intervals.



Plot of Surface Station data for 00Z 15 DEC 89

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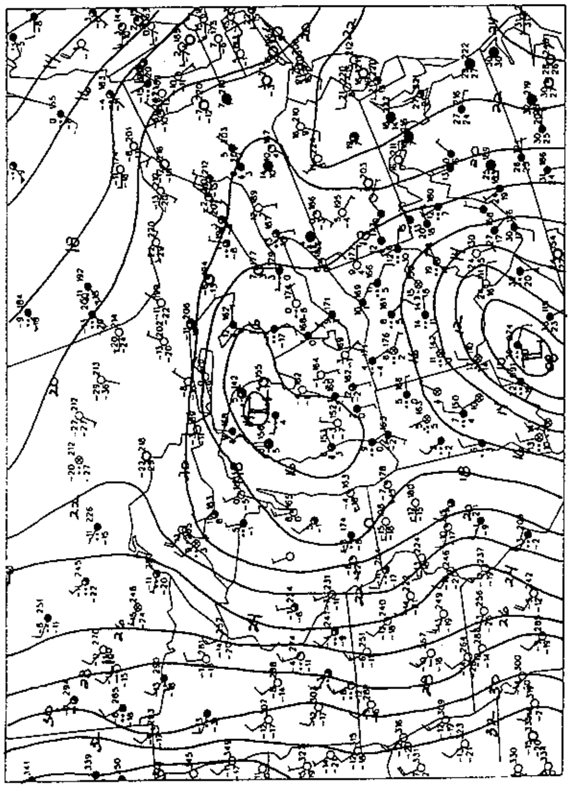

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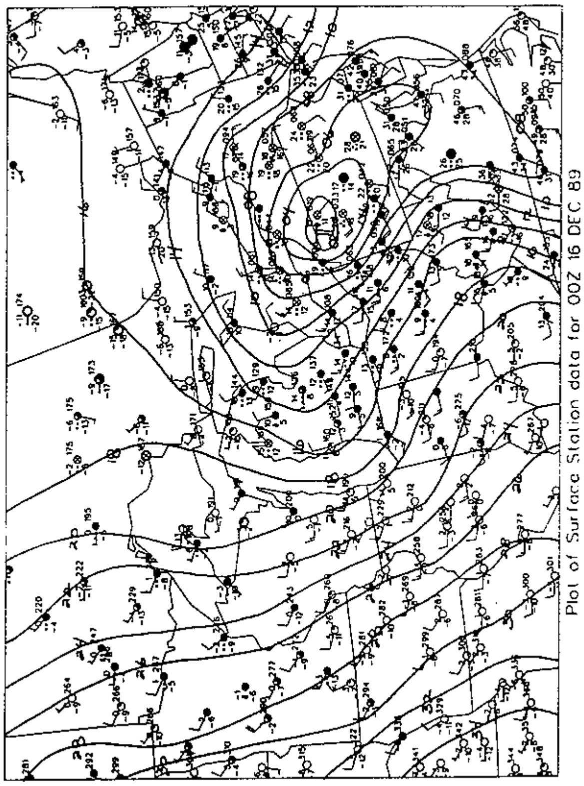

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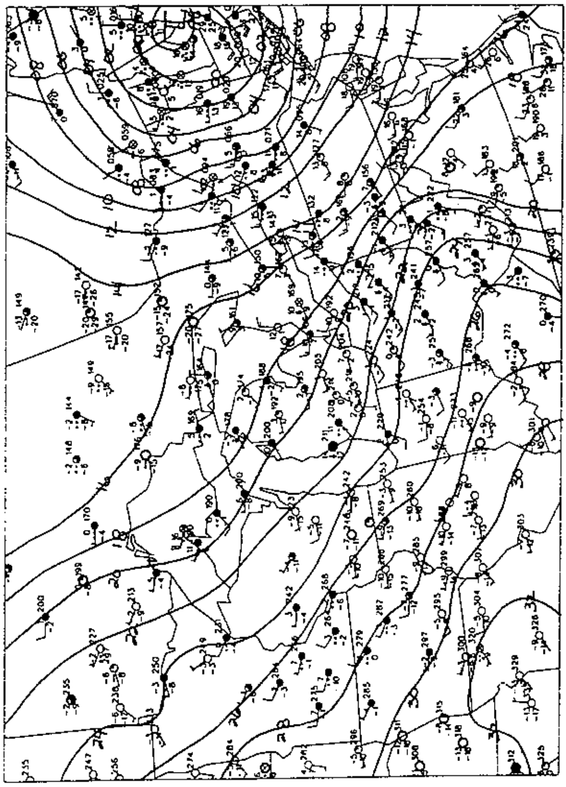

