THE PARAMETERIZATION AND PREDICTION OF SYNOPTIC-SCALE INFLUENCES ON GREAT LAKES SNOWSTORMS

By

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In 1962, Wiggin described what appears to be the essential ingredients for generating moderate to severe lake-effect snows:

(1) ...a deep closed low, a feature known to give upper air support to surface systems;

(2) ...a residual trough of low pressure...maintained by vorticity created by the heating of fresh cold air flowing across the much warmer lakes. [7]

The development of the "residual trough" was declared by Petterssen (1956) to be closely aligned to the instability and convergence created beneath the upper level low. The maintenance of such a trough was in keeping with Petterssen's discussion of the Great Lakes as a surface vorticity source, "a geographically bound heat source" in winter. [5]

Wiggin also referred to forecasters of lake-effect snow as being "concerned with vorticity on the mesoscale; some day we will have to develop a special technique for computing it." [7] Our present-day definition of "mesoscale", encompassing horizontal dimensions from 10 to 100km, would force us to conclude that Wiggin was interested in the prediction of vorticity generated solely by the lakes.

The primary concern of this paper involves the prediction of a medium scale (100 to 1000km) vorticity source passing through low levels of the atmosphere. This, in turn, enhances the production of vorticity by these relatively warm bodies of water.

Forecast Level and Equations

Danard (1964) found the level of maximum latent heat release within a storm to be equivalent to a nondivergent level. Unlike summer convective activity or large-scale winter storms, lake-effect snowstorms are unusually shallow with clouds tops typically reaching only 10,000ft (3.3km). The associated maximum omega (ω), and therefore nondivergent level, where

$$- \frac{\partial \omega}{\partial p} = \nabla \cdot \mathbb{V} = 0 \qquad (1)$$

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is near the 800mb surface (McVehil et al, 1967).

Diagnostic studies have shown the 500mb surface to be effective in forecasting large-scale cyclones and long wave phenomena, even though their level of true nondivergence fluctuates readily between 600 and 400mb (Stuart, 1964). Likewise, the error introduced by selecting the standard 850mb surface for predicting medium scale perturbations affecting these shallow lake storms has not proven serious in the nine forecasts made during three winter seasons.

The forecast equation requires only the 850mb height (Z_{850}):

$$\nabla^2 \frac{\partial Z}{\partial t} = 0.25\ \mathbb{J}\ (Z_{850}, \zeta + f_o) = F_{i,j} \quad (2)$$

$\mathbb{J}$ ≡ horizontal Jacobian operator

∇^2 ≡ horizontal Laplacian operator

where the right-hand forcing function is dependent on the relative vorticity (ζ) advection at 850mb to alter the height pattern in time through local height changes ($\partial Z / \partial t$). The small areal extent of the Great Lakes permits the use of a constant Coriolis parameter (f_o), thus preventing spurious anticyclogenesis.

The initial data are read in at 900 grid points spaced 127km apart over eastern North America, and are processed within 30sec on a UNIVAC 1108 computer. The forecast product includes the 6 hourly trough positions and attendant absolute vorticity maxima. The predicted 850mb u and v wind components are related to lake fetch. In particular, the orientation of convergence bands is prescribed by winds from 2000 to 5000ft.

To form a diagnostic omega equation for this simple model, we expand the vorticity equation to include the divergence term:

$$\frac{d\zeta}{dt} = \mathbb{V}_{850} \cdot \nabla\eta_{850} + \nabla^2 \frac{\partial Z}{\partial t}_{850} = \frac{\partial \omega}{\partial p} (\zeta + f) \quad (3)$$

The advection of absolute vorticity (η_{850}) and the local rate of change of relative vorticity are equivalent from Eq. (2), where

$$\zeta = \frac{m^2 g}{d^2 f} \nabla^2 Z_{850}, \quad (4)$$

$m = \frac{1 + \sin 60°}{1 + \sin \theta}$, map scale factor,

θ = latitude,

g = acceleration due to gravity,

and d = distance between grid points.

In finite difference form, Eq. (3) becomes

$$\frac{f^2 d^2}{g m^2 \Delta p} (\omega'_{700} - \omega_o^{\,0}) = 0.50\ \mathbb{J}\ (Z_{850}, \zeta + f) \quad (5)$$

with omega at 1000mb set equal to zero. The prime (') serves to indicate only a partial approximation to the 700mb vertical motion field.

850mb Analyses for 19 - 20 November 1969

To evaluate the effectiveness of this equivalent barotropic model, it is important to note the relationship between 850mb weather patterns and surface weather observed during a moderate lake-effect storm of 19 - 20 November 1969. Figures 1, 3 and 5 depict 850mb isoheights in decameters, isotherms in degrees Celsius and isotachs in knots at 12hr intervals. The initial height field at 12 GMT 19 November reveals a deepening 132dm low north of the Great Lakes, with a sharp north-south frontal trough extending toward the Gulf of Mexico. Along the Canadian-United States border, a secondary trough has formed beneath a 500mb closed low. This is the feature requiring prediction for accurate determination of snow squall onset and duration to the lee of each lake.

The accompanying relative vorticity field was hand calculated by graphically adding the radius of curvature (V/R) and shear term ($-\Delta V/\Delta N$), evaluated every 254km or 1 inch on a 1:10,000,000 map scale. The cyclonic rotation and strengthening of both troughs, seen in Figure 3, carries increased vorticity maxima across the eastern and western Great Lakes at 00 GMT 20 November. The 70kt jet over Canada couples large cyclonic shear and curvature vorticity to produce a $+14 \times 10^{-5} sec^{-1}$ relative vorticity maximum in Figure 4. Likewise, the development of a 50kt jet at the southwest tip of the secondary trough has increased its associated relative vorticity to $+8 \times 10^{-5} sec^{-1}$ centered over southern Wisconsin.

Favorable diabatic effects induced by the lakes' presence create this narrow zone of baroclinity. Surface heating resulting from the passage of cold air over relatively warm Superior and Michigan, plus the release of latent heat during the ensuing cloud formation and outbreak of snowshower activity have increased the overlying thickness between constant pressure surfaces at low levels. Undisturbed cold air advection around the western flank of these two bodies of water yields the correspondingly increased slope of the 850mb level in the region of the analyzed jet.

At 12 GMT 20 November, the cold frontal trough is weakening over New England (Fig. 5), while its associated relative vorticity maximum now equals the $+8 \times 10^{-5} sec^{-1}$ pattern situated over Lake Erie (Fig. 6). The continuation of a wind maximum orientated along the Ohio Valley explains the trailing tongue of positive vorticity extending from the secondary trough axis into Illinois.

Surface Analyses and Forecast Results

The surface chart for 18 GMT 19 November (Fig. 7) shows a strong cold front with a series of waves traveling northward, effectively delaying the front's eastward progress. The 1008mb surface low over Virginia was forecast by the National Weather Service to intensify as it moved north-northeastward toward the New England coast. These expected developments led Buffalo forecasters at 1 p.m. (18GMT) local time to predict a delay in the arrival of the secondary trough over lakes Erie and Ontario. NOAA research workers awaiting lake-effect activity for cloud seeding operations correspondingly planned to commence flights the following afternoon (Nov. 20).

