Forecasting

LAKE-EFFECT SNOW FORECASTING IN THE COMPUTER AGE

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ABSTRACT

Forecasters have gradually achieved a better understanding of snowfall generated from warm waters of the Great Lakes. Rules of thumb regarding wind speed, direction and other parameters have evolved for specific locations.

A study was made of the two most recent winters, specifically 20 cases bearing lake effect traits with many producing significant snowfall. In the first part of the paper, earlier assumptions of the subject are reviewed. Some earlier hypotheses conflict with the results of the new study, at least initially. However, if the case study examples are grouped into two separate categories — one which allows the presence of upper-level dynamics — the earlier hypotheses become more harmonious with the new results.

In the second part of the paper, the operational computer model, LFM II, is analyzed for predictive value of mesoscale lake-effect snowfall. New rules of thumb, using various LFM II parameters in conjunction with established principles are presented in decision tree form.

1. INTRODUCTION

Throughout the Great Lakes region, lake-effect snowfall plays a significant part in climatology. In terms of population impact, the snowbelt of the lower Great Lakes (Figure A) is annually the snowiest stretch in the United States (2). Because of their mesoscale nature, lake-effect snows have considerable impact on area transportation, economy, and safety (3,4,5). Despite modern tools such as one-half mile resolution satellite imagery and upwind radar dial-up accessability, forecasting the location, timing, and amount of lake-effect snow is generally agreed to be tricky to this day. The author's direct involvement with the problem prompted an intensive two-season study. Review of earlier writings was necessary to test various suppositions with the new data. Also, an attempt was made to use operational computer models, especially LFM II, to help forecast these local events.

2. METHOD

During the 1970's, physical models of several of the Great Lakes were devised with valuable success (6). Until the next generation of operational models arrives, forecasters must continue to deal with the current models' handling of the region. LFM II regards each of the Great Lakes ONLY as a smooth, dry plane, from which there is no heat or moisture transfer (in short contrast to the ocean, which allows sensible heat fluxes). Collectively the Lakes provide the principal moisture source; thus, LFM II is usually unable to produce ANY quantified precipitation. QPF, arguably the most cruical parameter for cyclone-related snow forecasts, becomes virtually useless for lake-effect snow events. There are other imperfections with the model, but this one is the most pronounced and perhaps enough to discourage lake-effect forecasters altogether.

Nevertheless, the study proceeded under the hypothesis that LFM II offers enough other clues to earn its keep. Other parameters, though somewhat altered by the Lakes' presence, might still be incorporated for predicting snow squalls. The forecaster would then manually add the heat and moisture transfer — on the mesoscale.

Nearly every lake-effect event of any degree (into midwinter) for both the 1983-84 and 1984-85 season was investigated.

Notable case studies included:

1983 — 24 Nov, 1-2 Dec, 22-26 Dec

1984 — 14 Jan, 2 Nov, 19-21 Nov, 3-5 Dec, 6-7 Dec, 31 Dec

1985 — 1-2 Jan, 7-9 Jan, 11-13 Jan, 14-16 Jan, 18-23 Jan, 5-7 Feb, 17-18 Mar

There was research of even a few "near misses", in which little if any snowfall occurred, lacking necessary ingredients (e.g., cold enough low-level air) such as:

1983 — 3-4 Nov, 10-12 Nov, 6-7 Dec

1984 — 5-7 Nov, 16-17 Nov

In most examples, each of the Great Lakes was examined, with an emphasis on the densely populated areas. From these case studies, certain parameters were found repeatedly to be extremely helpful; others were eventually dismissed as impractical for lake-effect snow forecasting.

3. EARLIER DOCUMENTATION AND HYPOTHESES

Writings of lake-effect events date back almost beyond belief — to at least 1903! Professor Henry J. Cox, head of the Chicago weather bureau on that Thanksgiving Day, described how South Chicago received over a foot of snow while "beyond Western Avenue the sun shone brightly all day" (7).

This phenomenon was explained later by, among others, Wiggin in 1950, establishing certain meteorological conditions necessary to produce it. Two of the most important factors were restated by Niziol in 1982 (8). They are:

1) A strong flow of arctic air across the relatively warm lakes creating lee shore lapse rates that are adiabatic or greater to 5,000 feet.

2) Wind trajectories that circulate the air across a long fetch of the warm lakes.

Niziol, in his 1982 case study, observed trajectories relatively constant for an extended period of time.

Other key variables have been noted by Jiusto and Kaplan during a three-year study in the early 1970's (9). They added:

- Snowfall was heavier when the body of water was warmer as there existed greater vertical flux of momentum, heat, and moisture over the water.

- Areas under positive vorticity advection (PVA) were subject to greater snowfall.

Regarding PVA, Eichenlaub and Garrett in 1972 considered it critical to the occurrence of Lake snowstorms (4). Yet Lavoie in 1972 remarked that excess snowfall near the Lakes compared to neighboring regions does NOT result from traveling disturbances; on the contrary, he claimed, it generally occurs in situations that might be termed "fair weather" on the synoptic scale (10). The LFM II parameter of vertical velocity, which clearly identifies presence of strong PVA, was monitored closely in this new 1980's study. The intent was to determine to what extent PVA played in producing accumulative snowfall.

Convergence also plays a part in the process of lake-effect snow. FRICTIONAL convergence, for example, has been shown to be a factor. Airflow across the smooth lake plane is faster than across terrain; the air is forced to lift upon reaching the lee shore (4). THERMAL convergence is at least equally, if not more, important. Land breezes originating along shorelines parallel to the low-level airflow push offshore toward each other, forcing vertical motions over the lake (Figure B). Along this convergence zone, the heaviest precipitation echoes are found (8).

In a 1981 paper on the role of winter land breezes in the formation of lake-effect snows, Passarelli and Braham added three additional points (11). First, they considered the airflow to be CONFLUENT rather than just convergent. They claimed continual heating of the cold offshore flow by the underlying warm lake generates a density gradient, which in turn reinforces the off-shore flow until overridden by a change in either the large-scale pressure gradient or boundary temperature field. Second, they did not consider another possible mechanism in lake snow development, latent heat release, as critical in the mesoscale warming cycle. Their study (of other cases) revealed persistent cloud bands without snow, probably with cloud tops too warm to produce any significant precipitation. Finally, they concluded that the continual warming of the airflow produces a downstream reduction in surface pressure. This mesoscale process repeated over several of the Great Lakes modifies enough arctic air to significantly affect the synoptic-scale by splitting the surface high pressure system, as noted years earlier by Pettersen and Calabrese (12). The 1980's study would be expected to show consistent error in LFM II surface presssure forecasts.

One final important ingredient in lake-effect snow does not occur over the lakes themselves, but rather downstream over higher elevations — Orographic effects. Muller in 1966 noted this extra lifting over hilly terrain supplements snowfall (13). The Tug Hill Plateau in New York, for example, is a maximum precipitation area east and downwind of Lake Ontario; Wilson in 1977 termed the region a "major obstacle" to airflow crossing the entire lake (14). Along this trajectory, there is a rise of approximately 1000 feet in only 25 miles from Interstate 81 to western Lewis County (Figure C). The annual snowfall of western Lewis County far exceeds that of the lake shore (Figure D); by contrast, downwind of the long fetch of Lake Michigan, on a line from Benton Harbor, Michigan, to South Bend, Indiana, the annual snowfall is nearly equal. One obvious difference is the slope here being only about 100 feet over 20 miles (Figure E). According to Hill (in a 1971 NOAA Tech Memo, restated by Dewey in 1979), annual snowfall increases by 13-20 cm (5-8 inches) for every 30 m (approximately 100 feet) of rise to the lee of the Great Lakes (15). A more important distinction, however, is the greater impact on the Michiana region. Despite lower annual snowfall, a considerably higher population is impacted, and several vital interstate highways linking East and Midwest are adversely affected.

