Lake-Aggregate Mesoscale Disturbances. Part III:
Description of a Mesoscale Aggregate Vortex

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ABSTRACT

The structure of a meso-α-scale vortex that developed over the Great Lakes in late autumn is described. Understanding the structure of this particular vortex is important because 1) it altered local- and regional-scale precipitation, 2) it developed in a complicated fashion, and 3) it represents a class of vortices that develop frequently during cold-air outbreaks over the Great Lakes and whose development is not yet understood.

Detailed perturbation analyses of the synoptic-scale and mesoscale conditions over the Great Lakes that led to the vortex development are presented using model output from previous numerical simulations that included all of the Great Lakes (WL) and none of the Great Lakes (NL). The initial thermal perturbation was characterized by an elongated warm plume near the surface that advanced southeastward toward the mid-Atlantic coast as cold air overspread the entire lakes region. The plume then became more circular and deepened as it rotated toward the northeast in response to the changing synoptic-scale flow. The perturbation winds revealed several small meso-β-scale circulations that developed during the first 36 h within the warm plume. By 48 h, a 3-km-deep meso-α-scale vortex developed several hundred kilometers to the northeast of Lake Huron with cyclonic flow in the lower half and anticyclonic flow in the upper half. Its size, location, and evolution indicate that it was likely generated by aggregate-lake as opposed to individual-lake heating and moistening. It is therefore referred to as a mesoscale aggregate vortex (MAV).

The MAV that developed represents a class of vortices that can be described as inertially stable, meso-α-scale warm-core vortices approximately 500–1000 km wide and 2–4-km deep that develop from aggregate heating and moistening over the Great Lakes. They are usually identifiable on standard surface weather charts as a weak low over the Great Lakes region with 1–3 closed isobars at 2-mb intervals. The outermost closed isobar typically encloses an area approximately as large as that spanned by the upper Great Lakes (e.g., Lakes Superior, Huron, and Michigan).

Because the MAV in this study developed nearly 36 h after the coldest air left the region, it is not clear whether other physical mechanisms besides sensible and latent heating were involved, to what extent they were important, and at what stages they occurred. Additionally, the MAV developed within a large elliptical region of lake-aggregate heated air, which suggests the importance of geostrophic adjustment, and from smaller individual-lake scale circulations, which suggests the importance of vortex merger. Development mechanisms will be discussed in a follow-up study.

1. Introduction

The impacts of the Great Lakes on local winter weather have been studied extensively in the past. Dozens of studies by Dewey (1975), Pasarelli and Braham (1981), Braham and Kelly (1982), Hjelmfelt (1990), Byrd et al. (1992), and Reinking et al. (1993) to name a few have described the effects of individual lakes (e.g., lake-effect storms) on nearby lake shore weather. Lake-effect storms are considered to be mostly the result of strong surface heat and moisture fluxes from individual warm lakes into the lower atmosphere during cold-air outbreaks. Only a handful of studies have examined the impacts of the Great Lakes aggregate on regional winter weather (e.g., lake-aggregate effects). Lake-aggregate effects are the result of strong surface heat and moisture fluxes from all of the relatively warm lakes into the lower atmosphere during cold-air outbreaks. The combined heating and moistening from all of the lakes can generate aggregate-scale or meso-α-scale [e.g., 200–2000 km according to Orlanski (1975)] changes in atmospheric fields such as pressure, temperature, and wind.
These changes can modify individual lake-effect storms, strengthen synoptic-scale storms, and generate meso-α-scale storms. For example, Cox (1917) noted that the Great Lakes tend to attract and deepen synoptic-scale lows in the winter. Petterssen and Calabrese (1959) noted that the surface pressure perturbation from the lakes during cold-air outbreaks can be 6–7 mb. They also noted that the aggregate effect may appear on surface weather maps either as a trough oriented perpendicular to the mean flow or as a closed low as shown in Fig. 1 depending on the strength, temperature, and other characteristics of the synoptic-scale flow. Danard and Rao (1972) and Boudra (1981) examined numerically the impacts of the Great Lakes on intense synoptic-scale storms. More recently, Sounis and Fritsch (1994) (hereafter referred to as Part II) examined the impacts of the Great Lakes on weak synoptic-scale lows.

Part II identified some regional and synoptic-scale impacts of the Great Lakes in winter by comparing results from a 48-h numerical simulation that included all of the Great Lakes (WL) to one that included none of the Great Lakes (NL). The Pennsylvania State University—National Center for Atmospheric Research (PSU–NCAR) hydrostatic mesoscale model MM4 was used for the simulations (cf. Anthes et al. 1987). The model had a coarse grid mesh (CGM) that was centered at 43.5°N, 84.5°W with 41 × 41 horizontal grid points and 90-km resolution and a fine grid mesh (FGM) that was centered within the CGM with 61 × 55 horizontal grid points and 30-km resolution. The model had 36 sigma levels with approximately 24 levels below 700 mb and a model top at 100 mb. The Blackadar formulation (Blackadar 1976; Zhang and Fritsch 1986) was used to model the planetary boundary layer. The Anthes–Kuo scheme (Anthes 1977) and the Kain–Fritsch (Kain and Fritsch 1993) scheme were used to model convection in the CGM and FGM, respectively. The simulations were initialized with data from 0000 UTC 13 November 1982. Lake-surface temperatures were obtained from a subjective composite of climatological data from Saulesleja (1986) and buoy temperatures taken during various times in November 1982. The model lake surface temperatures were held fixed for the 48-h period. The 48-h WL simulation was accurate at the surface as well as at upper levels (cf. Figs. 2, 3). More modeling and validation details are available in Part II.