Figures 9a and 9b show the 6hr forecast provided by the model

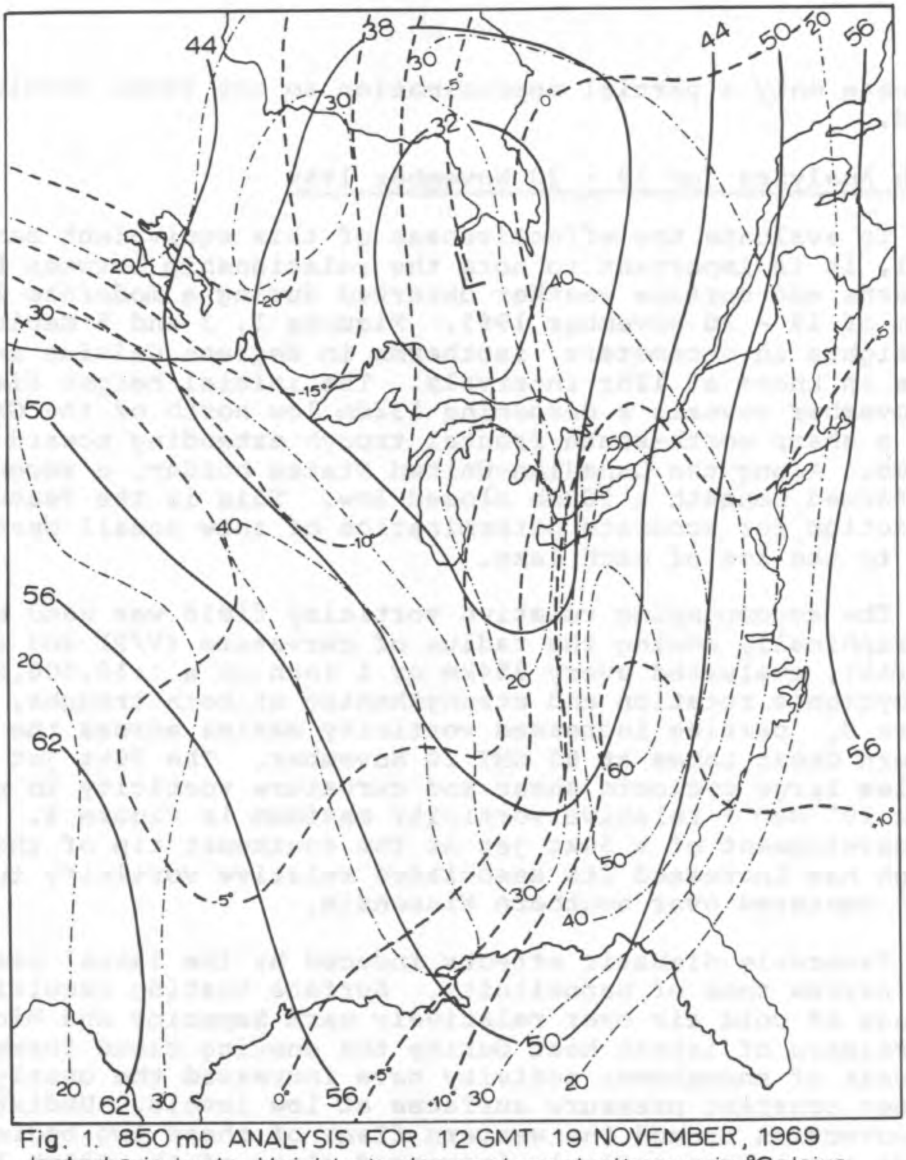

Fig. 1. 850 mb ANALYSIS FOR 12 GMT 19 NOVEMBER, 1969
Isotachs in knots; Heights in decameters; Isotherms in °Celsius

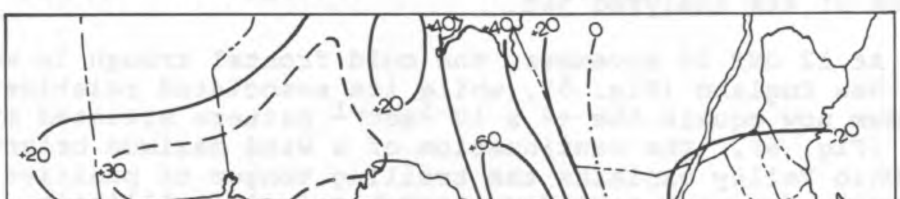

Fig. 2. RELATIVE VORTICITY ($x\ 10^{-6} sec^{-1}$) ON 850 mb SURFACE
12 GMT 19 NOVEMBER, 1969

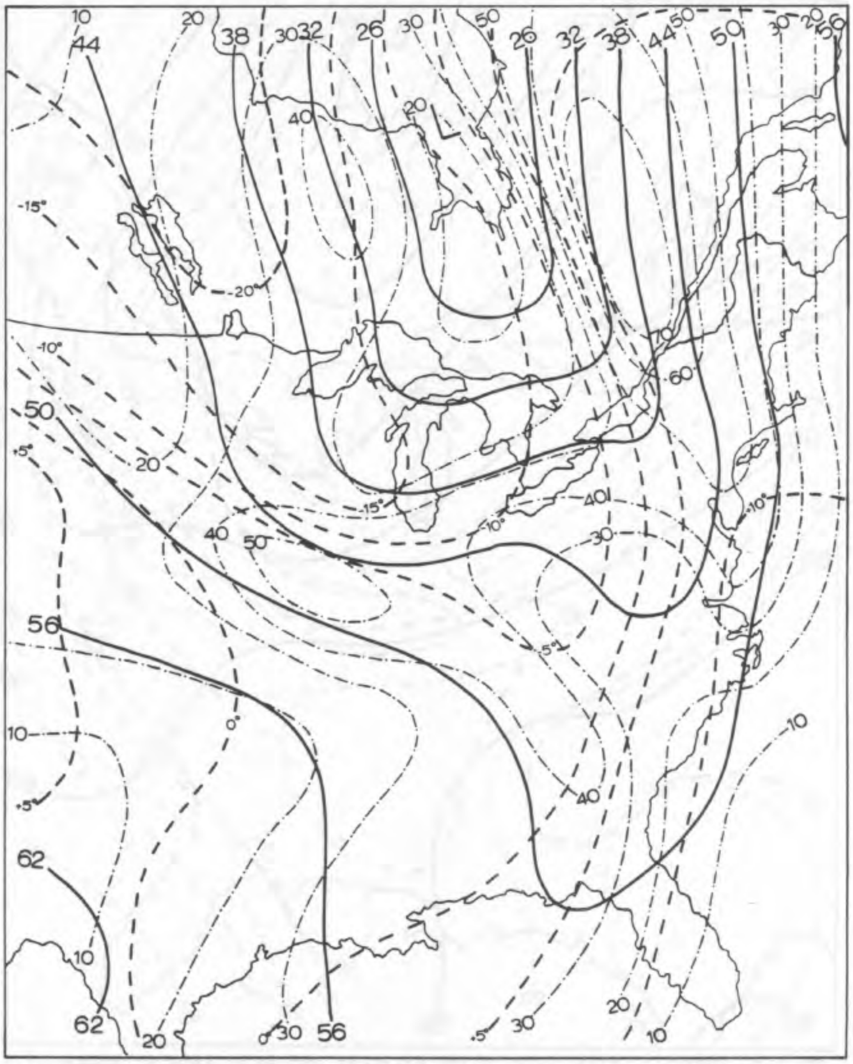

Fig. 3. 850 mb ANALYSIS FOR 00 GMT 20 NOVEMBER, 1969
Isotachs in knots; Heights in decameters; Isotherms in °Celsius