In one location along the Lakes, though, is a heavily populated area which exists along a significant orographic trajectory affected several times (from author's experience) each winter: Cleveland's south suburbs into the immediate Akron area (Figure F). At first glance, it would appear that a north-south airflow across the width (rather than the length) of Lake Erie does not conform to the long-established rules for lake-snow accumulation. But Lake Erie alone is not the main moisture source; rather, it is the long fetch of Lake Huron, upstream, which generates the snow (Figure G). Usually the winds direct the snow bands southeastward, but on occasion they turn southward, encountering a brief and slight rise (of at most 150 feet) over southwest Ontario Province (a) before continuing across Lake Erie (b). The travel over this generally flat terrain is compensated by a nearly equal journey over Lake Erie (approximately 55 miles). Upon reaching the Ohio shoreline (c), the air is forced upward over 600 feet in 20 miles to northern Summit County (d) with little change in elevation to Akron (e). This variation is one of the most critical yet least documented. When concurrent with a low-level trajectory of cold air over Lake Michigan into the Chicago vicinity, this pattern undoubtedly affects the most people of any lake-effect situation.

4. FORECAST RULES OF THUMB — REVISED

With the previously discussed vital conditions in mind, the study proceeded. Without regard for LFM II at first, the snowfall episodes themselves were carefully observed and compared. As patterns began to surface, some recognized by previous experience, some predictive values were established. Frankly, the new results were at least in partial conflict with certain established hypotheses.

For instance, criteria set by Rothrock (described in a paper by Braham in 1983) involved parameters such as fetch, temperature, and vorticity, all associated with 24-hr snows of > = 5 cm. Thirty cases affecting the south side of Lake Superior and the east side of Lake Michigan were studied (16). Some of the claims (followed by discussion by this author) were:

> 1) Minimum temperature difference of 13°C between the lake surface and the upstream airflow at 850 mb.

This rule, by itself, is theoretically sound, assuming a dry adiabatic lapse rate between the lake surface and 850 mb with no other factors. Holroyd in 1971 came to a similar conclusion, stating that a dry adiabatic temperature decrease indicates the presence of a layer of absolute instability (17). But regardless of the warmth of any lake, and with respect to the above-mentioned rule, the new data consistently elevates a particular 850 mb temperature as critical — the value <u>-10°C</u>. Assuming no upper level support, the new data showed each time the air at 850 mb must be -10°C or colder to produce accumulative snowfall. A look at a Skew T-Log P diagram (Figure H) helps to explain: The lapse rate is DRY adiabatic from -10°C at 850 mb (a) to the lake level, and a corresponding surface temperature of approximately 2°C (b). Wet snow could accumulate at this temperature, but any warmer reading at 850 mb would likely cause either a mixture of rain and frozen precipitation or simply rain (or drizzle). So Rothrock's first rule is open-ended (Holroyd included rain events). An 850 mb temperature of -10°C indicates superadiabatic conditions until the lake temperature is approximately 36°F, and, until the lake freezes, -12°C at 850 is as cold as is necessary for this state.

> 2) A fetch of 80 km (or approximately 50 miles) or more over open, warm water.

Again, results of the new cases refute this claim; virtually the entire width of western Lake Superior as well as Lake Michigan is greater than 50 miles (and less than 80 miles). By Rothrock's second rule, one would forecast snow accumulation from a due west wind across Lake Michigan or a northwest wind across western Lake Superior. The new study indicates flurries, blowing snow, and wind chill for these trajectories but little, if any, accumulation (despite the significant orographic lifting of the Iron Range in the western Upper Peninsula of Michigan). The Keweenaw Peninsula alone did receive significant accumulation occasionally, but only with trajectories from the west or west-southwest, both of which have trajectories of over 100 miles (Figure J). Similarly, extreme northeast Ohio, from Lake County eastward, received heavy snows from a trajectory from due west (over 100 mile fetch) but not from northwest (55 mile fetch) unless combined with airflow from Lake Huron (Figure K).

Why such a discrepancy? One logical possibility, of which Rothrock found several examples, is with the shorter fetch of 50 miles, although the majority may have been of the longer fetch of 100 miles. As was the case in the first rule, boundaries were not set at both ends. Under this premise, there was general agreement, because the recently researched cases indicated TWO distinct minimum fetch values: approximately <u>100</u> miles under conditions described in the <u>-10°C</u> rule (the author terms this "lake-effect"), and approximately <u>40</u> miles <u>IF</u> there is PVA and the 850 mb temperature <u>is</u> ≤ -5°C.

The latter process is what the author terms "lake-enhanced" snowfall, with the hypothesis that upper-level dynamics are necessary for snow accumulation. This can be demonstrated by assuming, as before, a warm lake ($T_w \geq 37°F$) but with marginally cold air at 850 mb ($-5°C \geq T_{850} > -10°C$). Under such a temperature profile, a layer of conditional stability exists between the lake surface and 850 mb. Lifting occurs by an independent mechanism, in this case, synoptic-scale upper-level dynamics (PVA). The layer of air is raised enough to produce precipitation. As is the case with cyclone-produced snowfall, higher vertical velocity means higher snow accumulation. The Skew T-Log P diagram (Figure M) offers an explanation for the critical -5°C value at 850 mb: the lapse rate under these conditions is MOIST adiabatic from this point (a) to the lake level (b), and, as was the case before, the corresponding surface temperature is 2°C. Wilson in 1977 gave numerous examples of this conditional stability state in which the 850 mb temperature is more than 7°C colder than the lake (14). This -5°C value at 850 mb is critical until the lake temperature falls to 36°; then, until the lake freezes, -7°C at 850 mb can be considered critical. Under "lake-enhanced" conditions, the air is lifted, cooled, and saturated (forming precipitation) much earlier along its trajectory.

This helps to explain the marked difference in the necessary fetch between "lake-enhanced" (Figure N) and "lake-effect" (Figure P). The 100-mile rule, at first empirically derived by this author's experience, was found to be supported by Lavoie (10). His 1972 physical model of Lake Erie, as well as the model's test case study of 2-3 Dec 1966, indicated ACCUMULATIVE snowfall occurs no less than 90-95 miles downwind of a trajectory over water.

> 3) Vorticity advection at 500 mb mainly negative and 3-hr surface pressure changes mainly rising.

As mentioned earlier, other documentation appeared split over the role of vorticity advection. However, under the new assumption that there are two basic classes of lake-effect snow, these conflicting conclusions may be sorted out. Snowfall observed under NVA and rising pressures would indicate true "lake-effect" because the mesoscale snowfall occurs solely from mechanisms below 700 mb DESPITE synoptic scale sinking. Thus, NVA and rising surface pressures should not be considered factors or causes of Lake snowfall, but rather DETERENTS to more favorable snow-producing conditions.

The new study indicates that higher surface pressures, especially greater than 1030 mb, confine the snow squalls to a thin band sometimes only several miles wide. Accumulation still occurs, but only very locally, affecting at most a small percentage of a densely populated area.

On the other hand, the new cases support the hypothesis that any evidence of upper-level support (PVA) to a pure "lake-effect" episode acts as an AID to the low-level mechanism, providing additional lifting to an already unstable mesoscale environment. The new study indicates a well-marked increase in snowfall intensity -- leading to additional accumulation -- upon arrival of an upper-level trough and associated PVA/positive vertical velocity. The author terms this as the "combination" (Figure Q), because it links the two basic types. It is frequently the heaviest and most socially adverse snowfall situation encountered in the Great Lakes Region.

4) Geostrophic wind speeds in excess of 5 MS^{-1} (16 kts).

For heat and moisture flux to occur, there must be some air movement, so 16 kts would seem like a low enough value. However, "combination" type produced over a foot of snow in the Door Peninsula area of Wisconsin in February, 1985, in spite of winds reported to be no higher than 11 kts at any level up to (and including) 700 mb. Similar documented cases involving light circulation (with geostrophic wind speeds of as low as 5-10 kts) under a weak upper-level trough were found to be some of the most "surprising" snowfalls -- to forecasters and area residents alike. It appears that the slightest of air movement can produce snow bands, assuming vertical wind shear it kept to a minimum.

5. HELPFUL HINTS OF LFM II

Being a standard forecast tool, LFM II has been frequently verified for its performance during important weather events, such as severe storms and winter cyclones (18,19). Yet, to date, there has been little, if any, documentation of its achievements regarding lake-effect snowfall.