Plot of Surface Station data for 12Z 16 DEC 89

H

Figure 5: continued

development. The structure at 850 mb (Fig. 6d) continued to indicate that the Lakes were making an impact on the height and temperature fields. The temperature structure indicated a strengthening baroclinic zone. This increased baroclinicity along with the position of the 850 mb low produced an area of strong WAD over the Green Bay, Wisconsin (GRB) region. As a result, GRB received about 25.5 cm (10 inches) of snow in 36 hours from this SSC (Fig. 9). In contrast, Madison (MSN) only received 1.5 cm (0.6 inches) from the system (Fig. 10). The liquid equivalent totals in the region were generally around 0.2 cm. However, areas directly downwind of a Great Lakes received as much as 1.5 cm liquid equivalent. Recall that temperatures were in the teens (^{o}F). Because typical lake-effect snow/water ratios are between 20-35:1 (e.g., Schmidlin 1993), snowfall totals in many areas may have ranged from 30 to 50 cm (12-20 inches) in one day.

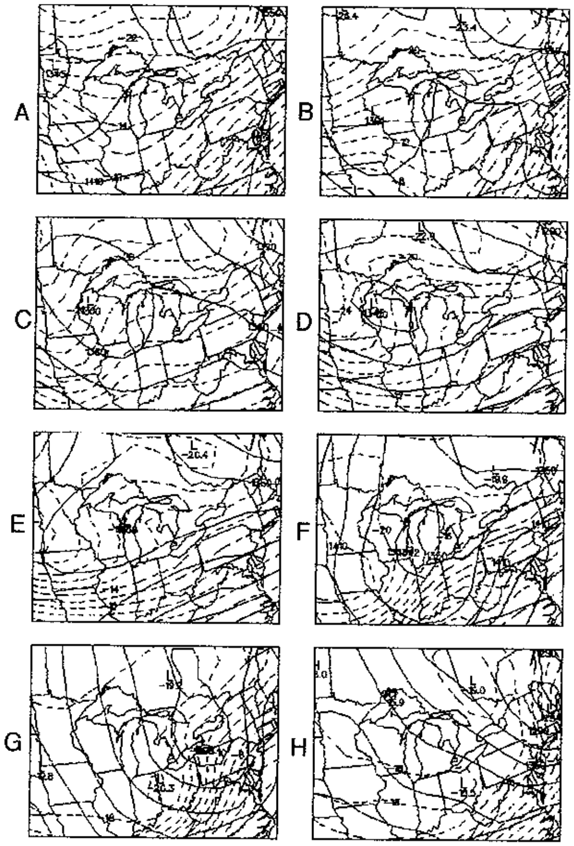

Figure 6: Analysis of heights (solid) every 30 m and temperature (dashed) every 2 ^{o}C at 850 mb for the period 00GMT 13 Dec. 1989 to 12GMT 16 Dec. 1989 at 12 hour intervals.

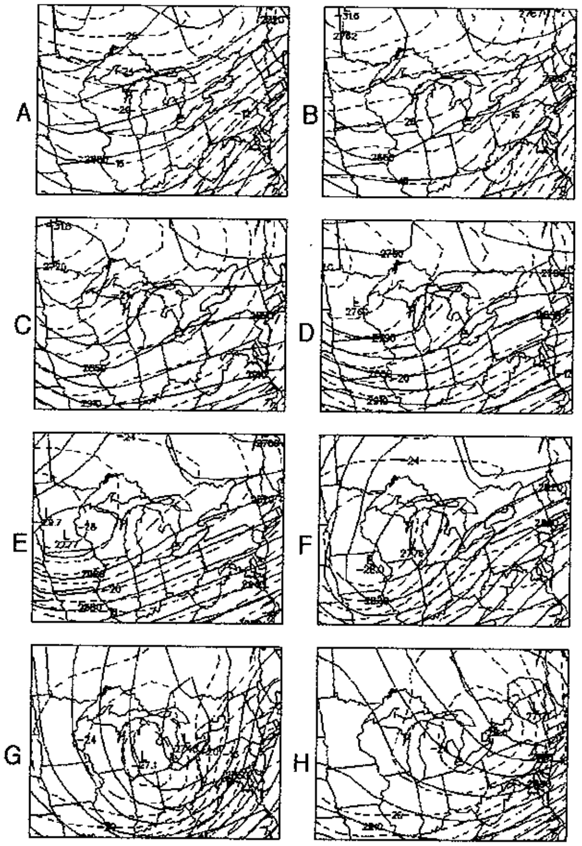

Figure 7: Similar to Fig. 6 except for the 700 mb level.

