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Lake Erie Induced Mesosystems—An Operational Forecast Model

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ABSTRACT

All Lake Erie lake-effect days for a 10-year period prior to the 1976–77 snowfall season were utilized in the development of an operational lake-effect snowfall forecast model. Upper air and surface observations were combined with overlake data and analyzed, using stepwise multiple-discriminant analysis. A nine-predictor mesoscale forecast model resulted from this statistical test and its performance was evaluated during the 1976–77 and 1977–78 snowfall seasons. The results of this evaluation indicate that it is possible to predict six intensities of the Lake Erie lake-effect snowstorm using this mesoscale model.

1. Introduction

The lake-effect snowstorm is a dramatic meteorological phenomenon which occurs each winter in the region of the Great Lakes. Cold arctic air spreading over the Great Lakes picks up heat and moisture from the relatively warmer lake surface. The efficient turbulent transfer of energy at the microscale renders these airstreams unstable and, consequently, initiates the development of mesoscale precipitation cells.

Snowfall amounts during these storms can be quite heavy. A 5-day lake-effect storm in January 1966 deposited a total of 259 cm of snow at Oswego, New York, and a lake-effect storm on 9 January 1976 produced 178 cm of snow in less than 24 h at Adams, New York (Dewey, 1977). Numerous studies (e.g., Wiggin, 1950; Muller, 1966; Eichenlaub, 1970; Strommen and Harman, 1978) have illustrated that although clouds have been observed several hundred kilometers inland, the heavier snowfalls are generally limited to an area within 150 km of the lake shoreline. Fig. 1 illustrates the bands of lake-effect clouds streaming inland to the lee of Lakes Michigan, Huron, Erie and Ontario on 30 November 1976. The area to the south and east of Lakes Erie and Ontario is snow covered as a result of a previous synoptic-scale frontal snowfall.

Since the lake-effect snowstorm has a limited spatial extent, the National Weather Service has not been able to give these systems much attention during the development of their forecast guidance products. According to Rieck *et al.* (1976), there are no centrally produced guidance products for the intensity of lake-effect systems. Forecasts of heavy snow are issued for a 12 h period (6–18 h after initial data time) for the conterminous United States, but this guidance package is prepared for the general synoptic-scale snowfall. Fig. 2 illustrates a 12 h forecast of synoptic-scale heavy snowfall for the Ohio River Valley region. The phrase "Lcly Hvy Snow" will also be added to the chart, with arrows pointing to the affected area, when the forecaster preparing the chart at the National Meteorological Center subjectively interprets that during the forecast period there is a potential for orographically induced or lake induced heavy snowfall. However, it should be noted that the arrows illustrated in Fig. 2 are for a single intensity forecast without an operational statement of probability of occurrence. It is significant to note that several forecast offices have developed, through experience and the collection of local data, nomograms or charts for assistance in forecasting lake-effect systems.

During 1976, a research effort was initiated within the Techniques Development Laboratory of the National Weather Service to develop an automated lake-effect forecast guidance product. It was the original intention of this study to produce a forecast model which could be used for lake-effect systems induced by any of the Great Lakes. It became apparent that due to the differing topography to the lee of each lake, the variation in lake dimensions, as well as the relative variation in predictor significance (e.g., ice cover, is far more significant on Lake Erie than it is on Lake Ontario) the same predictors and predictor coefficients would not be universally compatible for each of the Great Lakes. Therefore, a lake-effect forecast model was developed for each of the lakes with a different list of predictors and predictor coefficients for each lake. It is the purpose of this paper to summarize the development of the Lake Erie lake-effect forecast

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FIG. 1. Satellite photograph of 30 November 1976 illustrating the bands of lake-induced clouds streaming inland to the lee of the Great Lakes.

product and to illustrate how well it performed during two independent snowfall seasons (1976–77 and 1977–78).

2. Research methodology

The first step in this research effort was the isolation of all Lake Erie lake-effect snowfall events which had occurred during the 10-year period November 1967–March 1976. Utilizing a procedure outlined by Strommen (1975), climatological data and surface charts were examined to determine which days had temperatures lower than the lake surface temperatures and which days did not have synoptic-scale precipitation occurring in the area. In this manner, all nonlake-effect days as well as lake-effect days which occurred concurrently with synoptic-scale precipitation events were excluded. Due to the inability of determining the magnitude of the lake-effect component during synoptic events, this latter exclusion was necessary.