Part II showed that lake aggregate effects on wind, temperature, pressure, and humidity developed and extended for hundreds of kilometers downwind from the lakes region as cold air moved into and then out of the lakes region. The effects evolved over a 48-h period; from a seemingly broad distribution of meso-β [e.g., 20–200 km according to Orlanski (1975)] (individual-lake) scale responses at 12 h (cf. Fig. 4a) to a more coherently structured meso-α (aggregate-lake) scale vortex that developed northeast of Lake Huron near the surface by 48 h (cf. Fig. 4d). This vortex developed in part from the strong atmospheric heating and moistening by the Great Lakes, which hydrostatically reduced the sea level pressure and increased the cyclonic wind flow near the surface. It altered the convective precipitation from individual lake-effect storms (cf. Figs. 4a–d) and it also generated large-scale precipitation that extended several hundred kilometers northeast of the lakes region (cf. Fig. 4d).

Several features of this vortex substantiate its lake aggregate development. First, the development time was sufficiently long for heat from all the lakes to form a lake aggregate sized region of warm air. In fact, the vortex formed northeast of the lakes region

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1 Additional individual-lake simulations would be required to assess the individual-lake contributions and to verify that this vortex really did develop from aggregate heating.
FIG. 2. Surface Limited-Area Fine-Mesh (LFM) Model analyses (left column) and WL simulation results (right column) from Sousounis and Fritsch (1994) valid at 1200 UTC 13 November 1982 (top row), 0000 UTC 14 November 1982 (middle row), and 1200 UTC 14 November 1982 (bottom row). Sea level pressure (solid) contour interval is 2 mb, and 1000-mb temperature (dashed) contour interval is 4°C. Wind vector of length equal to grid separation distance is 20 m s$^{-1}$. 

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Fig. 3. Limited-Area Fine-Mesh (LFM) Model analyses (left column) and WL simulation results (right column) from Sousounis and Fritsch (1994) at 48 h valid at 0000 UTC 15 November 1982. (a) The 700-mb LFM heights (solid) and temperatures (dashed) with selected observations. (b) The 700-mb WL heights (solid), temperature (dashed), and winds (vectors). (c) Same as (a) but for 850 mb. (d) Same as (b) but for 850 mb. (e) Same as (a) but for sea level pressure. Temperature contours omitted. (f) Same as (b) but for sea level pressure and 1000-mb temperatures. Height contours are every 30 m, temperature contours are every 4°C, and sea level pressure contours are every 2 mb.
during prevailing southwesterly flow, approximately 36 h after the lakes had been warming and moistening cold and dry northwesterly flow over a region that extended southeastward to the mid-Atlantic coast and after the coldest air had left the region (cf. Fig. 2). Second, the location of the vortex was downwind from all of the lakes. Third, the scale of the vortex (e.g., 800 km wide at 850 mb) exceeded that of the largest individual Great Lake (e.g., Lake Superior ~400 km). Fourth, the MAV developed from smaller individual-lake-scale circulations, which suggests not only an aggregate development but a nonlinear transfer of energy from the meso-β scale to the meso-α scale.

Because of this evidence for aggregate development, the feature is referred to as a mesoscale aggregate vortex (MAV). The term vortex is appropriate because a closed circulation was observed at the surface in the total flow and not just the perturbation (cf. Figs. 1b, 2e, 4d). This MAV appears to be a different phenomenon from either the meso-β-scale vortex discussed by Forbes and Merritt (1984) that can form over individual lakes or the meso-α-scale polar vortex discussed by Agee and Lidbrauch (1989) that can form over the continental United States because

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2 If it can be assumed that each lake cannot generate a vortex larger than itself, then a vortex that is larger than the largest lake implies some degree of aggregate development.

3 Even though the dynamics of lake aggregate-induced circulations may not differ for open or closed lows, it is appropriate to limit the term MAV to those situations where the observed flow develops a meso-α-scale closed cyclonic circulation (e.g., vortex) at the surface over the Great Lakes region during cold-air periods.
The objectives of this paper are 1) to describe the kinematic structure of the MAV that was identified in Part II, and 2) to formulate a general definition so that MAVs can be more easily identified from standard synoptic-scale charts. While it may seem premature to define an atmospheric phenomenon based on detailed analysis of one event, there are two reasons for doing so. One reason is that similar vortices develop quite frequently during cold-air outbreaks over the Great Lakes. Bates et al. (1993) recently showed a 10-day average lake-aggregate-scale sea level pressure perturbation with a 3-mb amplitude centered over Lake Huron. Approximately 10–20 cold-air outbreaks occur each winter over the Great Lakes region. Each one lasts 2–3 days on average, which means that 20–60 days per season in the winter are characterized by a lake-aggregate effect of some magnitude. A second reason is that it is useful to present guidelines that will simplify the identification of MAVs in the future. To accomplish the above objectives, analyses of the wind and temperature fields associated with the MAV using output from the WL and NL simulations in Part II are presented in section 2. A generalized definition of MAVs and a discussion of how they may be identified on standard synoptic-scale charts is presented in section 3. A summary and conclusions are presented in section 4.