Dewey in 1979 derived predictors which were used in a conditionally operative model for each of the Lakes (15,20). His data for the forecast equations consisted mainly of predictors automatically produced by the National Meteorological Center, such as PE (Primitive Equation) model 850 mb temperature forecasts and MOS (Model Output Statistics) surface wind forecasts. Of the predictors employed for two specific Lakes, Erie (9 predictors) and Ontario (7 predictors), only 4 were on both lists. None of the top 3 predictors for Lake Erie (vapor pressure gradient, 850 mb saturation deficit, and water temperature - upwind temperature difference) were identical to the top 3 for Lake Ontario (T_w-T_{850}, surface wind fetch, percent Lake ice cover). Ironically, the percent ice cover parameter was the only predictor with nearly the same value for both Lakes, even though one of the most obvious differences between the two Lakes is that Erie (the most shallow) frequently becomes ice-covered, while Ontario (the deepest) often remains widely open. Nevertheless, Dewey claimed that the model "performed quite well with a slight tendency for over-forecasting" (15). Any operational lake-effect snow forecaster can certainly relate to such a tendency.

From this author's operational experience, supported by the new case studies, the following LFM II predictors were determined to be IMPRACTICAL (if for no other reason than another predictor superceded its value for a desired paramenter) for lake-effect snowfall forecasting:

- o MOS Surface wind direction
  (FOUS Boundary Layer Wind is a better indicator of mean flow)
- o 1000-500 mb Thickness (HH)
  (Does not account for low-level warm air)
- o QPF -- Quantified precipitation (PTT)
  (Previously discussed)
- o Average RH -- 1000-490 mb Relative Humidity (RH)
  (Does not account for low-level moist air layer)
- o MOS Max-Min Temperatures -- on lee side
  (Do not totally account for clouds or precipitation)
- o FOUS Lifted Index (LI)
  (On Dewey's original list, but this predictor is part of FOUS primarily for spring and summer conditions)

The following predictors, on the other hand, have been found to be QUITE VALUABLE:

- o 850 mb Temperature (isotherm)
- o FOUS Boundary layer wind direction and speed (DD & FF)
- o Vertical velocity (VV)
- o 500 mb Height and vorticity (determines PVA areas)

The following predictors are useful WITH CAUTION:

- o Surface pressure (PS)
- o FOUS Mean potential boundary layer temperature (TB)

The caution is advised because the modification of the Lakes is rather noticeable for these two parameters, but on a remarkably consistent basis. For instance, the new study has found that, regionally, during periods of STRONG cold advection, LFM II:

- o Forecasts PS too HIGH, generally by 3-6 mb (per 12 hrs)
- o Forecasts TB too LOW, generally by 4^{o}-8^{o} K (per 12 hrs)

And during periods of weak-moderate cold advection:

- o Forecasts PS 1-3 mb too high (per 12 hrs)
- o Forecasts TB 1-5^{o} K too low (per 12 hrs)

It is not surprising to see much divergence in error, considering that TB and PS are inversely proportional according to the hypsometric equation

$$\Delta P = \frac{e \, \alpha}{R \, \overline{T^*}}$$

in which Δ P represents change in surface pressure and $\overline{T^*}$ denotes change of the mean layer of potential boundary temperature.

A closer look revealed another pattern with the LFM II -- a diurnal temperature bias. The 12Z model run consistently showed higher error, at least with respect to TB (PS was not specifically tested for diurnal bias but the assumption can be made from the above equation that PS reflected a higher error on the 12Z run). Table 1 displays a systematic approach to determine the approximate TB (per 12 hrs) in a region downwind of at least one of the Lakes, accounting for both air modification and diurnal bias (an example will follow). One objective is to estimate the beginning time of accumulative snowfall. At lake level, 275^{o}K was found to be critical for "lake-effect" and cold enough for "lake-enhanced". Of course, at a higher elevation the value is slightly lower, but under most circumstances the cold advection is rapid enough to place all elevations below the critical mark within an hour or two. (The common exception is with the "lake-enhanced" closed circulation whereby the upper dynamics lift the marginally cold air enough to produce heavy wet snow at a 300-400 foot elevation, for example, but keep rain or a mixture of rain and snow over Lakefront communities.) The critical TB values are only considered ball park figures, however. The BEST indicator is still as described in Revised Rule #1, the 850 mb forecast -10^{o}C isotherm for both "lake-effect" and "combination," and the -5^{o}C isotherm for "lake-enhanced." The author deeply regrets that the 850 mb height/isotherm forecast is not available on NAFAX (however, a 24-hour 850 mb temperature forecast at selected stations is available as part of the TRAJECTORY FORECAST on the 1200-baud FAA 604 circuit).

The pronounced diurnal bias was documented by Schechter in 1984 in an analysis of average errors in LFM II variables calculated for the entire United States (21). Regarding PS and TB regional bias, Schechter found PS to be generally forecast too low east of the Rockies, particularly in the Upper Mississippi Valley; TB forecasts were cold bias near the Great Lakes but warm bias in the south, especially Florida. Such results are consistent under the following assumption: low-level cold air is forecast to cross the warm lakes (Figure R), but instead is modified (accounting for TB cold bias near the Great Lakes). Central high pressure is split, with a cold core diverted west and south of the Lakes (resulting in higher PS in the Upper Mississippi Valley). The detour of the coldest air continues, eventually over the South instead of an originally forecast path over the Mid-Atlantic region (accounting, in part, for the warm bias in the South). Figure S gives an example of the LFM II's typical mishandling of an arctic air mass over the Lakes. Two of the new cases researched, involving extremely cold surface air (22-26 Dec 83 and 18-23 Jan 85), indicate similar behavior: Rather than spreading across the Great Lakes as LFM II had forecast, the cold core air funneled into the Plains — where it met less resistance — and expanded Southeast. Figure T shows the LFM II 48 hr forecast valid 00Z Sunday, January 20, 1985 (along with verification). Both arctic outbreaks resulted in severe Florida orange freezes, although to date, only the "December '83 Freeze" has been meteorologically documented (22,23). Although the Great Lakes' rerouting of the air mass was not mentioned as a possible factor by either article referenced above, this author believes the significant blocking effect must be seriously considered.

6. STEP BY STEP PROCEDURE — BEFORE THE EVENT

As a general principle, arrival of arctic air is rather easy to forecast within 48 hours. Normally, though, even 36 hours is too early to forecast precise location or timing of Lake snowfall. Public awareness of the potential snowy conditions over a broad area is, of course, often initiated by this time, with validity. By 24-30 hours ahead of the potential snowfall, LFM II ususally has at least a fair handle of the wind flow and temperature profile (especially at 850 mb) and can be used as a rough guideline. Significant changes in the pressure and wind field can still occur between a 24-hour forecast and verification.

There were, in many of the case studies, a turn to more cyclonic surface winds and boundary layer winds than originally forecast. Unfortunately, there were also cases in which less cyclonic turning occurred, so a blanket adjustment could not be successfully made to boundary layer wind direction forecasts. One strong recommendation that can be made is that boundary layer wind direction forecasts beyond 30 hours should not be trusted for accuracy (at least within 020 degrees) for locations near the Great Lakes during periods of cold advection in the winter. It is rather surprising to see Condela in 1983 refer to FOUS boundary layer wind forecasts as if the values were absolutely accurate — even up to 48 hours (24). Such a rash assumption should not be made in a standard lake-effect forecast. Instead, it is recommended that a forecaster use patience until the 12-18 hour forecast time period arrives before sincerely believing it.

The 850 mb forecast, however, can be counted on earlier in time, especially the temperature forecast. A 24-hour 850 mb temperature forecast isotherm is normally reliable and a 12-hour one exceptionally accurate. Thus, for the critical values of -10^{o}C or -5^{o}C, reliance on the respective isotherm offers the best guidance for predicting the start time of possible snowfall. From this parameter, a series of steps can be taken to eventually lead to a general estimate of snowfall -- apart from any quantified precipitation forecast from LFM II — to the lee of the Lakes.

The second step is to plot the forecast wind flow in the boundary layer. This has been shown to be the best guidance (from the new cases tested) although it is best to restrict the forecast period to 24 hours or less for increased accuracy. This wind flow can be plotted from the 00Z and 12Z run FOUS output for stations in the Great Lakes region. An example of the FOUS bulletin with complete description of each selected predictor is shown in Table 2a. Two consecutive time periods should be chosen, covering a 6-hour time frame. The following predictors should be utilized: boundary layer wind direction and speed (DDFF), boundary layer temperature (TB — remember to adjust these values from the process described in Table 1 before implementing), vertical velocity (VV — note if either is a positive value), and quantified precipitation, if any (PTT).

A model of this suggested procedure, with wind barbs plotted, is shown (Figure U). It would be helpful to distinguish the wind barbs of separate time frames. In the example, the first forecast period wind barbs are represented by bold lines, while the following 6-hour period wind barbs are thin.