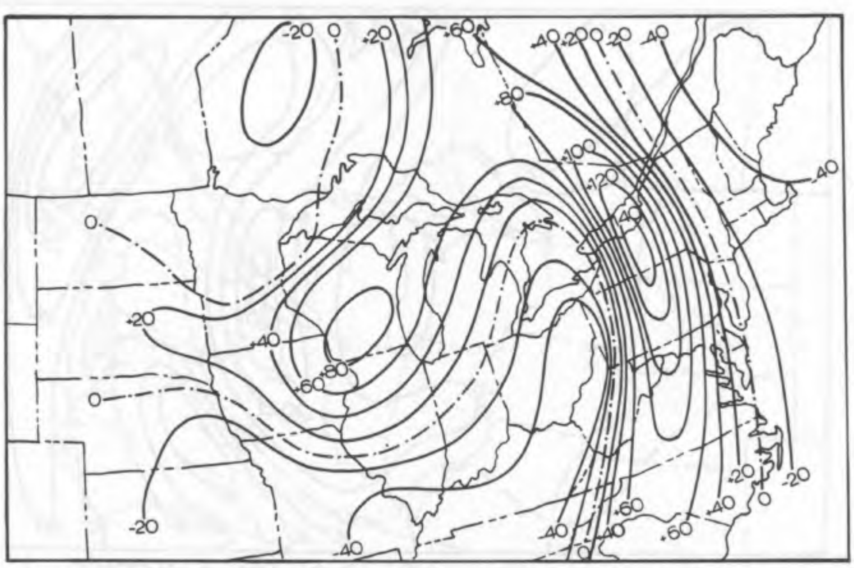

Fig. 4. RELATIVE VORTICITY ($x\ 10^{-6} sec^{-1}$) ON 850 mb SURFACE
00 GMT 20 NOVEMBER, 1969

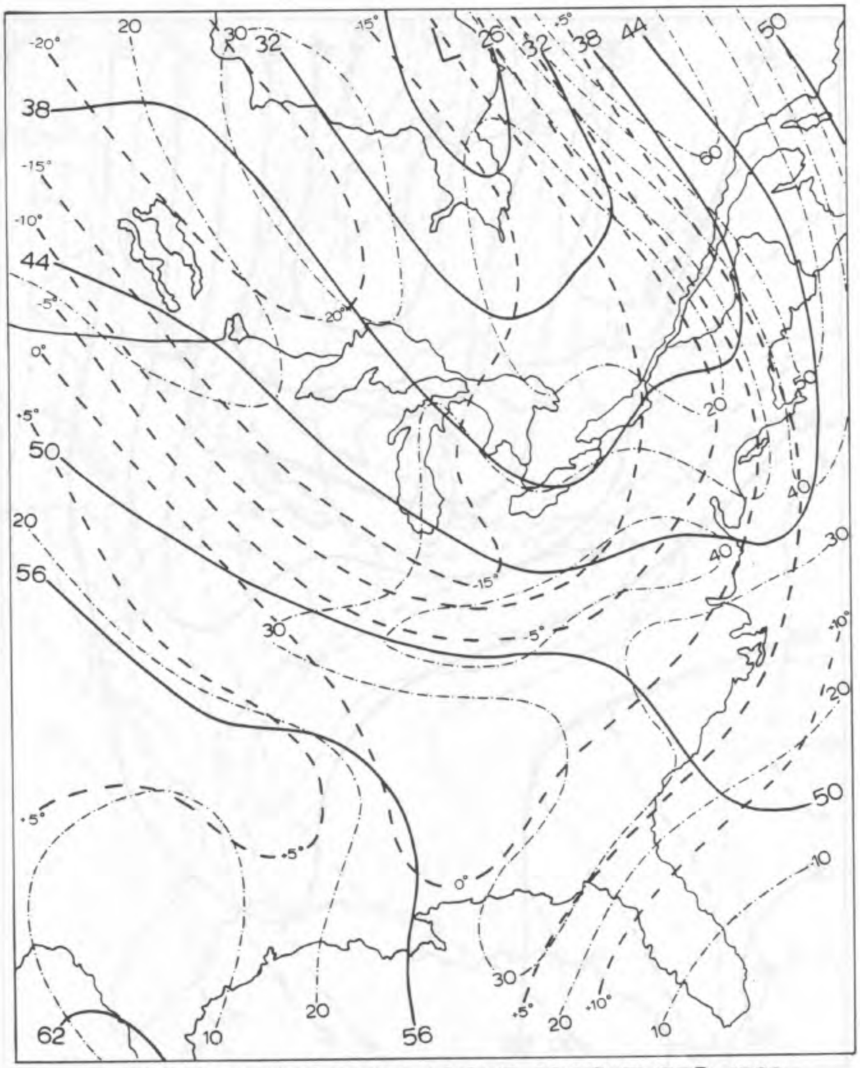

Fig. 5. 850 mb ANALYSIS FOR 12 GMT 20 NOVEMBER, 1969
Isotachs in knots; Heights in decameters; Isotherms in °Celsius.

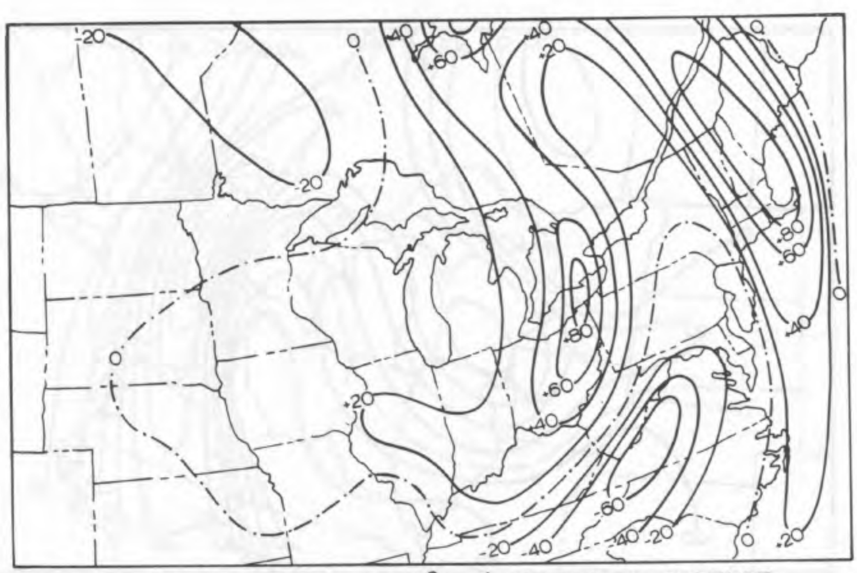

Fig. 6. RELATIVE VORTICITY ($x\,10^{-6}sec^{-1}$) ON 850 mb SURFACE
12 GMT 20 NOVEMBER, 1969

utilizing initial 850mb height data at 12 GMT 19 November and a 127km grid. The forecast heights in decameters are analyzed as solid lines in the left hand diagram. Short dashed lines depict forecast absolute vorticity (x $10^{-5}sec^{-1}$). A mean value of the earth's angular vorticity in the vicinity of the Great Lakes contributes 10 x $10^{-5}sec^{-1}$ to the absolute vorticity. The long dashed line positions the main trough associated with the cold front, while the dot-dash line defines the secondary trough.

Both plates contain a comparison of scales in their lower left-hand corners: 381km, the NMC standard grid length; 254km, the grid length used in determining hand calculated observed patterns of relative vorticity; 127km, the grid interval employed in the forecast model. On a grid of 381km, the secondary trough's vorticity pattern is essentially not detectable. At 254km, the absolute vorticity maximum associated with this same feature equalled +13 x 10^{-5} sec^{-1}. In Figure 9a, the 6hr forecast absolute vorticity maximum assigned by the 127km grid retains its initial value of +16 x 10^{-5} sec^{-1}.

The implication is clear and not surprising. We lose forecast accuracy in dealing with wavelengths at the lower end of synoptic scale phenomena whenever we employ grid intervals beyond a critical limit. We can achieve respectable predictability only when the reorientation and decreasing intervals between grid points no longer significantly alter vorticity patterns determined by finite differencing techniques.

Figure 7 provides an interesting comparison between observed weather and the 6hr forecast area of ascent associated with the trough at 850mb over the western Great Lakes. The formation of a weak surface trough at 18 GMT over northern Iowa with intermittent to continuous light snow extending back over Lake Superior is well depicted by the forecast ω'_{700} seen in Figure 9b. Furthermore, the weak ridging between both troughs with resultant negative vorticity advection reflects a correlation between forecast descent and observed clearing southwest of southern Lake Michigan.