2. Kinematic structure of the MAV

The perturbation (e.g., WL − NL) winds, temperature, vorticity, convergence, and vertical motion associated with the MAV are examined in greater detail in this section. Analyses from the entire 48-h period are included to illustrate how the structure evolved from aggregate heating and moistening by the Great Lakes.

Fig. 5. Perturbation winds $\Delta V$ and heights $\Delta h$ at 1000 mb for (a) 12 h, (b) 24 h, (c) 36 h, and (d) 48 h. Contour interval for heights is 4 m. Zero contour omitted for clarity. Wind vector of length equal to grid separation distance is 4 m s$^{-1}$. Heavy dashed contours and shading indicate regions where $\Delta h < -2$ m. Heavy solid contours indicate regions where $\Delta h > +2$ m. Heavy oval in (d) indicates approximate extent of MAV.
Figure 5 indicates how the perturbation wind field $\Delta V$ at 1000 mb evolved over 48 h. By 12 h, two meso-$\beta$-scale vortices straddled the upper peninsula (UP) of Michigan. A weak meso-$\beta$-scale vortex existed east of Lake Huron and cyclonic flow (e.g., a trough) existed along the eastern Lake Michigan shore. By 24 h, this weak vortex appeared to merge to some degree with the two vortices over Lake Superior. By 36 h, the eastern Lake Superior vortex weakened, the Lake Huron vortex strengthened considerably, and the western Lake Superior vortex remained stationary. Additionally, a fourth vortex developed over the lower lakes (e.g., Lakes Erie and Ontario). By 48 h, only the meso-$\beta$-scale vortex over Lake Superior and a meso-$\alpha$-scale vortex northeast of Lake Huron remained. The meso-$\alpha$-scale vortex was in part the result of the circulation from the lower lakes wrapping around and into the stronger circulation northeast of Lake Huron between 36 and 48 h and an indication that vortex merger was occurring (cf. Dritschel and Waugh 1992; Ritchie and Holland 1993). Evidence for this vortex merger can be seen in Fig. 5d from the strong southwesterly flow between Lake Huron and the lower lakes. Additional evidence for (possible future) vortex merger can be seen from the weak northwesterly flow in the region north of the lakes, which is the result of southwesterly flow from the Lake Superior vortex interacting with northeasterly flow from the Lake Huron vortex.

The meso-$\alpha$-scale cyclonic circulation just northeast of Lake Huron is the mesoscale aggregate vortex introduced in section 1. Its meso-$\alpha$-scale size, circulation, evolution, and downwind location substantiate its aggregate development. Its approximate extent at 1000 mb ($\sim$600 km $\times$ 400 km) is shown by
the oval contour in Fig. 5d. This contour was determined subjectively by considering approximately the intersections of the regions where 1) the angular deviation between the perturbation actual and geostrophic winds was less than about $45^\circ$ and 2) the actual and geostrophic perturbation wind speeds were within a factor of 2. This vortex at 48 h had a Rossby number of $R_0 \sim 0.1$ and a dynamic Rossby radius $R' \sim 200$ km. These values and the visual evidence at the surface (cf. Fig. 5d) and at upper levels (cf. Figs. 6d, 7d) suggest strongly that this vortex was dynamically large and inertially stable at 48 h (cf. Chen and Frank 1993).

The Lake Superior vortex is not a MAV even though it is more intense because of its smaller meso-$\beta$-scale size and because of its upwind location, which essentially preclude its aggregate development. The cyclonic flow that envelopes the entire Great Lakes region at 48 h is not a MAV either because it contains the two vortices described as well as other smaller vortices and troughs. This cyclonic flow represents the geostrophic adjustment to the outer edge of the very large thermal perturbation. Additionally, observations during and after the period of study do not indicate a single-centered closed low on such a large scale. In general, such large-scale circulations are not observed to develop over the lakes in winter; at least not as a result of lake aggregate heating and moistening.

Figure 6 indicates how the perturbation wind field $\Delta V$ at 850 mb evolved over 48 h. By 12 h, anticyclonic flow existed east of the lakes. By 24 h, this flow was

Fig. 7. Similar to Fig. 5 except for 700 mb. Contour interval for heights is 2 m. Positive regions are shaded instead of negative regions.

* With the exception of the southwest quadrant.

* The absence of such a large-scale circulation in the observations, however, should not preclude the importance of geostrophic adjustment for MAV development.
more organized and a sharp ridge existed over Lake Huron. But, during the next 12 h, the sharp ridge moved rapidly east northeastward in response to the changed synoptic-scale flow and a closed cyclonic circulation developed over Michigan. By 48 h, the sharp ridge exited the domain and/or dissipated, a sharp trough existed over Lake Superior, and an elliptically shaped closed cyclonic circulation was situated to the northeast of the lakes region. This latter feature, which was the 850-mb circulation associated with the MAV, had a horizontal scale of about 800 km × 600 km as shown in Fig. 6d. The strong southwesterly flow and the strong perturbation height Δ$h$ gradients to the southeast of Lake Huron in Fig. 6d indicate a nearly geostrophically balanced flow. Weaker northerly flow along the northwest flank existed that was not so nearly geostrophically balanced. The stronger ageostrophic signature on the north side was the result of interaction with the Lake Superior vortex.

