Lake-Effect Cloud Bands as Seen From Weather Satellites

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ABSTRACT

Satellite photographs of the TIROS and ESSA series were examined for the presence and dimensions of lake-effect clouds over the Great Lakes and Gulf of St. Lawrence. It was found that nearly all lake-effect clouds occurred when the 850-mb temperature was more than 13C colder than the lake surface temperature. The clouds were organized into parallel bands resembling but having larger dimensions than cloud streets. Enlarged cloud bands were found which were 2.5 times larger than normal lake-effect bands. These enlarged lake storms had preferred origins and appear to be generated by frictional differences between land and water, by the geometry of the body of warm water with respect to the prevailing wind, and by certain urban influences.

1. Introduction

Lake-effect (or sea-effect) snowstorms can occur when cold air passes over a warm body of water. Such storms are not only responsible for the large snowfalls observed on the lee shores of the Great Lakes but also those of the western portions of the Honshu and Hokkaido Islands in Japan. Since they generally form in an area well to the rear of a cold front and in advance of a cold high pressure system, which is normally cloud free, they should be easily observed in satellite photographs. A large collection of satellite photographs from the TIROS and ESSA series were collected and examined for the presence of lake-effect clouds.

2. Stability relations

It was found from an examination of the storm-band pictures from satellites and from surface and radiosonde observations that nearly all lake storms producing either rain or snow occurred when the 850-mb temperature was more than 13C colder than the lake surface temperature. (The dry adiabatic temperature decrease between the surface and 850 mb is ~13C.) This observation indicates the presence of a layer of absolute instability somewhere between the lake surface and the upper levels. This relation between storm occurrence and the temperature difference between the lake surface and 850 mb is shown in Fig. 1 for most lake-effect cases since 1962. Some of the most extensive satellite cloud formations and intense lake storms occurred when the temperature difference was substantially greater than 13C. It would appear that forecasts of lake-effect activity can be aided by predictions of the 850-mb temperature if the lake temperatures are known. In similar fashion, the Buffalo, N. Y., Weather Bureau station makes use of the temperature difference between the lake (Erie) and 700 mb as an aid in predicting snowstorm intensity (Collier Index, unpublished).

3. General appearance and size of satellite bands

The examination of the lake-storm photographs showed that lake-effect clouds are usually organized into

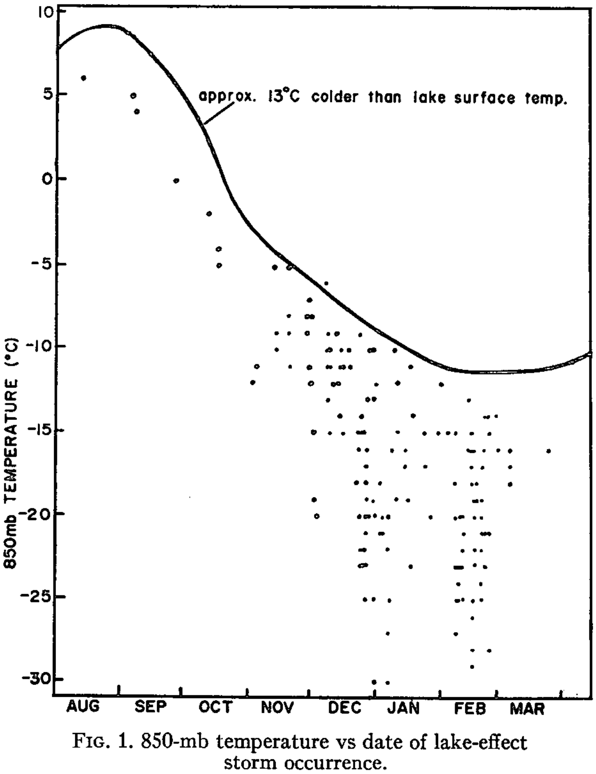

Fig. 1. 850-mb temperature vs date of lake-effect storm occurrence.