Figures 3 and 4 provide a comparison between observed 850mb heights and vorticity patterns with those predicted for 00 GMT 20 November (Fig. 10a). We note first that the predicted main trough position has begun to lag its observed axis across central Lake Ontario. However, it is encouraging to find that although a strong divergence field has begun to affect the ability to forecast the primary trough's movement on the 850mb surface, the secondary trough appears to be excellently predicted. Both troughs have deepened, the primary to +24 x $10^{-5}sec^{-1}$ and the secondary to +18 x $10^{-5}sec^{-1}$ in absolute vorticity maxima. The 70kt and 50kt jet centers now found with each feature represent an increasing contribution of thermal vorticity to each trough's strength.

Rather than increase the intensity of both troughs, the numerical model has followed the tendency dictated by both a theoretically barotropic atmosphere and unavoidable truncation error. The absolute maxima of predicted vorticity patterns have decreased two units in both troughs. Although the observed and forecast vorticity patterns are similar, their absolute magnitudes are in error by values of 4 to 6 units.

Figure 10b, regardless of these shortcomings, continues to show generally good correspondence between predicted ascent forced by positive vorticity advection and patterns of steady precipitation

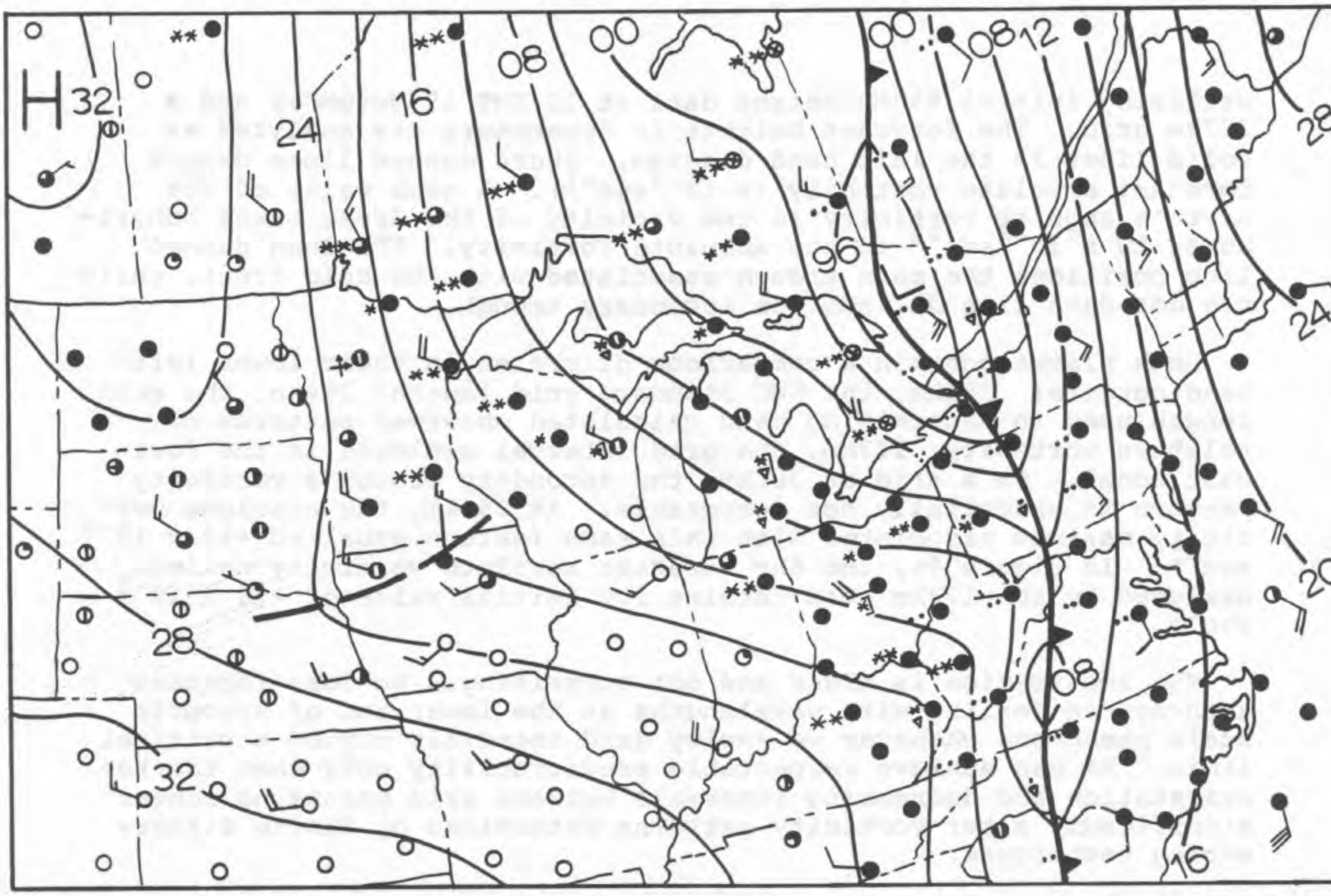

Fig. 7. SURFACE ANALYSIS FOR 1800 GMT 19 NOVEMBER, 1969

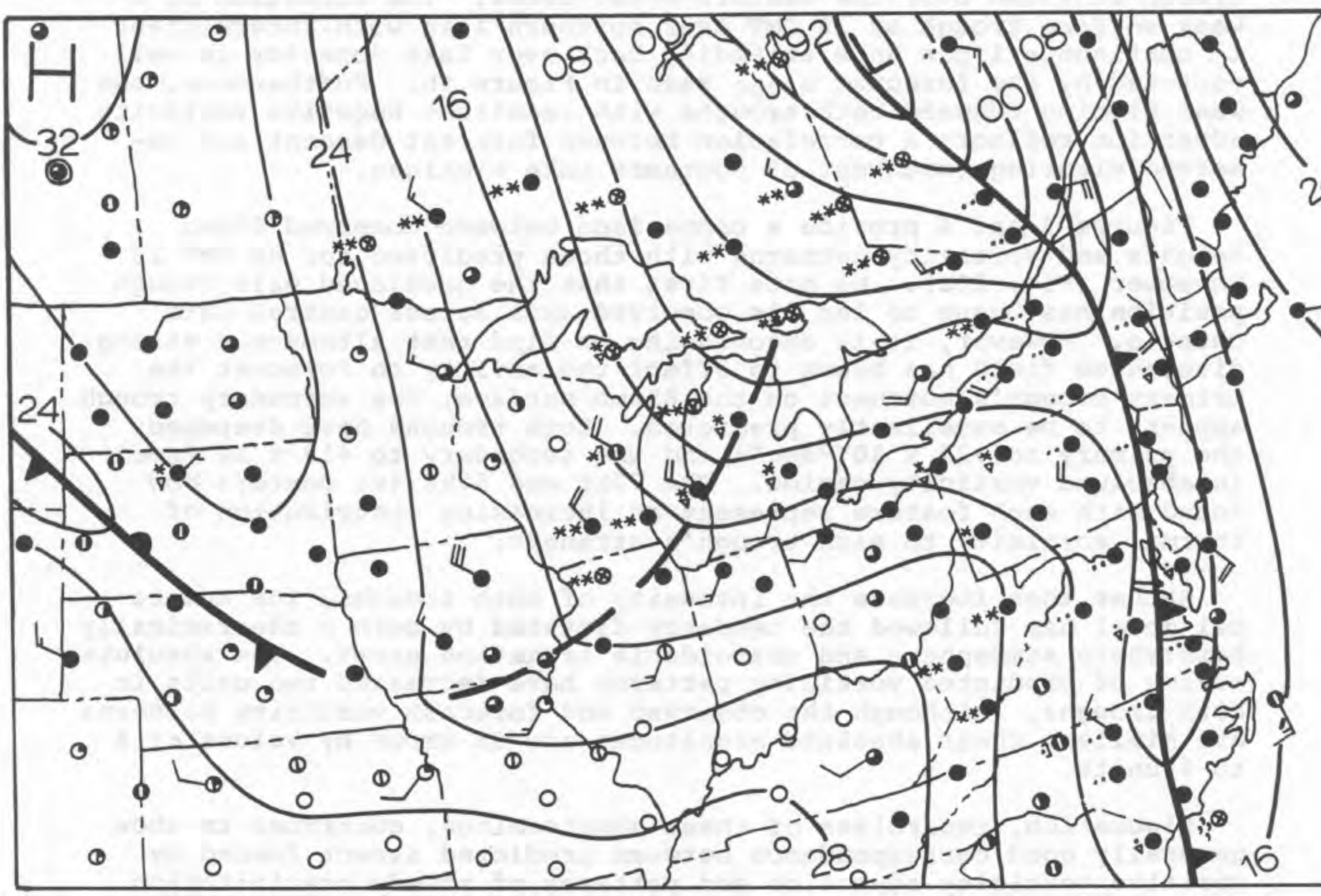