The other predictors are best indicated by being separated by a bar, with the first forecast period predictor above the bar and the following below. (Various colors are suggested to distinguish all parameters). In an arbitrary example, the forecast periods are 12-hour and 18-hour. With respect to the station, TB (a) is to the upper right with 12-hour TB_1 above 18-hour TB_2; PTT (b) is in parentheses to the lower right; VV (c) to the lower left; and specific wind direction DD (in tens of degrees) adjacent to the wind barb (d) for clarity. Forecast wind speed is rounded off to the nearest 5 kts, so in the arbitrary example, a 12-hour forecast of 30 kts becomes 20 kts by the 18-hour forecast valid time. Figure V displays plotted real-time FOUS data shown in Table 2b. The TB values shown have been adjusted using the technique described in Table 1, with the results displayed in Table 2c. In addition, the dashed line indicates the -10^oC T_{850} isotherm lifted from the LFM II 850 mb 12-hr forecast chart.

From this information, a visual estimate is made of the potential geographical areas affected by snowfall generated from the Lakes, or in the example, from Lake Erie. The assumption is made that winds parallel to the plotted wind barbs will carry the necessary lake moisture (and possible snowfall) ashore. Certain criteria must be met before the potential geographical area can be recognized. Vital questions must be answered before there can be serious consideration of snow accumulation: "Will the air be cold enough? Will there be the necessary fetch? Will the air be lifted by synoptic scale features? Is there a significant windshift forecast over the 6-hour period?"

An organized method to sort these questions — as well as a few more — is to design a decision tree. With the previously discussed physical mechanisms in mind, the Dockus Decision Tree (DDT) incorporates LFM II - produced predictors as well as visual interpretations (e.g. fetch, T_{850}, boundary wind curvature) to estimate 6-hour snow accumulation ranges for potentially affected areas. Table 3 displays the main truck of the DDT, with eventual estimates for "lake-effect" snowfall. Two other branches lead to estimates of "lake-enhanced" (Table 4) as well as "combination" (Table 5), both defined earlier in this paper. Because orographic effects vary snowfall intensity, accumulation ranges were divided into two categories, "X" and "O". Roughly speaking, maximum upslope regions at higher elevations near the Lake (indicated by "X") are given nearly twice as much accumulation per period than either lower elevations adjacent to the Lake or medium elevations considered to be downslope regions (both indicated by "O"). Figure W shows the area defined for category "O" and category "X" around each of the Great Lakes with Canadian territory excluded. Maximum upslope regions positioned a great distance downstream are excluded with regret: north to west facing slopes of the Allegheny Mountains are admittedly affected, receiving significant annual snowfall generated from the Great Lakes. Unfortunately, lack of both research time and observed data resulted in dropping plans for incorporation of this areas. (Frankly, lake-effect snowfall regarding the Applachians deserves separate attention.) Additional splitting of the categories could conceivably have been attempted. However, the limited sample did not reasonably justify narrowing the affected regions. Instead, the axis of the maximum upslope region had to be long enough, and the accumulation range wide enough, to compensate for the seasonal shift of INLAND DISPLACEMENT of maximum snowfall. Strommen and Harman, in a 1978 study of lower Michigan, concluded that the heaviest snowfall occurs progressively nearer the lake shoreline between November and January, but progressively inland thereafter (25). Until this consequence is compensated for (within the DDT), the forecaster needs to bear in mind the time of season and weight the average estimate approximately. Also, compensation must be made for any given 6-hour forecast period within which one or more of the predictors fails to qualify for the entirety. For example, figure V indicates the -10^oC isotherm is forecast to cross portions of western New York after the 6-hour forecast period begins. So for the first one or two hours of the period, the -10^oC rule for "lake-effect" may not qualify for Jamestown (JHW), so somewhat less than the maximum would be expected in that location (notice that "lake-enhanced" is ruled out despite $T_{850} \leq -5^oC$ because there are no positive vertical velocities forecast). Incidently, this example of Nov 30-Dec 1, 1983 produced heavy thunder-snow squalls in Buffalo as well as downstream at Rochester and even Oswego (2 1/2" fell in 40 minutes). According to the DDT, the example period (00Z-06Z) forecast the trajectory to shift slightly more westerly but still carry potential snow squalls mainly into western New York State. The DDT forecast 3-6" in the category "O" region (includes Buffalo International Airport, which officially measured 3" between 00Z and 06Z) and 5-9" in the maximum ("X") upslope area of southern Erie County, but somewhat less to the southwest where it may not have been quite cold enough at 850 mb for the first portion of the period. The trend for the following 12 hours was to keep boundary layer winds near 260^{o} at BUF, indicating on the DDT the heaviest snowfall would likely stay south of town. In reality there was slight drifting of the band, but eventually, a 10" snow depth was recorded officially in Buffalo, with over 18" to the south of town in the higher elevations of southern Erie County. If there was any obvious error in the DDT forecast, it was a tendency to forecast too much snow during a particular period. On the other hand, the DDT indicated the likelihood of heavy snow squalls in and near Buffalo for an 18-24 hour period. The LFM II alone forecast absolutely no quantified precipitation on several consecutive runs.

Of course, the DDT is better utilized once the snow bands have formed on radar or observed at reporting stations. Once the actual precipitation is tangible, a forecaster can use the boundary wind forecast as a more precise steering current of the band(s). So, one may consider the DDT as a "Band-aid".

7. FORECASTING WIND EFFECTS

Besides the snowfall itself, the strong winds often associated with lake-effect snow can have a significant impact. With the data collected from the past two winters (FOUS boundary layer wind forecasts, hourly observations, special statements, etc.), the author has devised a simple but effective method to forecast wind-related conditions. Table 6 displays the "Wind Branch" of the DDT, used in combination with any of the other branches. Supplementary consequences of a lake-effect storm are anticipated, depending solely on FOUS boundary layer wind speed forecasts. For instance, an FF of 35 kts will likely result in significant blowing and drifting of snow, enough to reduce visibility and hamper cleanup efforts of snow-removal crews. Recall from earlier discussion that lake-effect snowfall can take place with LIGHT low-level winds, so the Wind Branch does not always apply. Most of the time, though, it becomes the true villain of the storm, especially if the wind chill factor is taken into consideration.

8. OTHER TIPS

Because LFM II builds surface highs TOO STRONG and TOO FAST over the Lakes, two rules of thumb can be added to the list of Lake-Effect Tips:

- Skies will not clear nearly as quickly as LFM II would lead one to believe. Consequences of missing this fact include busting a minimum temperature forecast, as well as falsely encouraging the public to expect a sunny day. The latter subject is taken seriously by Great Lakes residents who normally don't see very many bright winter days and who relish the ones which turn out.

- Flurries, and even a few squalls, can persist long after accumulative snow has wound down. Remember the decision tree is applied only to accumulative snow. When the geostrophic wind slackens at the end of a pure lake-effect case, for example, flurries with little or no additional accumulation should be expected as late as the passage of the surface ridge.

9. SUMMARY

An attempt has been made to review and revise (when appropriate) numerous factors leading to lake-effect snowfall. Earlier conflicting hypotheses can apparently be sorted out under the assumption that certain requirements of PVA-induced (i.e. dynamically induced) snowfall are different from those which occur without upper-level support. An earlier hypothesis that geostrophic wind speeds be in excess of 16 kts was revised after several "lake-enhanced" cases with geostrophic wind speeds of 5-10 kts were recently documented.

A study was made of the operational computer model LFM II regarding lake-effect. The most obvious, consistent error was the model's low level cold bias over the Great Lakes. A hypothesis was drawn that cold waves in Florida are poorly forecast by LFM II partially because of the considerable modification of arctic air by the warm, open waters of the Lakes.

From the author's operational forecasting experience, supported by numerous case studies of the past two winters, certain LFM II predictors were determined to be most helpful for lake-effect snowfall forecasting. Remarkably, the LFM II allows no heat or moisture flux of the Great Lakes, so no quantified precipitation forecasts can be generated by LFM II alone. Instead, certain predictors (one which is manually adjusted) with visual estimates and judgments performed by the individual forecaster can result in a quantified real-time snowfall forecast. This can be achieved through the use of the lake-effect decision tree designed by the author. Various branches of the decision tree account for the inclusion of dynamically induced snowfall or significant wind.