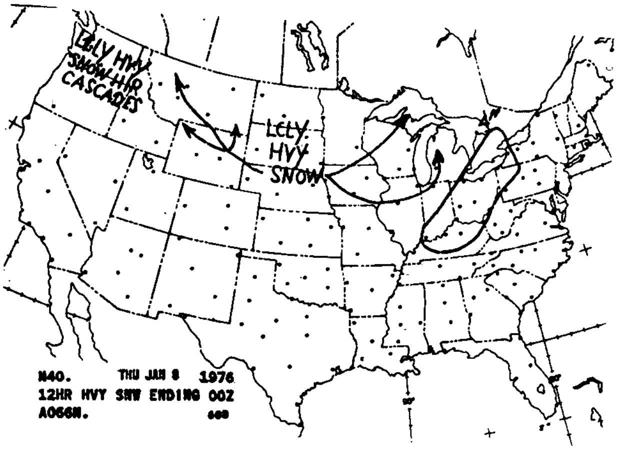

FIG. 2. Short-range heavy snow guidance forecast available on the National Weather Service facsimile system.

The precipitation records were examined for northeastern Ohio, northwestern Pennsylvania and western New York State, and each 24 period was classified into one of seven observed snowfall intensities. Although hourly or 12 h snowfall data would have been preferable for the model development, most of the Lake Erie lake-effect snowfall occurs to the south of the two hourly reporting stations (Buffalo, New York and Erie, Pennsylvania) which are located in the study region. Therefore, the primary data source for the lake-effect snowfall amounts was the network of climatological stations located to the lee of Lake Erie. The seven intensity categories used in this study are: no snow; ≤2.5 cm (1 inch); 2.5–10 cm (1–4 inches); 10–20 cm (4–8 inches); 20–30 cm (8–12 inches); 30–60 cm (12–24 inches); and >60 cm (24 inches). The classification of intensity was based upon the maximum observed lake-effect snowfall within the lake-effect snowbelt. A snowfall amount equal to the limit between two categories was assigned to the higher category. The category of "no snow" was included for it became apparent that on several occasions during lake-effect events, the energy flux was not quite large enough to initiate precipitation processes.

3. Development of a statistical framework

A search was then initiated to determine which predictors might be related to the observed variation in intensity of these snowfall systems. Based upon previous lake-effect investigations (Falconer *et al.*, 1964; Peace and Sykes, 1966; Paine and Kaplan, 1971; Jiusto and Kaplan, 1972; Lavoie, 1972; Dewey, 1975), 21 potential predictors were chosen for the initial statistical analysis. Many of these predictors already existed within the National Meteorological Center (NMC) computer system. These NMC predictors are based on observations collected on the synoptic scale. However, the lake-effect event is of mesoscale dimensions which necessitated the development, and inclusion in the model, of several mesoscale predictors.

The total list of potential predictors included wind speed at the surface and at several upper levels. Wind speed was included for it was assumed that the greater the magnitude of the wind, the greater the amount of turbulent mixing over the lake. The amount of fetch over the water for the advecting airmass was also included in the initial model. A westerly wind, for example, would allow far more mesoscale air mass transformation than with the shorter fetch of a northerly wind across Lake Erie. The relative stability or instability of the air mass being advected across the region could act to either attenuate or enhance the mesoscale processes occurring over the lake. Therefore, both the Lifted Index and George's *K* Index were examined for possible inclusion within the forecast model. The synoptic-scale vertical velocity field could also act to either enhance or attenuate the turbulent energy exchange over the lake and, it too was therefore included as a potential predictor in the model. It was assumed that the greater the atmospheric moisture content of the advected air mass, the greater the potential for significant snowfall when combined with the vertical transport of moisture over Lake Erie. Therefore, the moisture content of the advecting air mass was included for statistical analysis. The presence of any ice cover on the lake should limit the exchange of heat energy between the water surface and the atmosphere. Therefore, the percentage of ice cover on the lake was included as a potentially significant predictor. Although the actual magnitude of the lake-effect storm is a function of several scales of interacting processes, the primary cause of the lake-effect system is the vertical transport of energy over the lake. Therefore, in an attempt to assess the magnitude of the energy exchange, several estimates of the mesoscale thermal and moisture gradients over and near the lake were included in the study.