Figure 7 indicates how the perturbation wind field $\Delta V$ at 700 mb evolved over 48 h. The responses were expectedly weak at 12 and 24 h (cf. Figs. 7a,b). The weak perturbation height $\Delta h$ gradients at 24 h indicate that the perturbation winds, which were clearly anticyclonic over a limited portion of the region northeast of Lake Huron, were not very geostrophically balanced. By 36 h, the perturbation winds were more geostrophically balanced. Significant anticyclonic flow existed over a broad region to the northeast of the lakes region. By 48 h, a more elliptical pattern of anticyclonic flow, which was the 700-mb circulation associated with the MAV, existed farther downwind. A nearly closed and smaller anticyclonic circulation that was associated with the Lake Superior vortex appeared to be merging with it.

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* Portions along the east side, which was basically in geostrophic balance, are concave because of the adjacent perturbation high.
b. Temperature perturbations

Figure 8 indicates how the perturbation temperature field $\Delta T$ at 1000 mb evolved over 48 h. By 12 h, a warm plume extended eastward that barely covered the Great Lakes. The warmest air was over the lakes. By 24 h, the plume extended to the mid-Atlantic coast. A large pool of cool air existed to the northeast of the lakes, where the MAV eventually formed. It is not clear whether this cool air played a significant role in the development of the MAV, but it does indicate that the horizontal temperature gradient just to the south had intensified. By 36 h, the warm plume became distorted as a result of the western portion being advected northeastward and the eastern portion continuing to be advected southeastward. By 48 h, the cool air retreated northeastward and the warm plume advanced northeastward. A comparison of Figs. 5d and 8d indicates that the center of the MAV circulation was located just on the warm side of the tightly packed isotherms northeast of Lake Huron and that the wind perturbation led the thermal perturbation by approximately 200 km at 1000 km.

Figure 9 indicates how the perturbation temperature field $\Delta T$ at 850 mb evolved over 48 h. By 12 h, only a few meso-$\beta$-scale regions of warm air existed randomly over the lakes. By 24 h, a more continuous region of warm air developed as the warm air over the western lakes region began shifting northeastward. By 36 h, warm air covered nearly the entire area shown northeast of the lakes. The significant northeastward expansion of the warm air at 850 mb from 24 to 36 h may have been the result of eastwardly expanding synoptic-scale southwesterly flow or reduced synoptic-scale static stability that accompanied the southwesterly flow. By 48 h, the warm air spanned an elliptical region of approximately 2000 km × 1000 km. The warmest air was no longer over the lakes, but was 500 km downwind, which is where the MAV formed. A comparison of Figs. 6d and 9d indicates that the wind perturbation lagged the thermal perturbation by about 500 km at 850 mb.

Figure 10 indicates how the perturbation temperature field $\Delta T$ at 700 mb evolved over 48 h. Significant changes occurred during the second 24-h period. By
36 h, cool air (e.g., about $-4^\circ$C perturbation) existed northeast of the lakes region. By 48 h, the cool air left the domain and warm air began to appear just to the northeast. The evolution from cool to warm air at 700 mb by 48 h indicates that the depth of the MAV was continuing to increase as the warm air expanded upward. The strong height and wind perturbations at 48 h (cf. Figs. 5d, 6d, 7d) in this region at 700 mb were not accompanied by strong temperature perturbations as were the wind and height perturbations at the other two levels.

Figure 11 shows how the $\Delta T$ structure evolved along a vertical cross section oriented southwest to northeast between 30 and 48 h from a 2-km-deep warm plume that extended northeastward barely past the lakes at 30 h to a 3-km-deep warm plume that extended for hundreds of kilometers beyond the lakes at 48 h. This upward shift in the thermal perturbation from near the ground at 30 h to near 850 mb by 48 h induced a deeper cyclonic circulation (e.g., cf. Figs. 6c,d). This warming at 850 mb could have occurred from enhanced large-scale moist-adiabatic ascent that developed when the static stability was reduced and when the flow became southwesterly. Warming and cooling mechanisms associated with the MAV development will be examined in a follow-up study.

c. Vorticity, divergence, and vertical motion perturbations

Despite the large-scale organization in the perturbation wind and temperature fields, close inspection of the 1000–700-mb perturbation winds shows individual lake scale enhancements even at 48 h. These enhancements suggest more complicated perturbation structures of vorticity $\Delta \zeta$, convergence $\Delta \chi$ and vertical motion $\Delta \omega$. These fields are useful to examine because they can provide explanations for the enhanced precipitation associated with the MAV (cf. Fig. 4d).