The Spectral model was not discussed in this paper because its numerical predictor values (e.g. TB) have not been available to the operational forecaster. A casual inspection of the Spectral's handling of the Great Lakes in winter leads to the conclusion that it performs similarly to LFM II. Considering that the Spectral also allows neither heat nor moisture flux for the Great Lakes, such a conclusion is not surprising. To date, and to the author's knowledge, FOUS output from LFM II is still expected to be operational for at least the winter of 1985-86. Thus, the decision tree is recommended for the immediate future to all operational forecasters, for at least a second opinion. The staff of forecasters at the Weather Channel, for one, will have the option to use the DDT for the upcoming winter. Their comments and suggestions will be solicited, and several case studies will likely be documented to test the various branches of the DDT as basis for a follow-up paper.

It is anticipated that the newly operational RAFS model will allow some heat and/or moisture flux of the Great Lakes this coming winter. Its performance will be closely observed and compared to LFM II.

ACKNOWLEDGEMENTS

The author is sincerely grateful to the following individuals and institutions: Mr. Robert Sykes and Mr. James LaDue, SUNY/Oswego, for their tireless efforts in recording hourly weather data during the 1984-85 winter; Mr. Dick Goddard, WJKW-TV, Cleveland, for his spotter network snowfall data during several important lake-effect cases in northeast Ohio; Northeast Regional Climate Center, Cornell University, and Michigan Department of Agriculture, for the average annual snowfall information; The Weather Channel staff and management for their enthusiastic support and helpful suggestions, especially to Mr. Peter DiAngelo for his thoughtful input; last but not least to my wife, Carlene, for typing and correcting this manuscript.

FOOTNOTES AND REFERENCES

1. Dale Dockus is an on-camera meteorologist at the Weather Channel, Atlanta, Ga, where he originally was a lead forecaster. Previously, he was a radio/utilities forecaster at Weatherscene, WLWT-TV, Cincinnati, OH. He received his B.S. degree in meteorology from Penn State in 1978.

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Cold Advection Intensity <TB Loss per 12 hrs> \ Time of Initial LFM II Run	00Z	12Z
Weak <≤ 4° K> (includes warm advection)	Add 1° K	Add 3° K
Moderate <5° to 9° K>	Add 2° K	Add 5° K
Strong <≥ 10° K>	Add 4° K	Add 8° K

Table 1. Rough adjustment of LFM II forecast TB for lee side location of Great Lakes during winter. Value in brackets represents 12-hr forecast decrease of TB during cold advection.

OUTPUT FROM LFM 12Z 10/05/83

STA	RH	R1R2R3	VVLI	HHDDFF	TBPSPTT
ALB	78	998760	///06	642115	9109///
06	81	977682	01603	651916	9307000
12	91	969091	01602	632018	9304035
18	73	938834	00403	612518	9206008
24	52	877002	-0806	562818	9011002
30	43	815403	-1407	542817	0912000
36	43	805702	-1407	522818	8916000
42	36	724802	-1409	502918	8718000
48	26	623202	-1912	483017	8621000

Table 2a. FOUS 61 bulletin for Albany, New York (ALB). RH is the mean relative humidity of the lowest three layers of the model (1000 to 490 mb) in percent. R1, R2, and R3 are the mean relative humidities of the 50-mb-thick boundary layer, the lowest tropospheric layer, and the middle tropospheric layer, respectively, in percent. VV is vertical velocity at 700 mb in tenths of microbars per second with negative values representing downward motion. LI is lifted index in degrees Celsius with negative values designated by subtracting from 100 (-4 is represented by 96, for example). HH is 1000-500 mb thickness in decameters with the hundreds digit omitted. DDFF is the direction and speed of the boundary layer wind in tens of degrees and knots. TB is the mean potential temperature of the boundary layer in degrees Kelvin with the hundreds digit omitted. PS is sea level pressure in millibars with the hundreds position omitted. PTT is the six-hour accumulated precipitation in hundredths of an inch. Note that some of the forecast parameters in the FOUS 60-78 bulletins are not given in SI units. (Reprinted from Schechter, 1984).

Table 2b. FOUS bulletin for Detroit (DTW), Cleveland(CLE), and Buffalo (BUF) from 12Z 30 Nov 1983 through 18h valid time for all predictors and 24h valid time for TB only.

FOUS 64 KWBC 301200 1983

STA	RH	R1R2R3	VVLI	HHDDFF	TBPSPTT
DTW	80	729162	///17	232740	7313///
06	65	846853	-0520	232530	7014000
12	63	887045	00023	242627	6815000
18	54	846729	-0525	252722	6717000
24	→				66
CLE	75	748359	///17	262740	7415///
06	61	816940	-1218	252429	7216000
12	59	876343	-0120	252526	7116000
18	51	856127	-0423	262722	6917000
24	→				67
BUF	80	819365	///15	252637	7510///
06	77	798958	-1016	222329	7411000
12	73	858158	-0318	222528	7210000
18	64	937933	-0322	242623	6913000
24	→				67

Table 2c. Adjusted TB forecasts (using method described in Table 1) of sample FOUS data shown in Table 2b. The 18h value is interpolated, rounded up to the warmer whole value. The 24h is determined from the original value of 12h (rather than the adjusted value) minus the 24h value.

Valid Time (hours) \ Station	DTW	CLE	BUF
12	73	74	75
18	71	73	74
24	69	71	72

Table 3. Lake-Effect DDT (Dockus Decision Tree) for estimating snowfall fully or partially from the Great Lakes. Each question applies to a 6-hr forecast period. Vertical velocity (VV) units are in microbars sec^{-1}.

```
(Is   T850   <   -10°C ?)
 |              |
<Yes>          <No> - ["Lake-Enhanced" Possible]
 |
(Is trajectory over water > 100 mi?)
 |              |
<Yes>          <No> - ["Lake-Enhanced" Possible]
 |
(Is vertical velocity < 0 ?)
 |              |
<Yes>          <No> - ["Combination" Snowfall]
(Is there cyclonic curvature
 at the boundary layer?)
 |          |
<Yes>      <No> - [Thin band, perhaps only a few miles wide,
 |                 with very localized 1-3"/6 hr]
(Is the deviation in boundary
 wind direction <020°/6 hr?)
 |          |
<Yes>      <No> ____
 |               |
 |          Shifting band(s):
 |            1-2" -- Category O
 |            2-4" -- Category X
 |
Significant snowfall from heavy band(s):
   3-6" -- Category O
   5-9" -- Category X
```

Table 4. "Lake-Enhanced" Branch for estimating snowfall generated from the Great Lakes. Each question applies to a 6-hr forecast period. Vertical velocity (VV) units are in microbars sec^{-1}

```
(Is trajectory over water > 40 mi?)
 |              |
<Yes>          <No> - [Accumulation unlikely]
 |
(Is vertical velocity > 0?)
 |              |
<Yes>          <No> - [Accumulation unlikely]
 |
(Is   T850   <  -5°C?)
 |              |
<Yes>          <No> - [Marginal: if T850 <-3°C
 |                     in early winter, 1-3" wet
 |                     snow in category X region]
(Is vertical velocity > +1?)
 |          |
<Yes>      <No> ____
 |               |
 |          Moderate snowfall with light-moderate
 |          upper-level dynamics:
 |            1-3" -- Category O
 |            2-6" -- Category X
 |
Heavy snowfall with strong upper-level
dynamics:
   -6" -- Category O
   4-8" -- Category X
```

Table 5. "Combination" Branch for estimating snowfall generated from the Great Lakes. Each question applies to a 6-hr forecast period. Vertical velocity (VV) units are in microbars sec^{-1}.

```
(Is the deviation of the boundary wind direction < 020°/6 hr?)
 |          |
<Yes>      <No> ____
 |               |
 |          Shifting heavy band(s):
 |                2-4" -- Category O
 |                3-5" -- Category X
 |
(Is vertical velocity > +1?)
 |          |
<Yes>      <No> ____
 |               |
 |          Heavy snow squalls with light-moderate
 |          upper-level dynamics:
 |                4-8" -- Category O
 |                7-10" -- Category X
 |
Heavy snow squalls with strong upper-
level dynamics:
   6-9" -- Category O
   9-12" -- Category X
```