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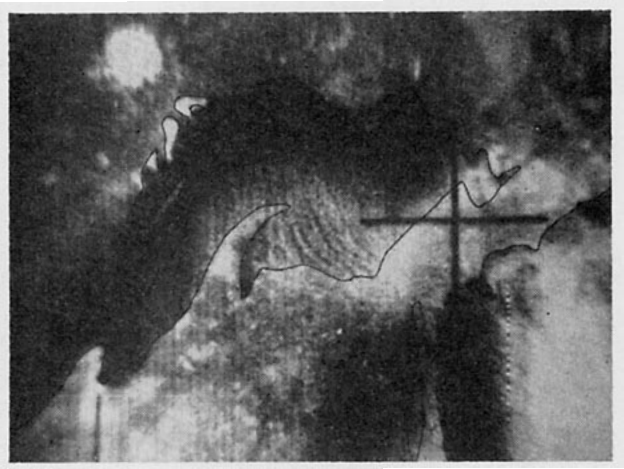

FIG. 2. Lake-effect cloud streets over Lake Superior (1934 GMT 5 March 1964). The wind direction as measured by radiosondes was northeast at 1200 GMT and northwest at 2400; it is generally northerly in this picture. Ice fills the bays on the north shores of the lake.

longitudinal bands or cloud streets as shown in Fig. 2. Such a structure indicates the presence of a vertical circulation of counter-rotating vorticies with horizontal axes, where air is rising along a cloud line and descending between lines. There are cases where the clouds are fused into masses whose elements are too small for resolution; such storms must lack the large circulation patterns. In general, most of the cloud streets are of equal size and length as there is usually nothing to favor the development of one band more than another. However, cloud bands about 2.5 times larger than adjacent cloud streets are observed in certain regions. One such example is shown in Fig. 3 where the cloud street coming from Chaleur Bay, Canada, is much larger than other cloud streets over the Gulf of St. Lawrence. Such bands will be called "enlarged lake storms" in this discussion. In each case where enlarged lake storms are seen, there is some phenomenon which favors premature formation of the cloud line or enhances its development. The resulting disturbance rapidly intensifies as the air becomes unstable over the warm lake.

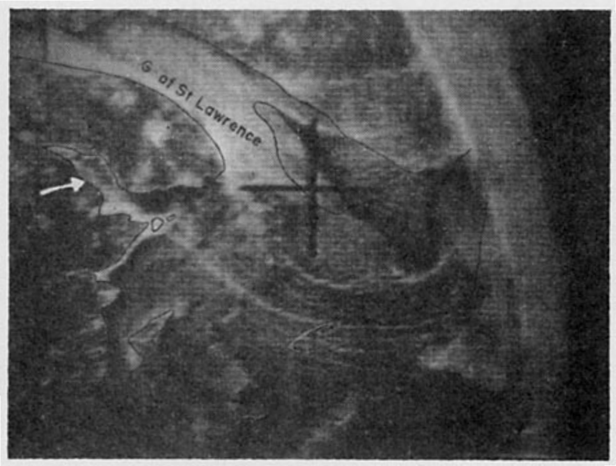

FIG. 3. An enlarged lake storm from Chaleur Bay (1549 GMT 4 February 1963). The arrow points to the bay. Ice on the edges of the bay and around the islands at its mouth make it impossible to determine if the bright cloud line is present over the bay itself. Large ice patterns can be seen in several locations on the Gulf of St. Lawrence. Clouds from a cyclonic storm system are located over Newfoundland.

Numerous satellite photos of lake-effect snowstorms were examined to determine the size of their cloud elements. The TIROS series was more useful than the ESSA series in measuring the smaller features, such as narrow cloud streets, since the photographs from the former were made at much lower altitudes. The results of this size survey are presented in Table 1 where previously published data on cloud streets (Kuettner, 1959; and others) are summarized for comparison.

It is readily seen that there are distinct differences between the three cloud types listed. The lake-storm cloud streets are wider and farther apart than normal cloud streets. There may, however, be some overlap between these two groups since most lake storms, which appear to be fused masses of cloud in the satellite photos, may have contained unresolved cloud streets. No overlap of size occurs between the second two cloud types. The enlarged lake storms are about 2.5 times larger than the lake-storm cloud streets and are therefore easily spotted in the satellite photographs. The line spacing of enlarged lakes storms is based on only four cases as it is rare to have two adjacent cloud lines of that size.