Figure 12 indicates how the perturbation vorticity field $\Delta \zeta$ at 1000 mb evolved from a pattern of many
small bands of weak $\Delta \zeta$ over the lakes at 12 h to fewer and larger bands of strong $\Delta \zeta$ at 48 h. By 12 h, the $\Delta \zeta$ bands were most prominent over Lakes Michigan and Huron, where the prevailing flow was approximately parallel to the long axes of these lakes. By 24 h, an elongated region of positive $\Delta \zeta$ existed across Lakes Superior and Huron, and an equally large region of weaker negative $\Delta \zeta$ with similar orientation existed just to the northeast. The band of positive $\Delta \zeta$ was associated with the developing circulations over Lakes Superior and Huron. The band of negative $\Delta \zeta$ was along the edge of the significant wind perturbations (cf. Fig. 5b) and was thus mainly shear vorticity rather than curvature vorticity. The signatures over the remainder of the region remained weak. By 36 h, the bands were oriented southwest–northeast and significant vorticity centers at 1000 mb had developed northeast of Lake Huron ($20 \times 10^{-5} \text{ s}^{-1}$), over Lake Superior ($17 \times 10^{-5} \text{ s}^{-1}$), and over Lake Erie ($12 \times 10^{-5} \text{ s}^{-1}$). A broad region of weak negative $\Delta \zeta$ existed northeast of the lakes region. By 48 h, the broad region of weak negative $\Delta \zeta$ left the region and the bands northeast of Lake Huron and north of Lake Erie merged to form a large meso-$\alpha$-scale region of positive $\Delta \zeta$. The band over Lake Superior rotated to a more northwest–southeast orientation and became the most intense band in the region ($27 \times 10^{-5} \text{ s}^{-1}$). The second strongest value of vorticity ($17.6 \times 10^{-5} \text{ s}^{-1}$) was associated with the largest band of positive vorticity and with the MAV just northeast of Lake Huron. The orientation of the bands over the entire region at 48 h resulted from the MAV-induced low-level northerly flow over Lakes Superior and Michigan and the low-level southerly flow over Lakes Huron, Erie, and Ontario.

Figure 13 indicates how the perturbation vorticity field $\Delta \zeta$ at 850 mb evolved over 48 h. The 850-mb pattern is consistent with the 1000-mb pattern. It shows more clearly that the northwest–southeast-oriented bands were generated over the lakes during the first 12 h and then rotated to a southwest–northeast orientation as they moved northeastward during the
next 36-h period (e.g., 12–48 h). The highest value of vorticity ($15.6 \times 10^{-5} \text{ s}^{-1}$) was associated with the largest and deepest band of positive vorticity and with the MAV just northeast of Lake Huron.

Figure 14 indicates how the perturbation vorticity field $\Delta \zeta$ at 700 mb evolved over 48 h. The signature at 12 h consisted of a northwest–southeast-oriented band of negative $\Delta \zeta$ that developed over the lakes region. It then moved northeastward and rotated slowly during the next 24 h as it grew, intensified, and evolved into an elliptical shaped region northeast of the region. By 48 h, additional bands of positive and negative $\Delta \zeta$ were oriented southwest–northeast across and downwind of the lakes region. The highest magnitudes existed several hundred kilometers northeast of the lakes region. The three regions of significant negative $\Delta \zeta$ were associated with the closed cyclonic circulations at 1000 and 850 mb over Lakes Superior and Huron, and the trough downwind (east) of Lake Michigan. The lowest value of vorticity ($-10.5 \times 10^{-5} \text{ s}^{-1}$) was associated with the largest band of negative vorticity and with the MAV just northeast of Lake Huron.

Figure 15 shows how the $\Delta \zeta$ structure evolved from 30 to 48 h at 6-h intervals along a vertical cross section oriented southwest–northeast across the lakes region. By 30 h, weak southwesterly surface winds over the lakes led to the generation of a cyclonic–anticyclonic (e.g., positive–negative) $\Delta \zeta$ couplet extending northeastward from Lake Huron near the surface. The anticyclonic $\Delta \zeta$ likely developed from compensating subsidence near the lake shore. By 36 h, the couplet shifted northeastward as the southwesterly flow increased and as a second region of weaker (outflow-induced) anticyclonic $\Delta \zeta$ developed upwind that was located above the region of positive $\Delta \zeta$. By 42 h, the regions of cyclonic and anticyclonic $\Delta \zeta$ extended several hundred kilometers northeast of the lakes. By 48 h, positive vorticity extended over the lowest 300 mb for about 500 km downwind. Farther downwind, the
two regions of anticyclonic $D\zeta$ merged to form a larger and deeper region that extended to approximately 500 mb. The northeastward tilt between the cyclonic and anticyclonic vorticity maxima at 48 h was likely a result of the strong ambient vertical wind shear and the rotation of the vorticity bands as the flow became more southwesterly.

The perturbation convergence $D\chi$ patterns at 1000, 850, and 700 mb are shown in Figs. 16–18. They resemble the vorticity patterns in that they indicate similarly banded structures that evolved in a similar way. Figure 16 shows that even by 48 h, only a weak band of convergence at 1000 mb was associated with the MAV. Stronger and larger regions of convergence were associated with the vortex over Lake Superior and with the circulations over the lower lakes. Figure 17 shows that the band of convergence at 850 mb that was associated with the MAV was nearly as strong as that associated with the vortex over Lake Superior, but was considerably longer. A comparison of Figs. 16 and 17 indicates that the divergence–convergence couplets over the lakes at 1000 mb changed to divergence–convergence couplets at 850 mb and suggests shallow vertical circulations. Figure 18 shows that the band of divergence at 700 mb that was associated with the MAV was the strongest and largest feature over the region.