Fig. 8. SURFACE ANALYSIS FOR 0000 GMT 20 NOVEMBER, 1969

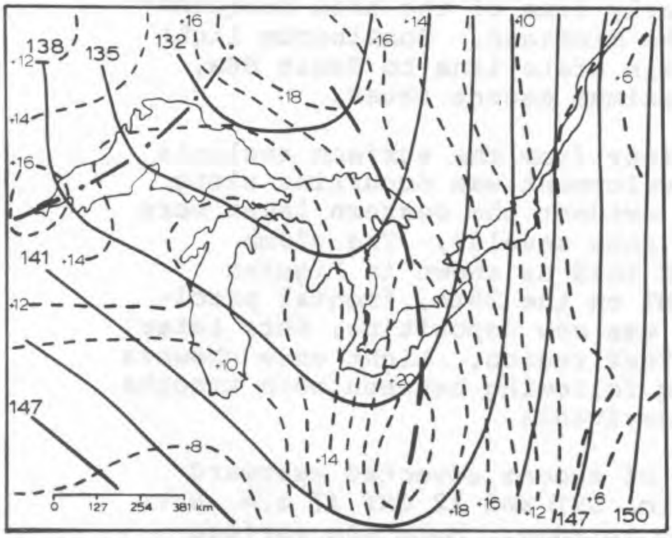

Fig.9a. 850 mb FORECAST HEIGHT & VORTICITY
November 19, 1969 1800 GMT

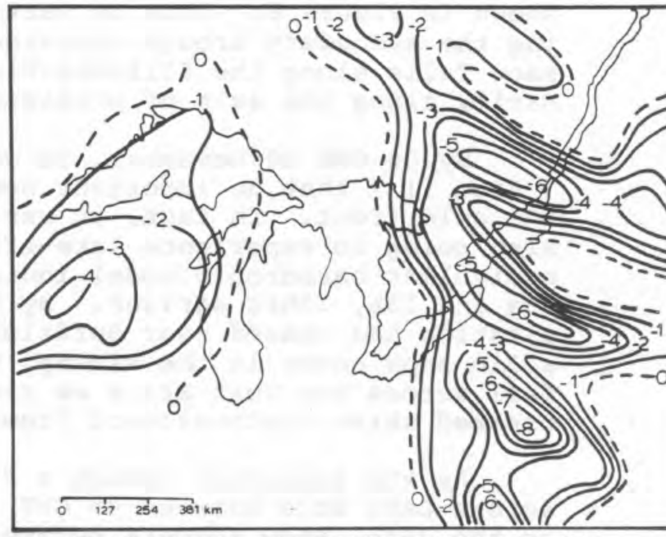

Fig.9b. VERTICAL VELOCITIES FORCED BY POSITIVE VORTICITY ADVECTION and $\nabla^2 \partial z/\partial t$ (microbars sec^{-1})

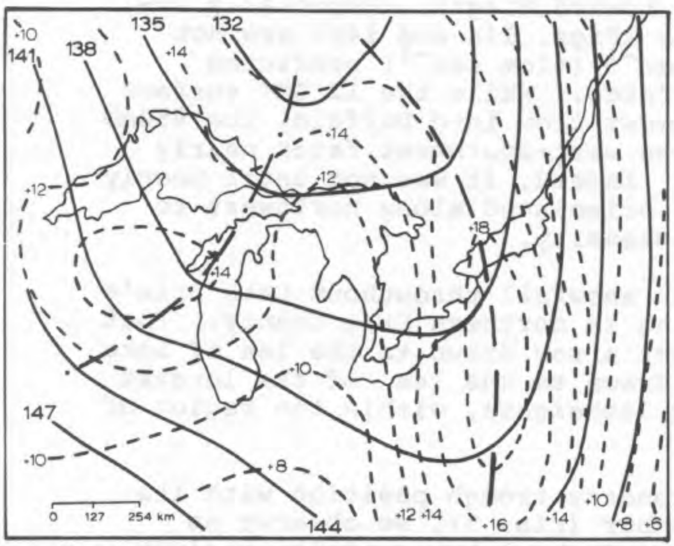

Fig.10a. 850 mb FORECAST HEIGHT & VORTICITY
November 20, 1969 0000 GMT

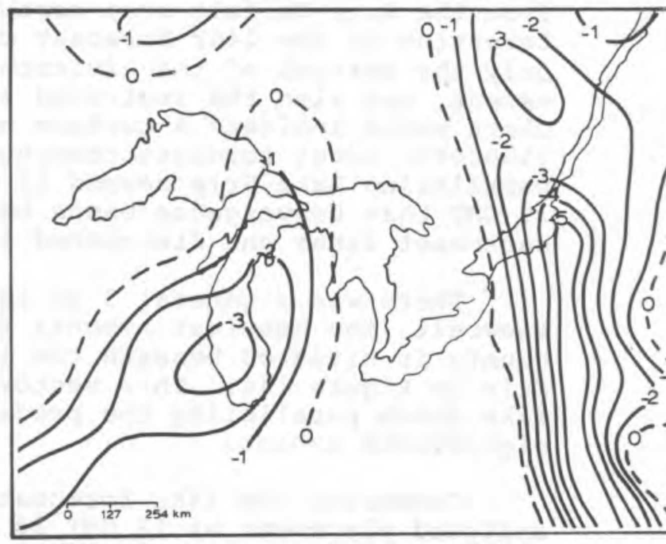

Fig.10b. VERTICAL VELOCITIES FORCED BY POSITIVE VORTICITY ADVECTION and $\nabla^2 \partial z/\partial t$ (microbars sec^{-1})

shown in Figure 8. This is particularly true of the area surrounding the secondary trough crossing Lake Michigan. Continuous light snow falls along the Illinois-Wisconsin state line to Sault Ste. Marie, along the axis of predicted maximum ascent rates.

By 06 GMT 20 November, it was clear from the surface analysis (Fig. 11) that no important new development was occurring along the cold front. In fact, it was now evident the eastern lakes were also going to experience lake-effect snow squalls. The 850mb equivalent barotropic model indicated this as shown in Figures 13a and 13b, 18hrs earlier. By 00 GMT on the 20th, frontal precipitation had ceased over Buffalo and was now depositing, 6hrs later, a 3in snow cover in the Albany, New York region. Light snow showers fell across New York State as ridging following between both troughs cleared skies southwestward from Pennsylvania.