The interpretation of the satellite photos is made difficult by ice on the water, snow on the ground, and narrow cirrus bands. Ice is present in large amounts only in the January, February and March photographs, not in those earlier in the storm season. Ice patterns are more persistent than cloud patterns and will usually appear the same on successive days. Ice coverage maps prepared by the United States and Canadian government agencies were checked when they were available. No ice patterns were found in this study which resembled lake storms for appreciable distances. Furthermore, an ice covering over most of a body of water terminates lake-effect activity except for light flurries.

Occasionally a lake storm will deposit its snow in a narrow band on the lake shore and inland. Such a band will persist several days and may be confused in satellite

TABLE 1. Dimensions (km) of cloud streets and lake-storm bands.

Cloud type	Cloud widths Range	Cloud widths Typical	Parallel cloud street spacing Range	Parallel cloud street spacing Typical	Typical ratio of spacing to convection depth
Cloud streets (from literature)	1–5	—	4–10	—	2–3
Lake-storm cloud streets	4–8	7	7–15	10	5
Enlarged lake storms	10–30	20	20–30	27	10

photos with a lake-storm cloud band, except that it will not extend over the water. Narrow cirrus bands sometimes appear near the lakes, but they usually have an origin and orientation that indicates that they are not related to the presence of the lake.

An attempt was made to see if the lake-storm band orientation was parallel to either the wind vector or the shear vector. The study produced no conclusive results. The winds are measured only twice a day at stations often remote from the lake storms. The winds over a lake are not necessarily the same as those measured at the nearest station several hours earlier or later, especially in rapidly moving synoptic situations. Furthermore, surface observations by the author of winds near lake storms have shown that those which can be called enlarged lake storms frequently possess strong mesoscale circulations and have wind shifts of up to 90° across the bands. Therefore all that can be said is that the lake-storm bands are generally parallel to the wind direction; nothing can be said about the shear vector. The 850-mb winds are plotted in Figs. 5 and 7, where they were generally constant with time.

4. Suggested sources of enlarged lakestorm bands

Satellite photos of lake storms over the Great Lakes on 146 winter days from 1962–69 were examined to determine if there were any preferred origins for the enlarged lake storms. Such positions were found and enabled a classification of possible mechanisms of convergence and cloud formation as follows:

a. Friction induced convergence

1) Wind blowing along a shoreline with land to the right looking downwind.
2) Wind blowing over a lake with the greater horizontal pressure gradient towards high pressure.

b. Thermally induced convergence

1) Wind blowing along the central axis of a bay or lake.
2) Wind blowing across a region of "thermal pollution"[1] of the air by industrial and/or urban sources.

Qualitative explanations for these respective mechanisms are as follows:

a. Friction induced convergence

Ground friction creates cross-isobar air flow in proportion to the amount of surface drag. Under a constant pressure gradient, air flowing over the land will be deflected more to the left from geostrophic flow than air flowing over water. If the wind direction over the water is parallel to a shoreline, convergence will result at or near the shoreline if the land is to the right, divergence and subsidence if the land is to the left. Air flowing past an island will converge on the left side of the island. Evidence of this convergence mechanism if the land is to the right and subsidence if land is to the left looking downwind is suggested in the work of Estoque (1962) where he numerically simulated a sea breeze under several wind conditions.