Figure 19 shows how the $D\chi$ structure evolved along a vertical cross section oriented southwest to northeast between 30 and 48 h from small regions of intense convergence near the surface of Lake Huron and divergence at 850 mb to very elongated regions of weaker convergence and divergence extending about 1000 km from southwest to northeast. Additionally, the level of maximum convergence changed from the surface to about 900 mb, indicating that perturbation convergence from warming had become more significant than that from friction. The elongated region of perturbation convergence at 48 h is consistent with the perturbation vertical motion pattern at 800 mb. Figure 20 shows that strong perturbation ascent and descent at 800 mb extended for nearly 1000 km downwind of Lake Huron. These enhancements of the vertical motion apparently were responsible for
Fig. 14. Similar to Fig. 12 except for 700 mb. Negative regions are shaded instead of positive regions.

the enhanced precipitation between 36 and 48 h in southern Ontario (cf. Fig. 4d).

d. **Mean vertical structure**

Profiles of some horizontally averaged quantities within the region enclosed by the $-10$-m height perturbation at 850 mb as they exist at 48 h are shown in Fig. 21. A comparison of the profiles in Fig. 21 with the horizontal distributions in previous figures shows that at any given level, the vorticity, divergence, temperature, and height perturbations have the same sign at nearly every point within the $-10$ m contour at 850 mb, so that the sign of the average quantity is indicative of the sign of the quantity at almost every point within the averaged region.

The thermal profile shown in Fig. 21a indicates that the MAV has a warm core. Maximum average temperature perturbations ($\sim 5^\circ$C) exist around 900 mb. The vorticity profile shown in Fig. 21b indicates that cyclonic vorticity extends from 1000 to 700 mb and that weak anticyclonic vorticity extends from 700 to 600 mb. Maximum average cyclonic vorticity perturbations ($\sim 5 \times 10^{-5}$ s$^{-1}$) exist around 900 mb. The convergence profile shown in Fig. 21c indicates that convergence extends from 1000 to 800 mb and weak divergence extends from 800 to 600 mb. Maximum average convergence perturbations ($\sim 2.5 \times 10^{-5}$ s$^{-1}$) exist around 950 mb. A vertical profile taken at the

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7 The region enclosed by the $-10$-m perturbation height contour at 850 mb in Fig. 6d may be considered as the inner half of the MAV.

8 Note that the vertical profiles of the horizontally averaged values that are shown in Fig. 21 differ from those taken along a tilted MAV axis although they reveal qualitatively similar structures.
850-mb center of the vortex shown in Fig. 21d indicates that the structures are qualitatively similar, but the magnitudes are significantly greater. Maximum values at the center of the MAV include $6^\circ$C for temperature, $20 \times 10^{-3}$ s$^{-1}$ for vorticity, and $6 \times 10^{-5}$ s$^{-1}$ for convergence. These values are roughly twice those associated with MCCs (cf. Menard and Fritsch 1989). The greater discrepancies between the single point values and the averaged values of vorticity and convergence reflect their smaller-scale structures relative to that of temperature.

3. Discussion

The fluxes of heat and moisture from the individual lakes were important aspects of MAV development. The distribution of the heat and moisture from the individual lakes over a larger area in the present case was accomplished in part by the development of lake-effect storms along the downwind lake shores as is the case during most cold air outbreaks. It is well known (e.g., Braham and Kelly 1982) that typical cloud-top heights associated with these storms range from 2 to 4 km. These heights are determined by the lake-air temperature differences and the stability of the over spreading air mass. These same environmental criteria also govern the depth of developing lake-aggregate-scale disturbances. It is therefore not surprising that the MAV had a depth $H \sim 3$ km. Unlike lake effect storms, however, which can have cloud-top heights below 2 km, it is unlikely that MAV circulations that are shallower than about 2 km will have a meso-$\alpha$-scale size and be inertially stable. It is also unlikely that the deepest MAV circulations will extend beyond 5–6 km without some synoptic-scale assistance. The assumption of a vertically symmetric response yields additionally that a 1.5-km-deep cyclonic circulation can be expected in the lower half.

The horizontal size $L \sim 500$–1000 km of the MAV in the present case was likely influenced by several factors including 1) geographic size of the Great Lakes region, 2) vortex merger, 3) enhanced synoptic-
scale forcing, and 4) geostrophic adjustment. Recall that the lake-aggregate-scale was noted in Part II to be approximately 2000 km (cf. Eichenlaub 1979). Although WL–NL effects in wind did extend over these distances downwind from the lakes, a single circulation did not develop over such a large area. A possible reason is that the Great Lakes themselves occupy less than 50% of the region (e.g., total drainage basin) and hot spots over the individual lakes would (at least initially) preferentially force smaller-scale vortices over the lakes (cf. Fig. 5a). Even if these vortices merge as described below, the resulting (meso-α-scale) vortex would still be smaller than 2000 km.

Melander et al. (1988) and Dritschel and Waugh (1992) showed that vortex merger between two co-rotating vortices of equal strength and radius $R$ occurs when they are separated by a distance $d < \sim 3.5R$. The resulting vortex has the same vorticity but is larger in size. An extension to $n$ Rankine vortices each with radius $R$, and vorticity $\zeta$ that meet the merger criteria yields a single vortex with vorticity $\zeta$ and radius $R_{\text{MAV}} = \sqrt{nR}$. If each Great Lake generates a lake-sized vortex, then the geometry (geography) of the lakes would allow vortex merger to generate a single vortex that is larger than the individual lake vortices and that has stronger winds. For example, if all of the lakes generate vortices with radius $R \sim 100$ km (e.g., comparable to those from small Lakes Erie and Ontario), then the smallest merged (aggregate scale) vortex would have a radius $R_{\text{MAV}} \sim 225$ km or a horizontal extent $L_{\text{MAV}} = 2R_{\text{MAV}} \approx 450$ km. If all of the lakes generate individual lake vortices with radius $R \sim 200$ km (e.g., comparable to those from large Lakes Superior and Huron), then the merged vortex would have a radius $R_{\text{MAV}} 450$ km. The above considerations yield a range of sizes given by 450 km $< L_{\text{MAV}} < 900$ km.