The largest problem in the collection of data for the predictors was the estimation of the energy fluxes over the lake. However, utilizing a series of regression equations developed by Phillips (1972), it was possible to estimate the air temperature and dew point fields at 2.5 m over the lake. The input to these equations included the National Weather Service satellite measured lake surface temperatures, and the Atmospheric Environment Service-Canada airborne radiometer lake temperature surveys and upwind data on the Canadian side of Lake Erie. It was then possible to estimate the thermal and vapor pressure gradient between the lake surface and the 2.5 m boundary layer. Using upper air data, it was also possible to estimate the vertical energy gradient between the lake surface and several upper levels. Wind speeds over the lake were estimated using upwind data and overlake stability classifications as illustrated by Richards *et al.* (1966) and Phillips and Irbe (1978). Although this research effort concentrated on the lower atmospheric modification occurring over and quite near the lake, Baker (1976) illustrated that it is possible to measure the lake-induced changes in temperature and dew point fields well downstream from the lake.

TABLE 1. Predictors which were utilized in the forecast model.

Predictor	*F*-value for inclusion*
1. $e_s - e_a$ (vapor pressure gradient at 2.5 m over the lake)	39.12
2. 850 mb saturation deficit	17.33
3. $T_w - T_u$ (temperature of the water minus temperature upwind)	14.60
4. Surface wind velocity over the lake	9.93
5. Percent ice cover on the lake	7.86
6. Stability of the air mass (Lifted Index)	2.98
7. $T_w - T_{850}$ (temperature of the water minus temperature at 850 mb)	2.46
8. 850 mb wind speed	2.43
9. Surface wind fetch over the lake	2.18

* Significant *F*-value for inclusion at $\alpha = 0.05$ is 2.13.

The data were then subjected to statistical analysis utilizing multiple discriminant analysis. The intensity of the snowfall system for each lake-effect day in the 10-year study period was known beforehand, so it was not the object at this point to predict intensity levels. Instead, the discriminant analysis program examined the predictor values of each 24 h period and indicated whether the combination of predictors was statistically similar to the other days in its group or perhaps more indicative of the predictor values in one of the other six groups. The first step in the statistical analysis in essence, was an evaluation of the hypothesis that it should be possible to discriminate between intensities of the lake-effect system using these predictors. It was expected that there might be some colinearity between the predictors, therefore a "stepwise" procedure was incorporated into the predictor selection process. The predictor which offered the most ability to discriminate between groups was selected first and the procedure was replicated until the last predictor (the one with the least ability to discriminate) was chosen. It was also possible to set a statistical

TABLE 2. Lake Erie lake-effect snowfall intensity probabilities for 16 January 1977.

No snow	≤2.5 cm	2.5–10 cm	10–20 cm	20–30 cm	30–60 cm	>60 cm
0.1%	1.8%	23.5%	67.9%	6.5%	0.2%	0.0%

limit beyond which a predictor would be eliminated due to its lack of offering additional discriminating ability. A level of significance of $\alpha = 0.05$ was chosen for the standard F test and the initial list of predictors was trimmed to the nine predictors listed in Table 1.

4. An independent test of the forecast model

The next and final step in this study was an independent test of the discriminant analysis equations and coefficients which had been developed from the 10-year data base. The 1976–77 and 1977–78 winter seasons were ideal periods for the testing of the lake-effect model as there were numerous lake-effect occurrences throughout the snowfall season. The forecast model was utilized to produce 24 h forecasts (beginning at 0000 GMT) of lake-effect snowfall intensity to the lee of Lake Erie during these two winter seasons. Data for several of the lake-effect predictors were automatically produced by NMC. The average surface temperature conditions surrounding the lake were determined from the 24 h MOS (Model Output Statistics) Max–Min forecasts. The forecast surface wind speed was based on the 12, 18 and 24 h MOS projections for the Lake Erie region. The 12, 18 and 24 h MOS surface wind forecasts were also used to determine the airstream trajectory over the lake and, hence, the fetch of the air mass over the lake. The 850 mb temperatures for the forecast period were derived from the PE (Primitive Equation) model 24 h forecast of 850 mb temperature and associated parcel trajectories.

Since several predictors were not produced automatically for the forecast period, latest available data were also included in the model. Phillip's (1972) model was combined with the forecast values of the NMC data and the latest available surface water temperatures to produce forecasts of the thermal and moisture gradients over and near the lake. The percent of ice cover on Lake Erie was estimated from the satellite ice reconnaissance charts of the Great Lakes which are available twice a week on the National Facsimile network (and slightly more frequent by mail from the National Environmental Satellite Service). The 0000 GMT analysis of the Lifted Index was utilized to determine a spatially averaged stability index for the study region. The 850 mb wind velocity over Lake Erie was determined using the latest available data on the 0000 GMT analysis. The 850 mb saturation deficit was also calculated using the 0000 GMT analysis and a spatial average of the temperature and dewpoint conditions between Buffalo, New York, and Flint, Michigan.