Strong horizontal pressure gradients may cause greater cross-isobar air flow than weak gradients. At the boundary between two adjacent regions of differing pressure gradient, convergence will result if the greater pressure gradient is on the side toward higher pressure. A possible example of such convergence is shown by Cochran *et al.* (1970). Unless the pressure gradients are influenced mainly by terrain features rather than synoptic-scale systems, there will be no preferred geographic origin for cloud lines created by this form of frictional convergence.

b. Thermally induced turbulence

In arctic air of dry neutral stability, the preferred origin of convection will be over any heat source with a resulting convergence of air toward it. In general, the convection should be strongest over or downwind from the source center. This leads to the formation of lake storms downwind from bays, along the center lines of lakes, and downwind from sources of thermal (and particulate) pollution. Examples of the latter mechanism are given by Tsuchiya and Fujita (1966), Conover (1966) and Changnon (1968).

c. Analysis

The question then arises as to which convergence mechanism, friction or thermal, will be dominant in an area where both are operative. The enlarged lake storms appearing in satellite photographs were classified according to their geographic origin and convergence mechanism. For each of the Great Lakes and specific band origin, the frequency or percentage of occurrence of enlarged lake storms was determined with respect to lake-effect activity anywhere on that lake. Days without enlarged lake storms had lake-effect activity in the form of uniform cloud streets or fused cloud masses. These frequencies cannot be added to give the total frequency of enlarged lake storms in times of lake-effect activity as it is not uncommon to have two or more enlarged storms occurring on the same lake. The indicated frequency may be somewhat biased because it is based on the number of pictures of lake-effect activity in our collection; these pictures were often selected because of the occurrence of enlarged lake storms. For any one lake, the frequencies do show the

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[1] The term "thermal pollution" of the air as used herein includes not only sensible heat inputs but also possible water vapor and freezing nucleus additions from an urban and/or industrial source.