The above range is based on the assumptions that 1) each lake generates an equal-sized vortex, 2) the individual vortices are circular, equal-strength, Ran-
kine vortices, and 3) MAVs develop exclusively from vortex merger. The fact that the MAV in the present case showed some signs of vortex merger and the fact that the observed width $L_{\text{MAV}} \sim 700$ km fell within the range computed above do not imply that vortex merger was solely responsible for the development of the MAV. For example, the weaker and smaller vortex over the lower lakes did appear to wrap into the larger and stronger vortex over Lake Huron that became the MAV (cf. Figs. 5d, 6d). But, the trough over Lake Michigan and the 1–2 vortices over Lake Superior remained as separate entities through 48 h. It is not known whether these features eventually merged with the Lake Huron vortex.

The size of the MAV could have also been influenced by synoptic-scale dynamics. For example, the large amount of heat and moisture that was transferred into the lower atmosphere could have led to enhanced large-scale horizontal temperature advections and/or low-level vorticity advections that could have generated a meso-α-scale circulation. Specifically, the enhanced southerly flow at 850 mb on the east side of the developing circulation at 36 h coupled with the existing synoptic-scale temperature gradient oriented approximately north–south could have enhanced warm advection and low-level ascent that could have assisted in further development. These enhanced synoptic-scale advections may explain why the MAV did not develop during the period when the coldest air was over the region (cf. Fig. 2a,b), but instead developed after the synoptic-scale flow changed (cf. Figs. 2e,f). Development mechanisms will be examined in a follow-up study.

Regardless of the mechanisms that led to development, the MAV became dynamically large by 48 h. Dynamically small responses ($R < R'$) lack a high degree of geostrophic balance and radiate away much of the energy used to maintain them in the form of gravity waves while dynamically large responses ($R > R'$) achieve some degree of geostrophic or gradient wind balance and trap the energy within the system, which allows them to strengthen (cf. Schubert et al. 1980). The MAV likely became dynamically large as a result of an increase in physical size and a decrease
in static stability (cf. Chen and Frank 1993) as warming spread over a larger region and when the synoptic-scale flow changed. This dynamical growth was likely significant to its further development.

The MAV in the present case can be described as an inertially stable, meso-\(\alpha\)-scale warm-core vortex approximately 800 km wide and 3 km deep that developed from aggregate heating and moistening over the Great Lakes. Observations over the Great Lakes during wintertime cold-air outbreaks suggest that this description is valid for other meso-\(\alpha\)-scale vortices (e.g., Petterssen and Calabrese 1959; Bates et al. 1993) that develop near the surface during synoptic-scale conditions similar to those in the present study. But, not every dynamically large meso-\(\alpha\)-scale surface low in the vicinity of the Great Lakes in winter is generated from lake-aggregate heating. The only unambiguous way to differentiate between synoptically forced closed lows and lake-aggregate forced lows is by performing numerical simulations like those in Part II. Nonetheless, there are features that exist within the observations on standard synoptic-scale charts that can suggest very strongly the presence of MAVs.

Examination of the WL fields or the actual observations by themselves (cf. Figs. 2, 3) does not conspicuously reveal the MAV signature. But, careful comparison of WL and NL fields can indicate significant differences, especially near the surface, that can be used to identify MAVs in other similar situations. Figure 22 shows the 48-h NL simulation fields (e.g., the synoptic situation) at the surface, 850 mb, and 700 mb for 0000 UTC 15 November 1982. At the surface, a comparison of Figs. 3e,f with Fig. 22c reveals the presence of a weak low situated northeast of Lake Huron (e.g., the MAV) in the WL (e.g., observed) sea level pressure field and only a very weak trough to the south of the lakes region in the NL sea level pressure field. Further comparison reveals the presence of a distinct meso-\(\alpha\)-scale thermal ridge over the lakes in the WL surface temperature field that does not exist in the NL surface temperature field. The meso-\(\alpha\)-scale surface low and temperature fields are hydrostatically consistent.

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**Fig. 18.** Similar to Fig. 16 except for 700 mb. Negative regions are shaded instead of positive regions.
Identification of MAVs from upper-level charts is more difficult. The associated warm core means that the negative height perturbations and the cyclonic wind flow perturbations decrease in magnitude with increasing elevation. The baroclinic structure of the synoptic-scale flow means that a given height or wind perturbation embedded within the flow becomes increasingly more difficult to detect with increasing elevation. These features almost preclude the existence of a closed low above the surface, although enhanced cyclonic flow will typically exist within 1.5–2.0 km of the surface.

For example, in the present case (cf. Fig. 3c,d and Fig. 22b), the MAV is identified on the 850-mb chart as an enhanced trough over the lakes. The synoptic-scale contribution indicates the typical westward tilt with height but lake-aggregate heating has caused enhancement directly over the surface low. This enhancement has increased the height gradient on the downwind side of the trough, giving the appearance of a more confluent, more positively tilted (e.g., southwest to northeast) trough. Winds on the downwind side are correspondingly stronger (from the south-southwest).