By 00GMT 15 Dec., the SSC was located over West Central Lower Michigan (Fig. 5e) with a central sea-level pressure of 1014 mb. It appears that the system may have weakened; however, at this time a large Arctic high was building into the Northern United States. So, the SSC may still have been deepening relative to the synoptic scale conditions. Also at this time, some areas in the lee of the Lakes were experiencing moderate to heavy lake-effect snow. For instance, Alpena, Michigan (APN) received moderate snow for several hours from lake-effect snow bands produced by Lake Huron. Meanwhile, snow continued at GRB with a surface wind from the northwest; however, the flow at the 850 mb level was still easterly from the GLR. Elsewhere, development of a synoptic-scale, extratropical cyclone (SEC) was taking place in the Southern Plains. This was a result of strong positive vorticity advection (PVA) at the 500 mb level over that region and an intensified baroclinic zone at the surface, 850 mb level, and 700 mb level. Also by this time, a jet streak developed on the west side of the 500 mb trough. This aided to dig the trough south into the Northern Plains.

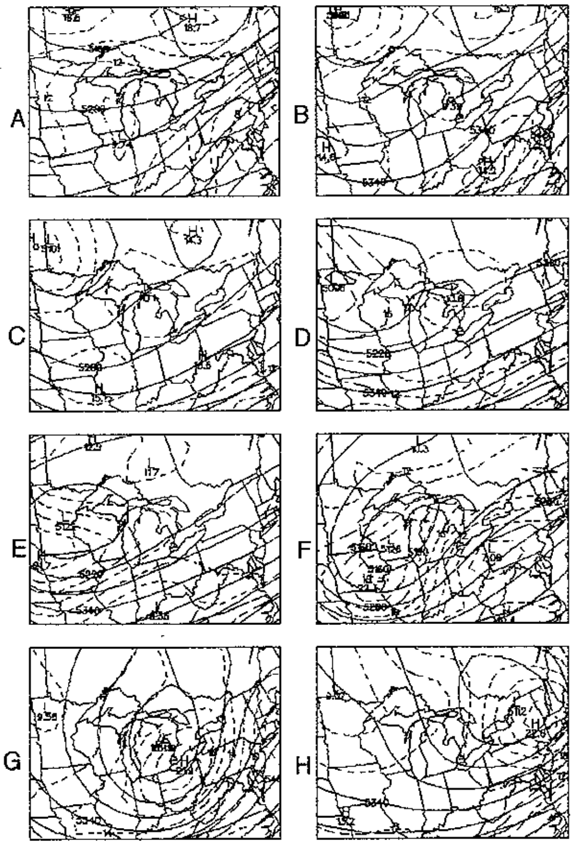

Figure 8: Analysis of heights (solid) every 60 m and absolute vorticity (dashed) every $2x10^{-5}\ s^{-1}$ *at 500 mb for the period 00GMT 13 Dec. 1989 to 12GMT 16 Dec. 1989 at 12 hour intervals.*

By 12GMT 15 Dec., the SSC drifted to Northern Lower Michigan with a central sea-level pressure of 1014 mb (Fig. 5f). Only a small region of cloudiness and light snow was associated with it. Meanwhile, the SEC moved into Central Kentucky. As is evident in Fig. 5f, the weaker SSC was becoming linked with the larger SEC to its south by a surface trough. At levels above the surface, both systems shared common features (Fig. 6f, 7f, 8f). However, the interaction between the SSC and the SEC at the surface could have had some impact on the SEC. If so, then the LAE may have had some influence on the development of the SEC. Possibly, the LAE may have thermodynamically primed the downwind region for the development of the SEC as is suggested by SF94.

The 500 mb trough continued to dig south into the Midwest Region as a result of the jet streak located over Missouri and Illinois (Fig. 8f). At 850 mb, the temperature gradient weakened over the GLR. Meanwhile, the persistent pattern of diffluence/ divergence continued at 500 mb and 700 mb.