As the secondary trough's field of ascent advected eastward across Lake Erie between 06 GMT (1 a.m. EST) and 12 GMT (7 a.m. EST) on the 20th, snow showers became more intense. Note the surface wind shift from sothwest to that of west-northwest and northwest at lakeside and Ohio stations in Figures 12 and 15, showing the 09 and 12 GMT surface weather.

Heavy continuous snow began falling before daybreak on the 20th from the Erie-Buffalo area northward toward Niagra. Especially interesting in the 24hr forecast charts (Figs. 14a and 14b) are not only the arrival of the -2microbar sec^{-1} ($\sim$2cm sec^{-1}) predicted ascent, but also the indicated lake fetch. While the 12 GMT surface chart would indicate a surface northwest flow into Buffalo, the 850mb ($\sim$5000ft) level forecast continues the west-southwest fetch nearly paralleling Lake Erie beyond 12 GMT. Indeed, it was not until nearly 18 GMT that convergence bands became orientated along northwest to southeast lines and diminished in intensity.

There was a general 3 to 18 inch snowfall throughout Lake Erie's snowbelt, the heaviest amounts falling in northern Erie County. That county is situated beneath the longest arrow drawn to the lee of Lake Erie in Figure 14a. This vector is drawn to the lee of the longest lake fetch paralleling the predicted isoheights, within the region of significant ascent.

Comparing the 24hr forecast secondary trough position with its analyzed placement at 12 GMT 20 November (Fig. 5), we observe no greater than a 50mi lag. The predicted absolute vorticity maximum has now decreased to $+13 \times 10^{-5} sec^{-1}$, whereas the actual vorticity center continues at $+18 \times 10^{-5} sec^{-1}$ (Fig. 6).

Unfortunately for the day's cloud seeding operations, the Buffalo based equipment became airborne after the secondary trough passage. The predicted northwest fetch and descent across Lake Erie at 18 GMT, not shown here, was now preceded by a long lake fetch over Watertown, New York. This community, to the lee of Lake Ontario, experienced its share of the snowburst as continuous heavy snow fell beneath the advancing forecast ascent.

In conclusion, a satellite picture for $\sim$ 14 GMT 20 November (Fig. 16) clearly depicts the primary effect of vertical motion predicted by the model. Lying along the East Coast, we see the cold frontal band of cloudiness associated with the main trough's upward increase of positive vorticity advection. This is followed by clearing over southeastern New York and Pennsylvania, between both troughs,