Additionally, a weak thermal ridge can be seen in the WL temperature field northeast of Lake Huron. The NL temperature field shows smooth isotherms with a strong northwest–southeast temperature gradient. Although the perturbation flow in the current case was anticyclonic at 700 mb, this feature is not easily observable on the 700-mb chart given the weak perturbation signature and the strong synoptic-scale flow (cf. Figs. 2a,b and Fig. 22a). Subtle differences include slightly more diffuence on the downwind side of the WL trough than for the NL trough as a result of the positive height perturbations.

In general, MAVs are most easily identified at the surface from wind, temperature, and sea level pressure patterns. Specifically, surface lows with 1–3 closed isobars (at 2-mb intervals) and with a corresponding meso-α-scale thermal ridge pointing toward the synoptic-scale cold air that develop over the lakes in cold air (e.g., 10°C lake-air temperature difference) likely
develop from lake-aggregate forcing and hence are probably MAVs. Additionally, the temporal evolution at the surface may provide clues toward identification. For example, an existing weak surface low that moves into the lakes region and that does not intensify despite favorable synoptic-scale forcing may not be a MAV (cf. Agee and Lidbrauch 1989). In contrast, a weak trough that accelerates into the lakes region in winter during relatively cold conditions and then lingers as it begins to deepen slowly (e.g., 6 mb per 12 h) into a closed low despite unfavorable synoptic-scale forcing is likely a MAV. Subtle features, strong synoptic-scale flow, and existing coarse upper-air resolution make identification of MAVs very difficult above the surface despite the significant values of vorticity and divergence that are associated with them.

4. Summary and conclusions

The with-lake WL and no-lake numerical NL simulations described in Part II were examined more thoroughly in this study to describe the structure of a meso-α-scale vortex that developed when lake-aggregate heating and moistening spread across the Great Lakes region during a 48-h period. The vortex is referred to as a mesoscale aggregate vortex MAV because 1) it formed within the heat and moisture from the lakes that was spread over a large region, 2) it formed downwind of the lakes region, 3) it formed during prevailing southwesterly flow approximately 36 h after the lakes had been warming and moistening cold and dry northwesterly flow, 4) its scale at the surface exceeded that of the largest individual Great Lake (e.g., 1000 km versus 400 km for Lake Superior), and 5) it developed from smaller individual-lake scale circulations. The heating and moistening from the aggregate-lake rather than from any individual lake was therefore important for development.

Wind analyses at 48 h indicate that the MAV exhibited cyclonic circulation at the surface and 850 mb, and anticyclonic circulation at 700 mb. Temperature analyses indicated that the MAV was warm core, with...
a maximum temperature perturbation near 850 mb. Additional analyses indicate that cyclonic vorticity extended from 1000 to 700 mb, convergence extended from 1000 to 800 mb, weak anticyclonic vorticity extended from 700 to 600 mb, and weak divergence extended from 800 to 600 mb. Maximum average relative vorticity was about $5 \times 10^{-5}$ s$^{-1}$ at 900 mb, and maximum average convergence at 800 mb was $5 \times 10^{-3}$ s$^{-1}$. Maximum values at the center of the MAV were roughly twice those associated with MCCs (cf. Menard and Fritsch 1989). The size of the MAV was likely influenced by several factors including 1) geographic size of the Great Lakes region, 2) vortex merger, 3) enhanced synoptic-scale dynamics, and 4) geostrophic adjustment.

The MAV in the present case can be described as an inertially stable, meso-$\alpha$-scale warm-core vortex approximately 800 km wide and 3 km deep that developed from aggregate heating and moistening over the Great Lakes. Observations of similar structures (e.g., Petterssen and Calabrese 1959; Bates et al. 1993) suggest that this description is valid for other meso-$\alpha$-scale vortices that develop near the surface during similar synoptic-scale conditions over the Great Lakes region.

This study indicates that because MAVs are a warm-core phenomenon embedded within a baroclinic synoptic-scale environment, they are most easily identified on standard synoptic-scale charts at the surface as a weak meso-$\alpha$-scale low in the sea level pressure field with 1–3 closed isobars at 2-mb intervals and the presence of a meso-$\alpha$-scale thermal ridge over the lakes region. They are more difficult to identify on upper-level charts (e.g., 850 and 700 mb) given current rawinsonde resolution.

It is concluded that the mesoscale aggregate vortices MAVs that develop downwind from the Great Lakes in winter are fundamentally different from other mesoscale cold-air vortices that have been documented in the literature because of their meso-$\alpha$-scale
size and because lake-aggregate heating is required for their development. It is also concluded that these vortices likely require more than just sensible and latent heating from the Great Lakes aggregate because development occurred about 36 h after the coldest air left the region. Possible mechanisms for development include vortex merger, geostrophic adjustment, and enhanced synoptic-scale advections of temperature and vorticity. Development mechanisms will be examined in a follow-up study.

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Fig. 22. No-lake (NL) results from Sousounis and Fritsch (1994) at 48 h valid at 0000 UTC 15 November 1982. (a) No-lake 700-mb heights (solid) and temperatures (dashed). (b) No-lake 850-mb heights (solid) and temperatures (dashed). (c) No-lake sea level pressure (solid) and 1000-mb temperatures (dashed). Height contours are every 30 m, temperature contours are every 4°C, and sea level pressure contours are every 4 mb. Wind vector of length equal to grid separation distance is 20 m s
-1.