The liquid equivalent precipitation amounts for the day once again were around 0.2 cm. Areas in Wisconsin, Michigan, and Ontario were still experiencing light snow. Some areas received more than 1 cm liquid equivalent. These regions were primarily downwind of one of the Great Lakes.

The SSC, by 00GMT 16 Dec., dissipated into a trough over the GLR. Meanwhile, the SEC deepened to 1001 mb and moved into Northwestern Pennsylvania (Fig. 5g). The impact of the Lakes was still evident by the sharp trough trailing the SEC. This is a characteristic of the Lake's impact in the wake of strong synoptic-scale cyclones (Boudra, 1981). Elsewhere, at 500 mb, the jet streak rotated into the southeast portion of the trough causing the trough to begin to lift northeastward into the Eastern Lakes Region (Fig. 8g). At 850 mb, the low finally moved from the quasi-stationary position over the Western Lakes Region into the Central Lakes Region (Fig. 6g). Furthermore, the strong baroclinic zone at the 850 mb level was situated along the Appalachians. A similar flow and temperature configuration existed at 700 mb (Fig. 7g).

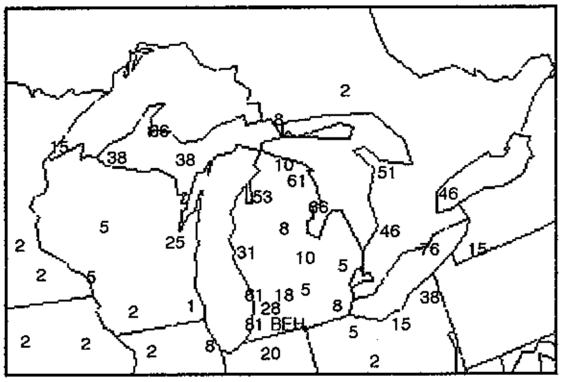

Figure 9: Snowfall distribution (cm) for the sub-synoptic scale cyclone. The maximum amount is at Benton Harbor, MI (BEH) with a 3 day total of 81.2 cm (32 inches).

Finally at 12GMT 16 Dec., the SEC quickly moved to the New England Coast and deepened to 997 mb. The surface trough over the Lakes dissipated as the large Arctic high dominated the synoptic-scale situation over the Central U.S. (Fig. 5h). Aloft, the 500 mb low continued to lift northeast into New England (Fig. 8h). However in the Lakes Region, persistent lake-effect snow squalls occurred. As a result of the passing SEC to the south of GLR, the LAE was disrupted for about 24 hours. However, on 17 Dec. the LAE re-developed and influenced another Alberta Clipper.

The snowfall amounts produced by the SSC were generally less than 1 inch, with a few exceptions, in the Dakotas, Minnesota, Iowa, and Western Wisconsin (Fig. 9). Snowfall totals in the GLR away from the lake shores ranged from 1 to 9 inches. Moreover, some lake shore communities received 2-3 feet of snow in the three day period 13-16 Dec.

4. LAKE-AGGREGATE EXTRACTION METHOD

This method used to extract the lake-aggregate effect is based upon the assumption that the effect is constrained to the lower layers of the atmosphere, i.e., below the 600 mb level. Therefore, there is some level in the atmosphere assumed not to be influenced by the LAE, i.e., the level of non-influence. For this investigation, the level of non-influence is taken to be 700 mb because the extraction is performed during the early stages of the case when the depth of the LAE is limited. At this level, the influence of the LAE is minimal if not totally absent. Hence, it is assumed that the entire domain within the Arctic air mass is nearly homogeneous as indicated by the sounding profiles in Figure 12.

This extraction method uses parcel theory and a finite difference form of the integrated hypsometric equation presented here (from Bluestein, 1992) as:

$$z_{100} = z_{70} - \left(\frac{R}{g}\right)\sum_{i=70}^{100}\overline{T}_i \ln\left(\frac{p_{i+1}}{p_i}\right),$$