It should be noted that this is a conditionally operative model which was employed only when the following three criteria were satisfied: 1) the expected wind direction put the study region downwind of the lake; 2) the forecast air temperatures were expected to be less than the lake surface temperatures; and, 3) there was no large-scale precipitation expected within the vicinity of the lake.

The statistical relationship

$$P(k) = \frac{\exp(fk)}{\sum^{k} \exp(fi,k)} \qquad (1)$$

was utilized for the forecasts of lake-effect intensity, where $P(k)$ is the probability of membership in group k, fk is the discriminant index value for group k, and

$$\sum^{k} \exp(fi,k)$$

is the sum of the discriminant index values for all groups i–k. This equation produced a discrete probability for each group and a forecast was made based on the group with the highest probability. This forecast selection process was based on the procedure outlined by Miller (1962). However, it should be noted that an alternate method of selecting forecast categories is through the use of the "ranked probability score" (Epstein, 1969). The advantage of this alternate scoring rule is that it is possible to assess or consider the categories to which the bulk of the probability is assigned as opposed to the single selection "highest probability" rule. Table 2 illustrates the probabilities generated for 16 January 1977 and the Lake Erie snowbelt. A forecast of moderate snow (10–20 cm, 4–8 inches)

TABLE 3. Two season (1976–77 and 1977–78) forecast verifications for the Lake Erie lake-effect model.

Observed group (cm)	Predicted group (cm)						
	No snow	≤2.5	2.5–10	10–20	20–30	30–60	>60
No snow	6	1	1	—	—	—	—
≤2.5	1	3	2	—	—	—	—
2.5–10	3	3	23	6	2	—	—
10–20	1	—	2	13	2	2	—
20–30	—	1	1	3	5	1	1
30–60	—	—	—	3	1	3	1
>60	—	—	—	—	—	—	—

Number of days (Predicted minus Observed) > 1 classification category = 15 = 16.5% of the forecasts.

Number of days (Predicted minus Observed) > 2 classification categories = 2 = 2.2% of the forecasts.

was selected based on the "highest probability" rule. As indicated in the research methodology, the classification of intensity in the 10-year data sample was based upon the maximum observed lake-effect snowfall within the lake-effect snowbelt. Therefore, the forecasts generated during these two independent winter seasons were for the maximum expected snowfall to the lee of the lake. On this specific day, a maximum of 13 cm (5 inches) was observed to the lee of Lake Erie.

5. Verification of forecasts and evaluation of the model

The observed snowfall amounts were made available from the Environmental Data Service, National Climatic Center, Ashville, North Carolina, and were compared to the forecast snowfall amounts. It is difficult to measure the relative success of this forecast product for there are no other operational lake-effect intensity forecast models available for comparative purposes. A measure of this model's success can be illustrated, however, through a subjective evaluation of the forecast verifications.

Table 3 illustrates that less than 17% of the verifications were more than one classification category from the predicted intensity of snowfall. And the forecast error exceeded two classification categories only 2% of the time. It is significant to note that on no occasion was there a complete failure of the model (i.e., a forecast of category 1 with a verification of category 7). Although neither a forecast nor a verification of a 24 h snowfall greater than 60 cm occurred during the two winter seasons, this intensity category was retained (and listed in Table 3) due to its occurrence within the 10-year data base.

6. Conclusions

The last few years have seen the development and partial implementation of Automation of Field Operations and Services (AFOS). Part of the functioning of the AFOS system will be the availability of minicomputer facilities within the individual forecast offices. This will allow the development of localized or regional forecast models which can be utilized in the few regions where required without tying up the National Meteorological Center computer facilities. It is anticipated that there should be an improvement in forecast accuracy once these local and regional guidance products are made available within the AFOS system. There is no centrally produced lake-effect intensity guidance product. Therefore, the individual forecast offices have had to rely on local experience for the forecasting of lake-effect activity. The model described in this paper can produce an automated forecast of lake-effect snowfall with a discrete probability of occurrence for each of seven snowfall intensities. Much of the data for the nine-predictor model already exists within the central computer system and the few mesoscale predictors in the model can be easily derived, utilizing the series of equations developed by Phillips (1972). The model will be further evaluated during the 1978–79 lake-effect snowfall season. It is hoped that this model, or one similar to it, will be considered for possible implementation within the lake-effect snowbelt sometime in the near future.

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