Table 6. Wind Branch, used in addition to any of the snowfall accumulation decision trees, for both Categories "O" and "X". FOUS boundary layer wind (DDFF) is utilized. Each question applies to a 6-hr forecast period.

```
(Is boundary wind > 20 kts?)
 |
<Yes> - [Drifting snow prolonging slippery road
 |        conditions]
 |
(Is boundary wind > 30 kts?)
 |
<Yes> - [Significant blowing/drifting, reducing
 |        visibility and hindering cleanup operations]
 |
(Is boundary wind > 40 kts?)
 |
<Yes> - [Frequent blizzard conditions; severe blowing/
          drifting making cleanup operations futile]
```

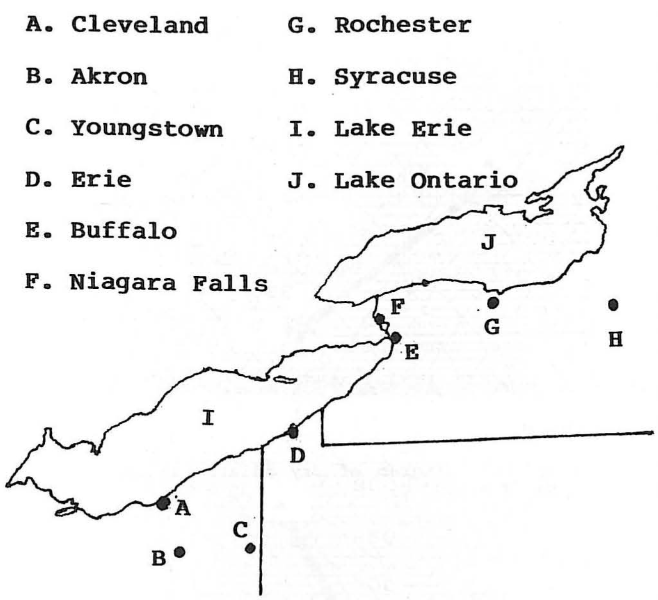


Figure A. Major cities of the lower Great Lakes snowbelt.

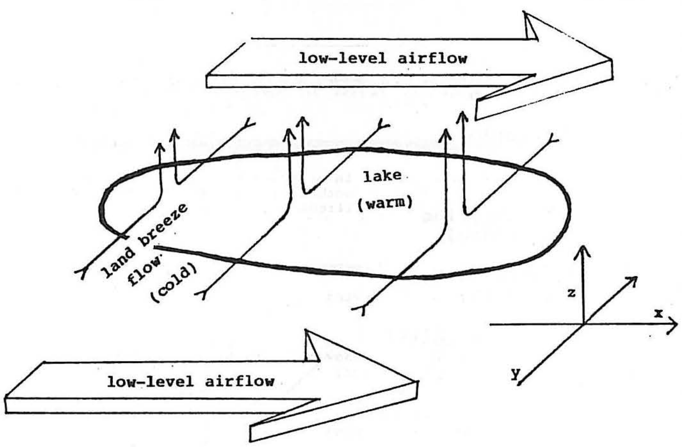


Figure B. 3-Dimensional diagram of thermal convergence. A simplified model represents one of the Great Lakes.

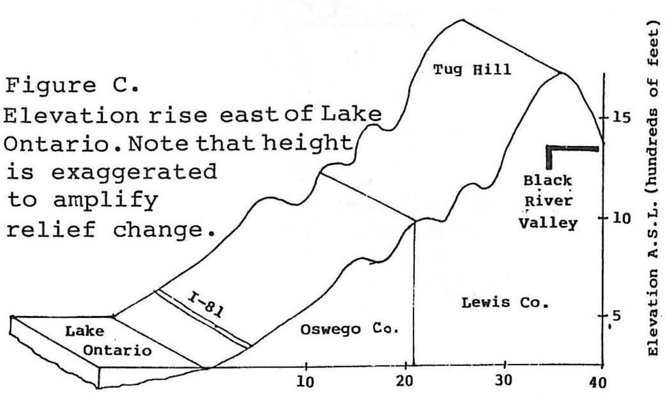


Figure C. Elevation rise east of Lake Ontario. Note that height is exaggerated to amplify relief change.

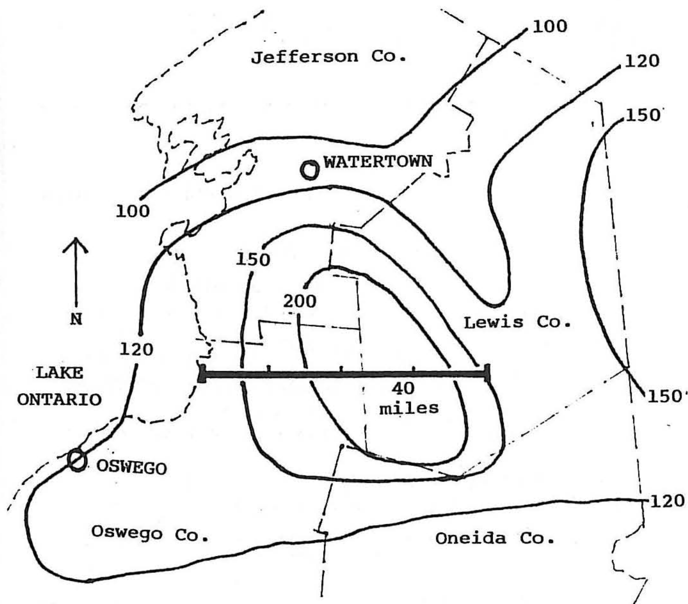
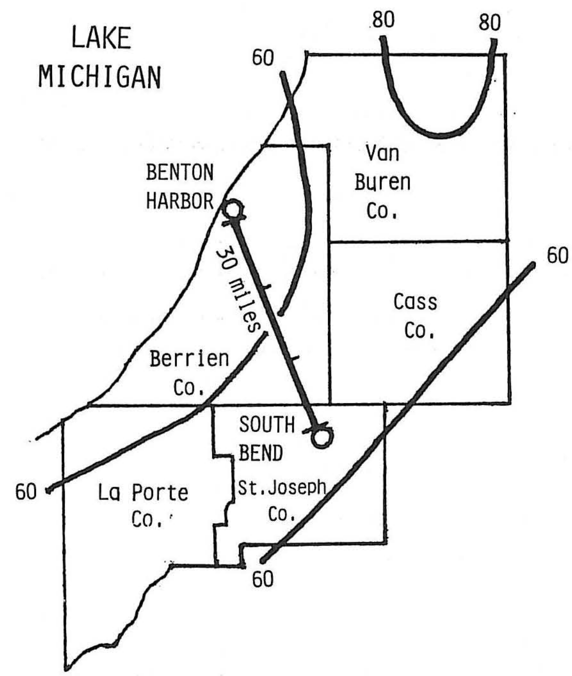


Figure D.

Average annual snowfall (in inches) over snowbelt east of Lake Ontario 1950-1980 (top) and south of Lake Michigan 1940-1969 (bottom). Sources: Northeast Regional Climate Center, Cornell University and Michigan Department of Agriculture.



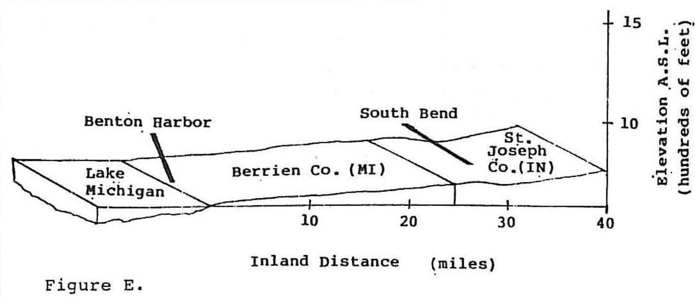


Figure E.

Elevation rise southeast of Lake Michigan, from Benton Harbor, MI. Note that height is exaggerated to amplify relief change.

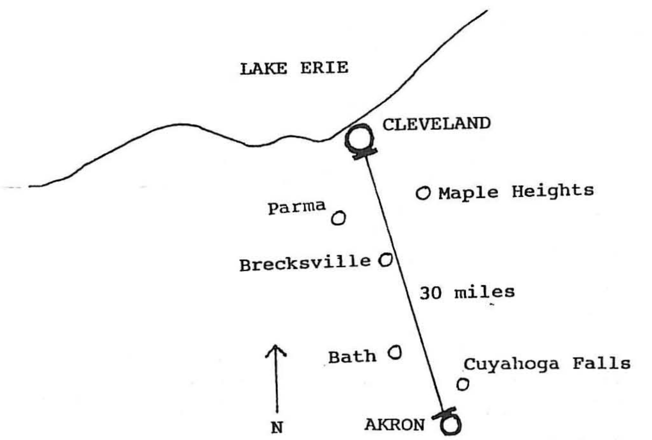


Figure F.