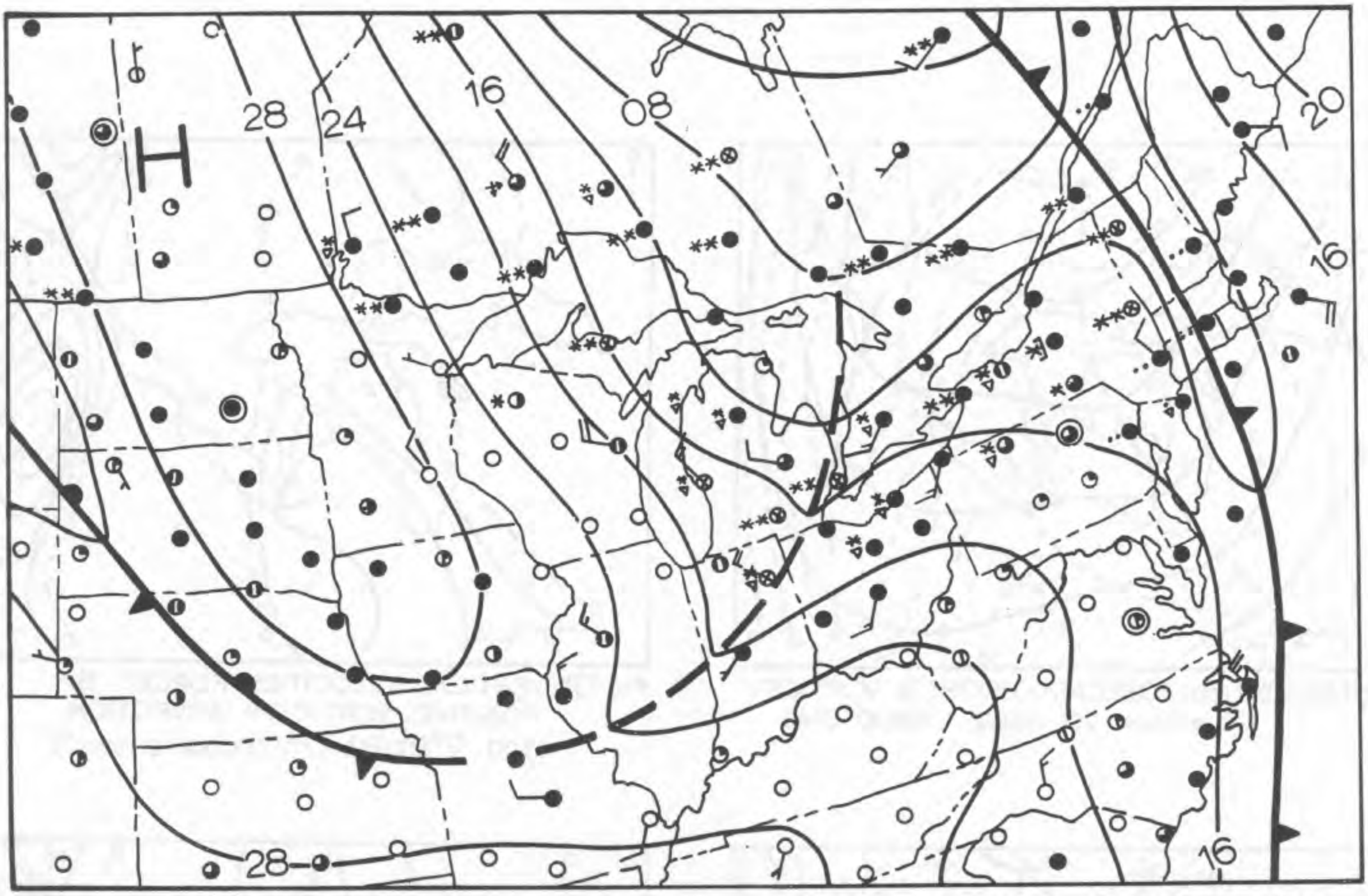

Fig. 11. SURFACE ANALYSIS FOR 0600 GMT 20 NOVEMBER, 1969

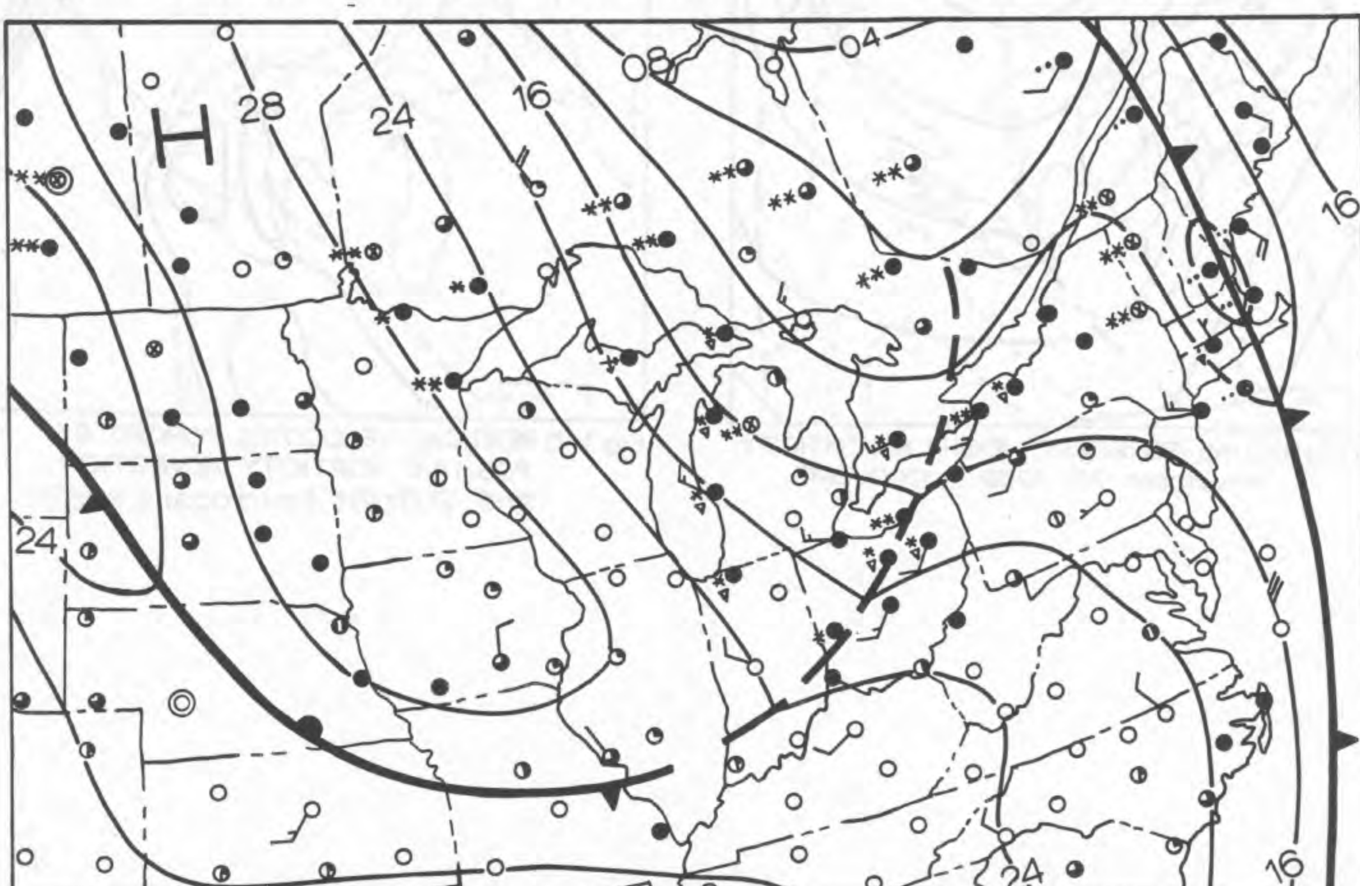

Fig. 12. SURFACE ANALYSIS FOR 0900 GMT 20 NOVEMBER, 1969

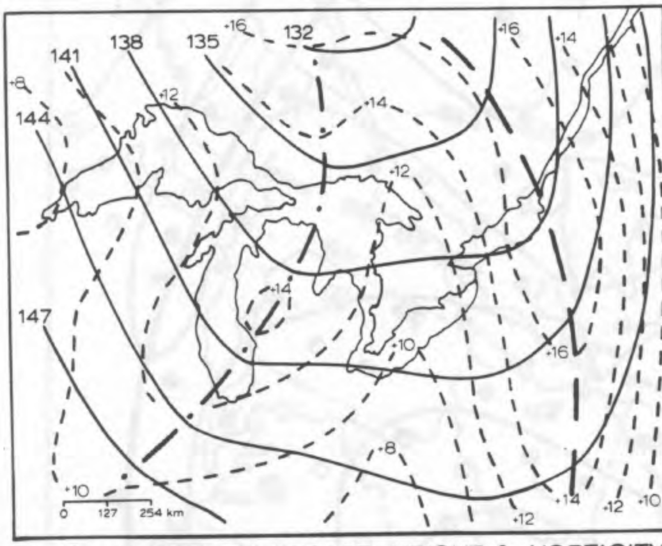

Fig.13a. 850 mb FORECAST HEIGHT & VORTICITY
November 20, 1969 0600 GMT

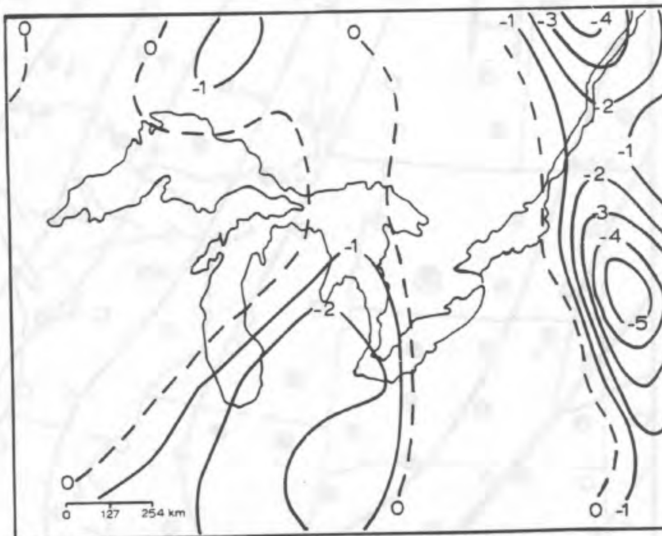

Fig.13b. VERTICAL VELOCITIES FORCED BY POSITIVE VORTICITY ADVECTION and $\nabla^2 \partial z/\partial t$ (microbars sec^{-1})

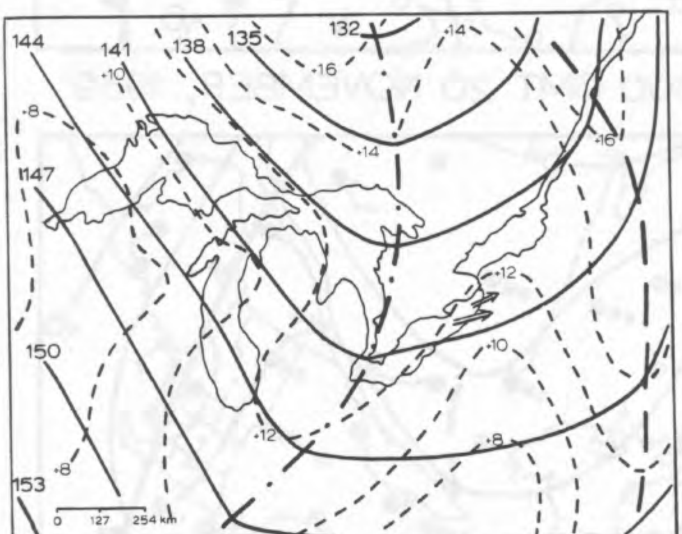

Fig.14a.850 mb FORECAST HEIGHT & VORTICITY
November 20, 1969 1200 GMT

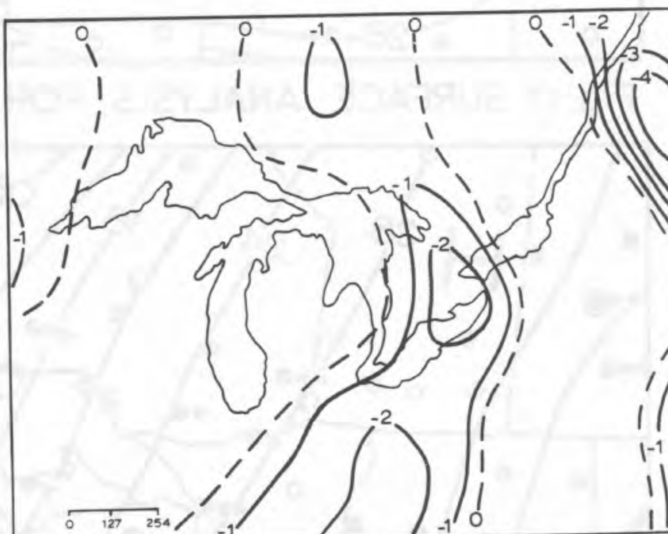

Fig. 14b. VERTICAL VELOCITIES FORCED BY POSITIVE VORTICITY ADVECTION and $\nabla^2 \partial z/\partial t$ (microbars sec^{-1})