where z_{100} is the 1000 mb height to be determined from the known 700 mb height z_{70} and the average temperature $\overline{T}_i$ between p_i and p_{i+1}. The quantities R and g are the specific gas constant for air and the gravitational constant respectively. The parcel is moved down at constant pressure intervals $\Delta p_i = p_{i+1} - p_i = 10$ mb using a characteristic lapse rate from the characteristic sounding (Fig. 10) to calculate the temperature $\overline{T}_i$. The characteristic lapse rate on the sounding is based upon upper air data from stations that were not affected by the Great Lakes. This allows the impact of the Lakes to be isolated. For each pressure interval i, the corresponding height drop $\Delta z_i = z_i - z_{i+1}$ is proportional to the mean temp $\overline{T}_i$ in the interval; the warmer the air the greater the height drop. For a sounding unaffected by the Great Lakes, the reconstructed 1000 mb height z_{100} should be close to the observed. For a sounding that is affected by the Great Lakes, the reconstructed 1000 mb height z_{100}, using the characteristic sounding, should be significantly higher than the observed. The extracted 1000 mb height is the difference between the observed and the reconstructed heights.

The upper air stations used in this case (Fig. 11) fit into three categories -- isothermal, adiabatic, or non-applicable. The stations classified non-applicable (N/A; Fig. 11) were stations that were unaffected by the Arctic air mass. Therefore, their profiles were not characteristic of the air mass and were neglected from the composition of the characteristic sounding. The stations with adiabatic profiles (A; Fig. 11) were also neglected from the characteristic sounding because they were modified by the LAE. The stations that demonstrated isothermal, or even inverted, structures (I; Fig. 11) were used in the computation of the characteristic sounding. These stations exhibited the vertical thermodynamic profile of an Arctic air mass (Sousounis and Shirer, 1992). Figure 12 illustrates a set of unmodified soundings and Figure 13 a set of lake-modified soundings. By casual inspection, the difference between these two sets is obvious. The unmodified soundings are predominantly isothermal or even inverted below 800 mb. In contrast, the lake-modified soundings are significantly less stable.

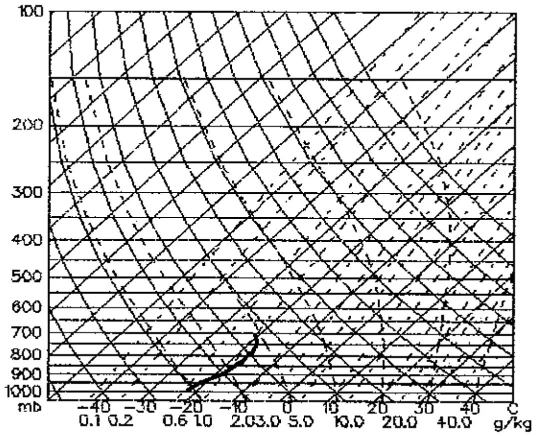

Figure 10: Skew-t log-p diagram illustrating the characteristic lapse rate sounding valid 12GMT 14 Dec. 1989.

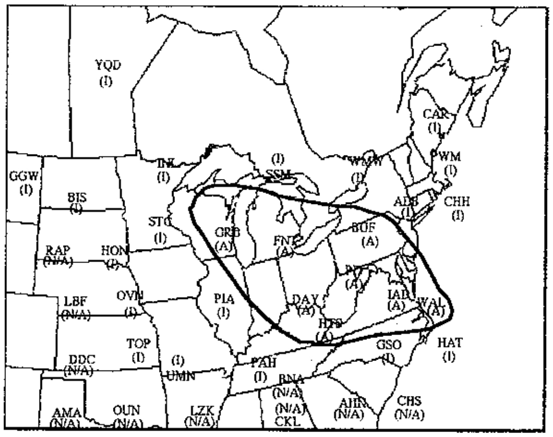

Figure 11: Map displaying the distribution of upper-air stations used in the case study. The stations denoted with a N/A were excluded from the characteristic lapse rate sounding. Those denoted by an I were typical of the Arctic air mass. Those denoted by an A and outlined by the contour were modified by the lake-aggregate effect.

The characteristic sounding valid for 12GMT 14 Dec. (Fig. 10) for the extraction method is composed of the profiles from the following unmodified soundings labeled (I) on Fig. 11 which are YQD, GGW, BIS, INL, SSM, WMW, CAR, PWM, ALB, CHH, HON, STC, OVN, PIA, TOP, UMN, and PAH. SSM (Sault Saint Marie, Michigan) seems unlikely to not be modified by one of the Great Lakes; however, the sounding (Fig. 12b) is isothermal and unmodified. The reason is that a persistent east wind at SSM existed at this time. Therefore, the air advected into the SSM region did not encounter any of the Great Lakes.