Cleveland-Akron vicinity, including some key towns/suburbs often impacted by lake-effect snowfall.

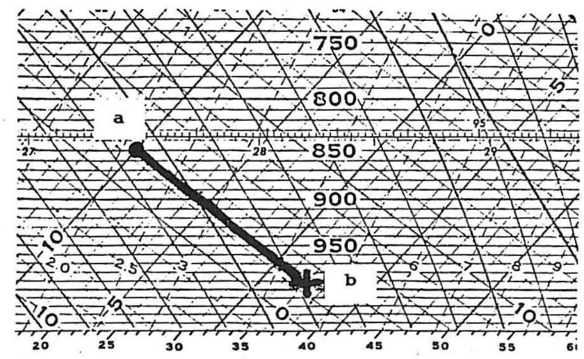


Figure H.

Skew T-Log P diagram of dry adiabatic lapse rate at critical T = -10° C.

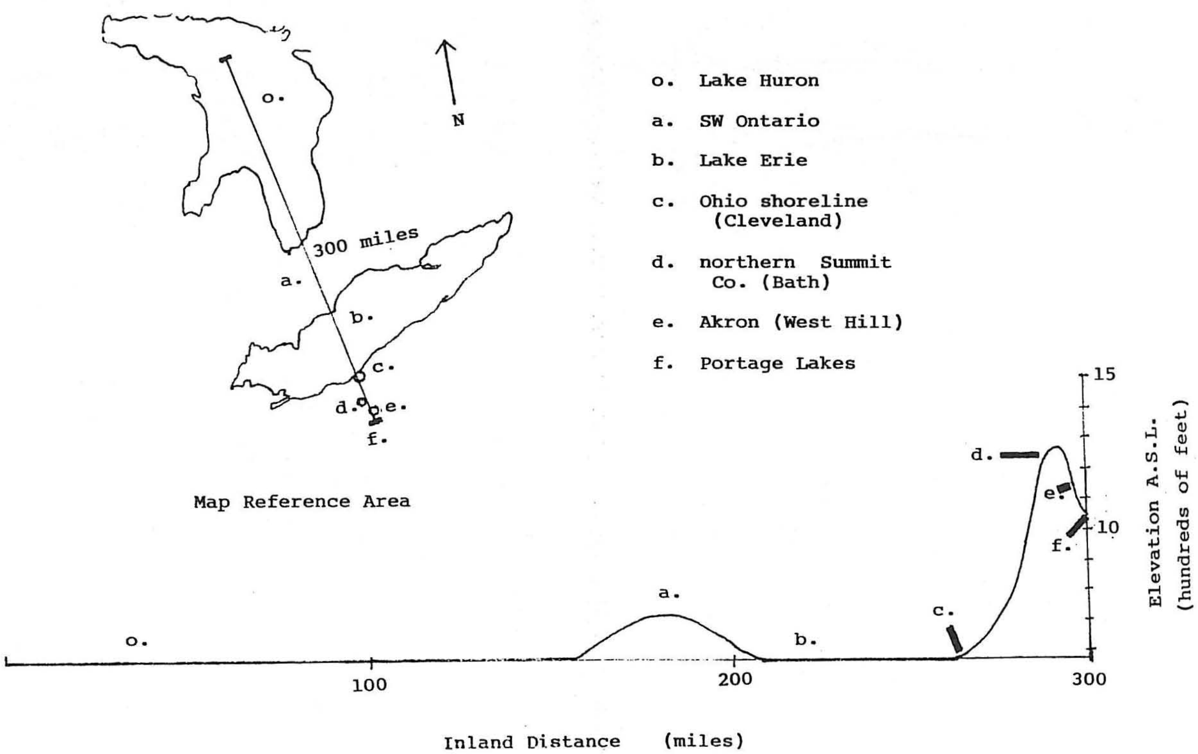


Figure G. Map reference area and corresponding cross-section of idealized lake-effect trajectory from Lake Huron to Akron, Ohio. Note that elevation (height) of cross-section is exaggerated to amplify relief change.

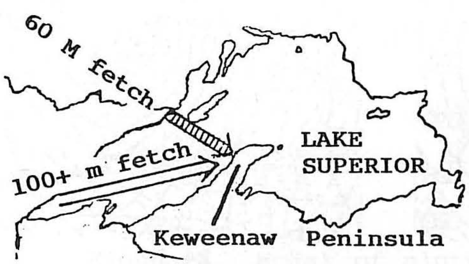


Figure J. Selected trajectories over Lake Superior.

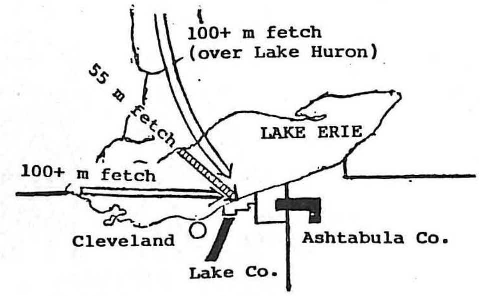


Figure K. Selected trajectories over Lake Erie.

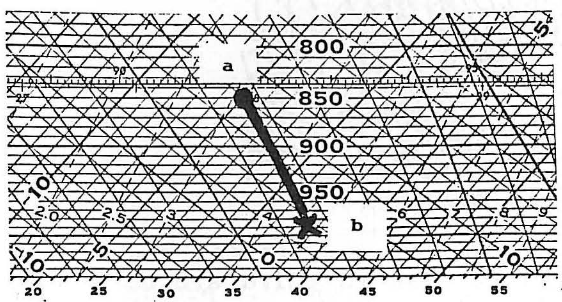


Figure M.

Skew T-Log P diagram of moist adiabatic lapse rate at critical T = -5° C.

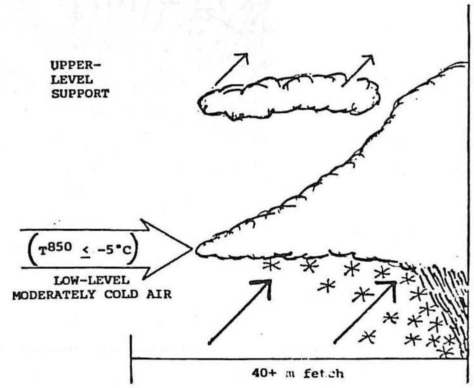


Figure N.

Diagram of idealized "Lake-Enhanced" conditions as defined by author.

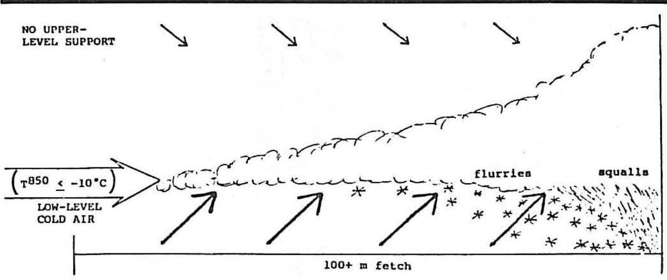


Figure P.

Diagram of idealized "Lake-Effect" (as opposed to "Lake-Enhanced") conditions as defined by author.

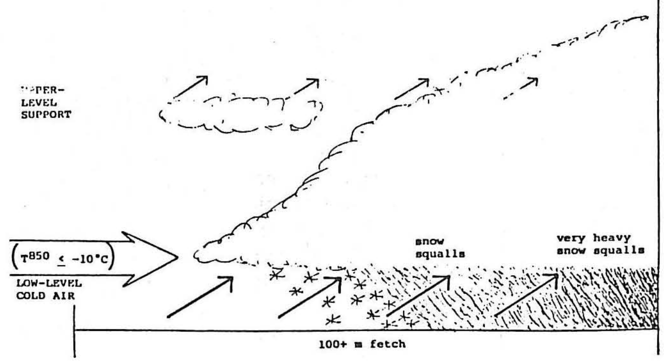


Figure Q.