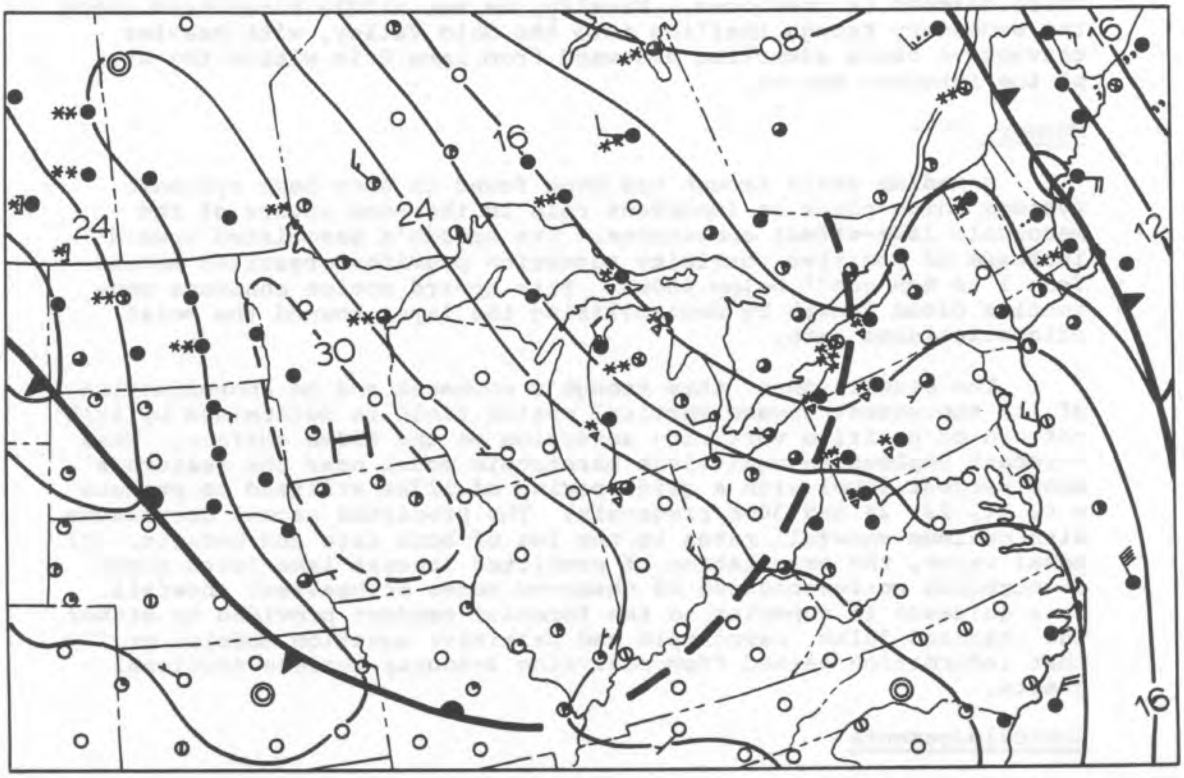

Fig. SURFACE ANALYSIS FOR 1200 GMT 20 NOVEMBER, 1969

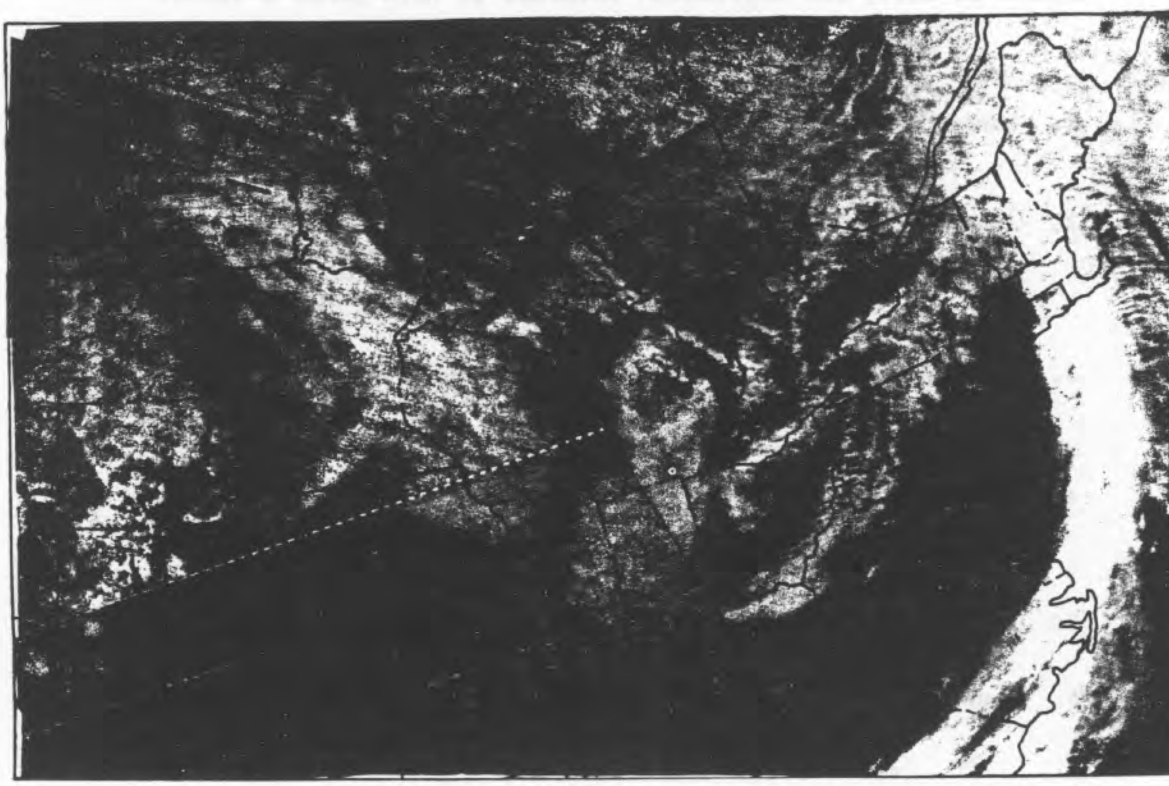

Fig. ESSA IX PHOTOGRAPH FOR ~1400 GMT 20 NOV., 1969 where descent is predicted. Finally, we see middle cloudiness along the secondary trough trailing into the Ohio Valley, with heavier convective bands advecting eastward from Lake Erie within the area of the forecast ascent.

Summary

A medium scale trough has been found in some deep cyclonic systems which plays an important role in the more severe of the mesoscale lake-effect snowstorms. The trough's associated upward increase of positive vorticity advection provides organized ascent from 1 to 6cm sec^{-1} below 600mb. This upward motion enhances convective cloud growth by destabilizing the layer toward the moist adiabatic lapse rate.

The prediction of this trough's movement and an approximation of its subsequent upward vertical motion field is determined by it's pattern of positive vorticity advection on the 850mb surface. This forecast employs an equivalent barotropic model near the feature's nondivergent level with a grid spacing of 127km utilized to produce a 6, 12, 18, 24 and 30hr prognosis. The predicted ascent correlates with maximum snowfall rates to the lee of both Erie and Ontario. Of equal value, the orientation of predicted longest lake fetch shows encouraging correspondence to observed zones of heaviest snowfall. This guidance is superior to the forecast product provided by either the standard 381km barotropic and primitive equation models, or that information gained from analyzing 3-hourly surface sectional charts.

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