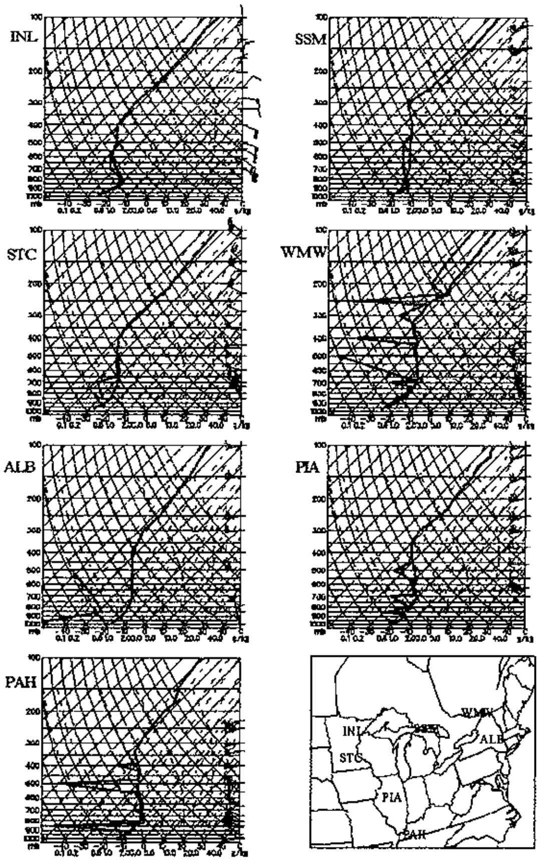

Figure 12: Skew-T log-p thermodynamic diagrams for the unmodified stations at 12GMT 14 Dec. 1989 along with their locations.

Once the characteristic sounding is constructed, the extraction analysis is performed by subtracting the reconstructed height field (not shown) from the observed 1000 mb height field. The extracted height field is interpreted to be the 1000 mb height perturbation caused by the LAE. Figure 14 depicts the perturbation geostrophic wind velocities at 1000 mb for 12GMT 14 Dec. that correspond to the extracted 1000 mb height field (not shown). The prominent feature is a meso-α cyclonic circulation from Minnesota extending east to the Mid-Atlantic States which is similar to the results that SF94 found numerically. The magnitude of the meso-α circulation is on the order of 10 m/s. Also within the meso-α circulation, two smaller, meso-β, cyclonic circulations are evident. The first is located in the Central Upper Peninsula of Michigan. The second is located in Eastern Ohio. These are most likely residual circulations forced by individual Great Lakes. Similar meso-α scale cyclonic circulation signatures existed at the surface for the surrounding time periods (not shown).

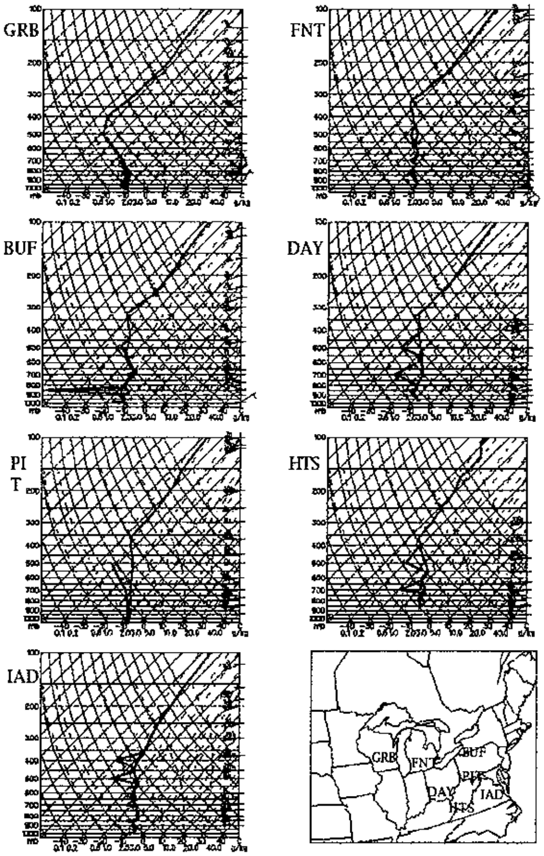

Figure 13: Similar to Fig. 12 except for the lake modified soundings.