Diagram of idealized "Combination" lake-effect conditions as defined by author.

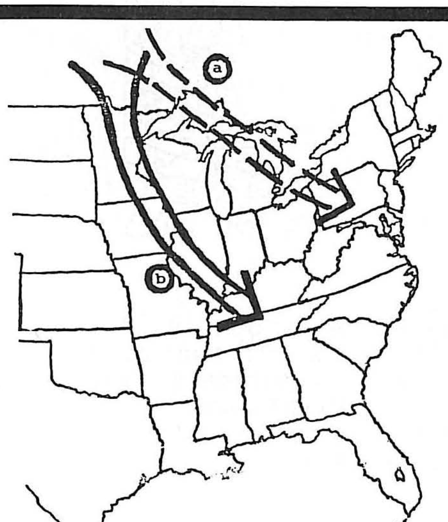


Figure R.

Forecast (a.) and actual (b.) path of low-level cold air during an idealized cold wave into the eastern United States when Great Lakes are open.

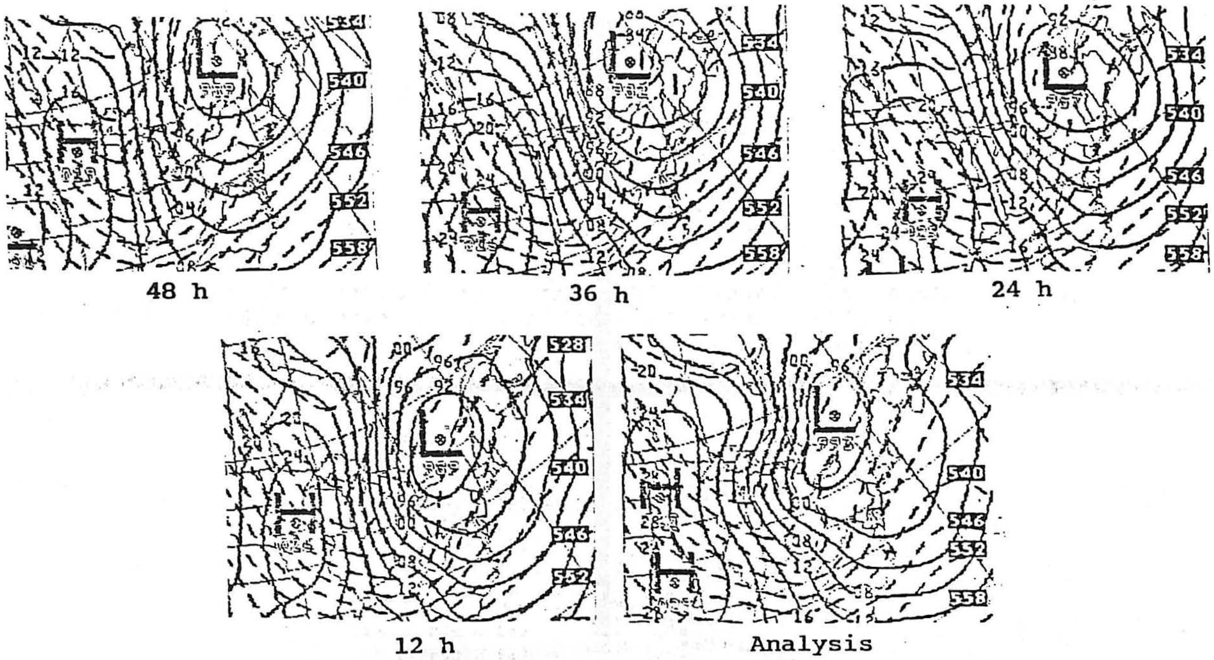


Figure S. LFM II MSL pressure/1000-500 thickness valid 00Z Tue 15 Jan 1985. Despite LFM II's bias to build arctic surface high over the Great Lakes, the warm (open) Lakes support regional trof to force surface high center over northern Plains. Note surface high on analysis (1029 mb) is 10 mb stronger than originally forecast on 48-h prog.

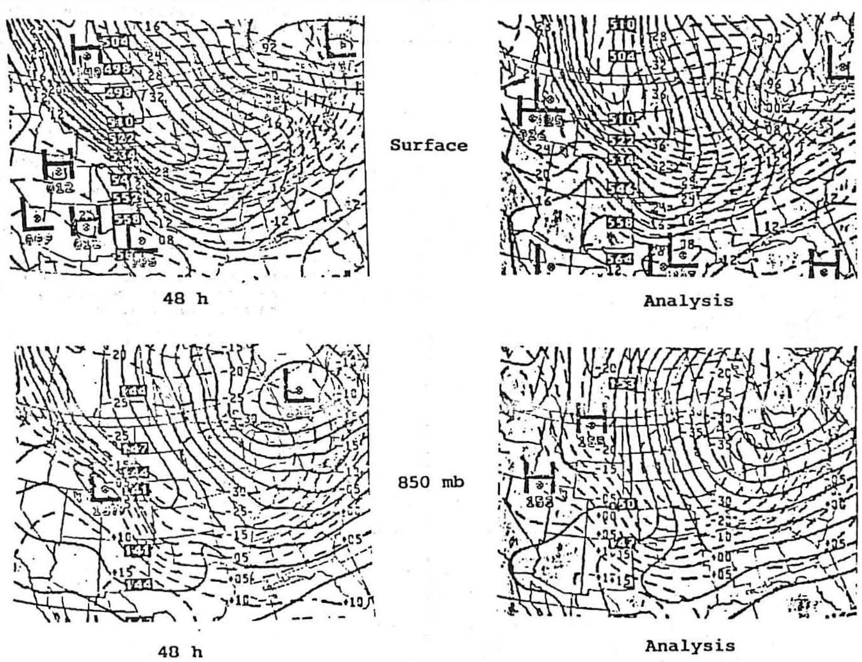


Figure T. LFM II MSL pressure/1000-500 thickness of U.S. (top) and 850 mb heights/temperature valid 00Z Sun 20 Jan 1985. Note in both cases the 48-h forecast (left) centers cold dome over central Great Lakes. In reality, the analysis (right) indicates center of cold dome is over Upper Mississippi Valley.

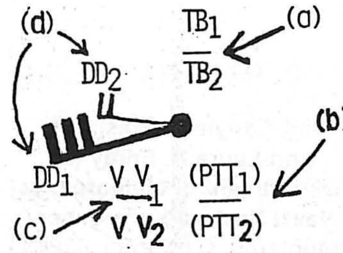


Figure U. Model of plotted FOUS output predictors utilized for lake-effect snow forecasting. Parameters DDFF, VV, PTT, and adjusted TB are shown.

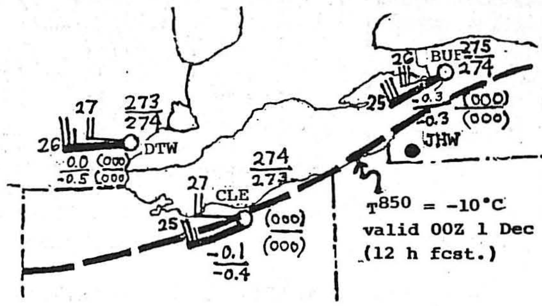


Figure V. Sample of plotted real-time FOUS data in model form of Figure U. Data originates from Table 2b, with TB values adjusted in Table 2c. Also plotted is -10°C T^{850} isotherm from LFM II 850 mb 12-h forecast chart (dashed line).

Figure W. Area defined for categories "X" (maximum upslope area) and "O" (adjacent lee side region or more distant locations from lake not considered maximum upslope areas) for use in determining snowfall accumulation. "X" areas are outlined by dotted lines and "O" areas by dashed lines. Canadian territory is excluded. Area Xa is used for trajectories from over Lakes Michigan and Superior, but area Xb applies only to trajectories from over Lake Huron and area Xc from Lake Michigan only. Area Xd in central and eastern section of Michigan's U.P. (including the Keweenaw Peninsula) applies ONLY trajectories from NNE-E. Note the insert of Lake Superior indicating area Xe, including the Keweenaw Peninsula and the western end of Michigan's U.P. Regarding the eastern section of Michigan's U.P., area Xe applies ONLY to trajectories from W-N, noting the shadowing effect of the Keweenaw Peninsula on the Marquette and Baraga County areas. The Area Xe regarding Wisconsin may apply to trajectories from NE.