At 850 mb (not shown), a cyclonic circulation was present in the Western Lakes Region. This may be an indication that the 850 mb low's motion was retarded by the Lakes. Also, it may be a result of the enhanced CAD in that region near the surface. This would lower the heights at 850 mb hydrostatically and induce a stronger cyclonic circulation. Conversely, a divergent, anti-cyclonic circulation existed over the Central and Eastern Lakes Region. This is a result of the raised heights caused by the heated boundary layer and the enhanced WAD. Both of these features confirm the points illustrated in the conceptual model of the Lake Aggregate and its impact on sub-synoptic scale systems in section 2.

Extracted Lake Aggregate Circulation
valid 12GMT Dec. 14, 1989

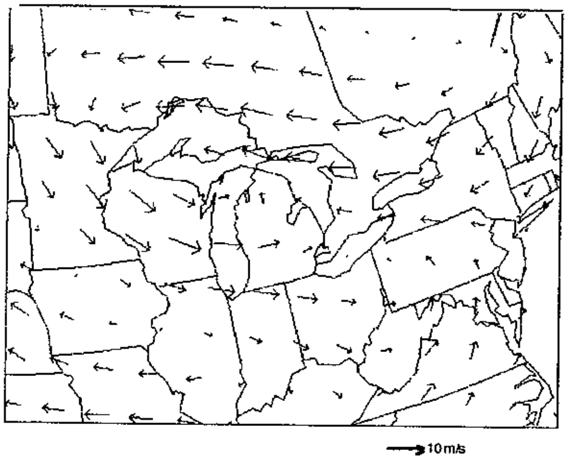

Figure 14: Perturbation 1000 mb geostrophic wind vector analysis valid 12GMT 14 Dec. 1989 calculated from the extracted 1000 mb heights.

The precipitation across the entire region may be substantially greater due to the lake-aggregate for several reasons. First, the path and intensity of the Alberta Clipper was modified. This results in the system remaining stationary and with approximately the same intensity. This quasi-stationary behavior allows for precipitation to occur over the same region for an extended period of time. The quasi-stationary behavior coupled with the enhanced convergence forced by the lake-aggregate circulation could have greatly increased the precipitation amounts across the GLR. The fact that the convergence over the region increases the moisture inflow from the Great Lakes also lends to increased precipitation. The enhanced cyclonic flow (Fig. 14) contributed to the surface WAD across the region (not shown). The surface WAD in the region destabilizes the lower troposphere forcing broadscale ascent. The ascent also enhances the clouds and precipitation. When all of these factors are combined, the result is an enhancement of cloud cover and precipitation over the GLR.

5. SUMMARY AND CONCLUSIONS

This investigation focused on a case that occurred 13 Dec. 1989 to 16 Dec. 1989. The cyclone was a characteristic Alberta Clipper passing to the south of the Lakes Region. The case analysis suggests that the cyclone was diverted into the Lakes Region and remained stationary over Lower Michigan for approximately 48 hours because of the lake-aggregate heating and moistening. The system was finally absorbed into a larger, synoptic-scale system passing through the Ohio Valley Region. Precipitation amounts associated with the sub-synoptic cyclone were substantial in some areas. For instance, regions immediately downwind of an individual Great Lake received 2 to 3 feet of snow. Throughout the rest of the region, snowfall totals ranged from 1 to 9 inches. In contrast, the system produced snow amounts of only an inch or less in the Plains States.

The study highlights four significant aspects of the lake-aggregate effect.

(1) Heating and moistening of a large region extending from the Great Lakes to the Eastern Seaboard resulted in a large lake-aggregate induced cyclonic circulation at the surface.

(2) The circulation enhanced a large area of convergence at the surface and "trapped" a dynamically weak SSC.

(3) The modification of the path and intensity of the system intensifying the large scale convergence likely enhanced cloud cover and precipitation over the entire GLR.

(4) Finally, the circulation probably enhanced lake-effect snow amounts in certain areas , and because the snow was so persistent, it was probably responsible for the 2-3 foot snowfall totals in portions of Lower Michigan and Ontario.

Improvement in forecasting these events may start with observing the development of the meso-β scale circulations over each of the individual lakes. The development of cloudiness over the interior of the region, e.g., Lower Michigan, may be a precursor to the development of the LAE. Once the development of the LAE can be resolved, the possible influence upon the SSC must be determined. Hopefully, the observational study presented in this investigation provides some insight on the impacts of the LAE on the SSC. However, a numerical simulation of this case may provide more insight on the development mechanisms involved with the lake-aggregate effect and its impacts on other sub-synoptic scale cyclone.

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