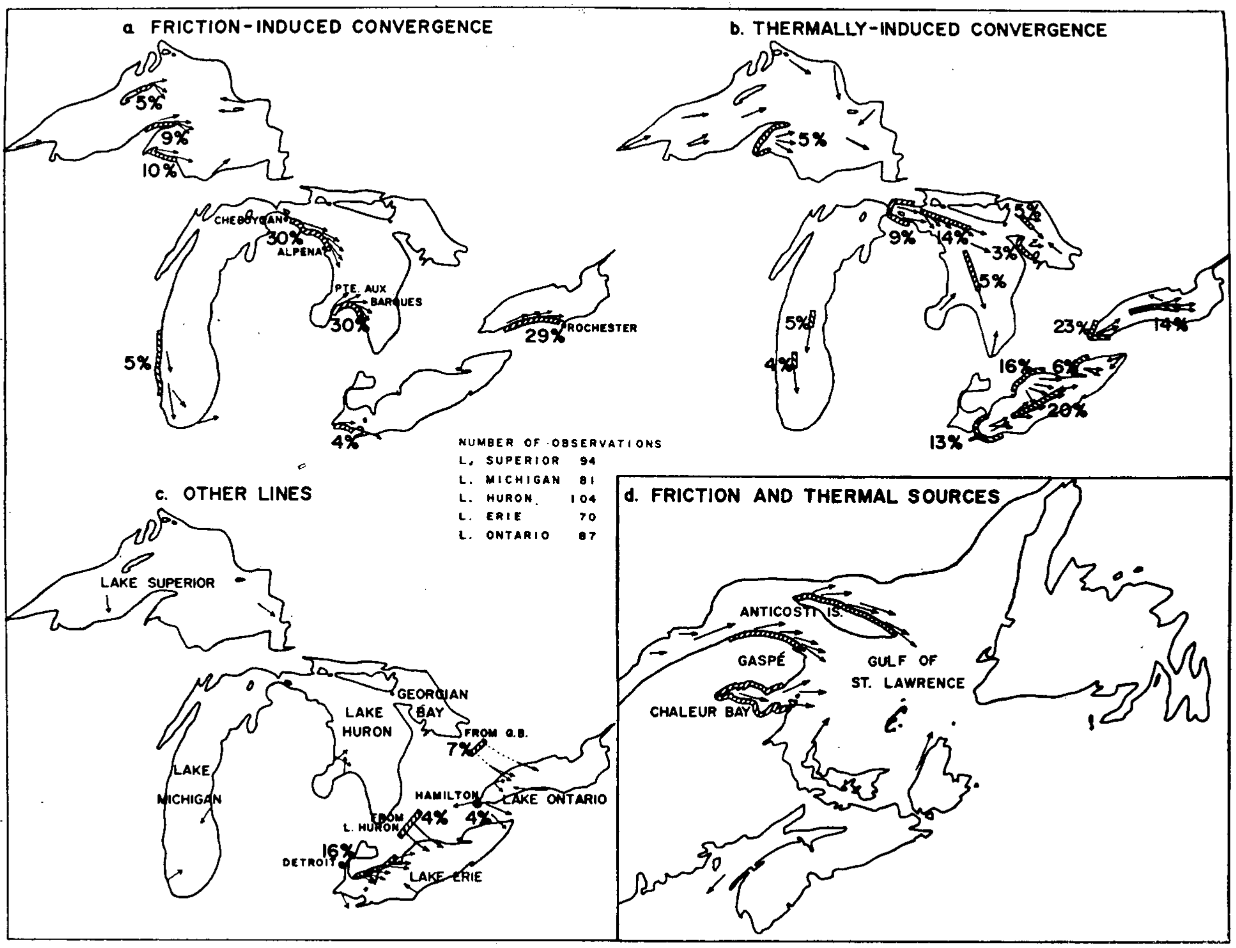

FIG. 4. Activity frequency of preferred sources of enlarged lake storms as observed from satellites.

relative importance of each location in generating enlarged lake storms.

Fig. 4a shows the locations of shorelines which promote enlarged lake storms by the method of friction induced convergence. The most active locations are the south shore of Lake Ontario between the Niagara River and Rochester, N. Y., and the Cheboygan-Alpena shoreline and the Pte. aux Barques shoreline of Lake Huron.

The origins of thermally induced lake storms of the bay and center-line varieties are presented in Fig. 4b. The most active heat source regions are the center line, the southwestern end and the north-central shore of Lake Erie, the western end and the center line of Lake Ontario, and the northwestern end of Lake Huron.

Fig. 4c shows all other lines that could not be classified according to the previous types. They include lines from upwind storms on other lakes that drift over the indicated lake, storms or cloud lines apparently caused by thermal pollution of the air by industrial or urban sources, and a few other lines of undetermined origin. The lines which most clearly indicate thermal pollution are those which begin over the land before the heat from a lake begins to affect the air. Detroit, Mich., and Hamilton, Ont. are the two most obvious source regions. Both areas presumably generate a large output of heat (and freezing nuclei) from their numerous steel mills. In Fig. 4d are plotted the origins and orientations of enlarged storms over the Gulf of St. Lawrence. Three zones are most active: the north shores of Anticosti Island and Gaspe Peninsula, both starting friction induced bands, and Chaleur Bay which supports thermally induced bands.

The relative frequencies indicate that the friction mechanism is dominant on Lakes Superior and Huron and the thermal mechanism on Lake Erie; on Lake Ontario they are about equal. If the wind orientation is such that both mechanisms are equally likely at adjacent locations, then the friction mechanism tends to dominate. There are numerous cases where an enlarged band can be created and strengthened by a series of mechanisms. For example, storms over Lake Ontario under a west wind will receive a small initial impulse of heat from the industry in Hamilton, then experience

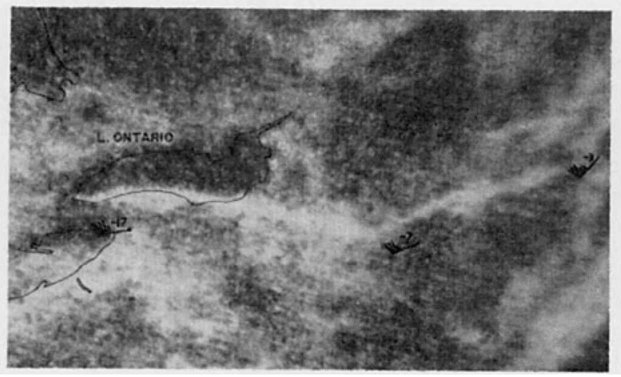

Fig. 5. An enlarged lake storm at the south shore of Lake Ontario (1459 GMT 26 December 1967). The 850-mb winds and temperatures at 1200 GMT have been plotted. The relatively warm temperatures between Albany, N. Y. (center station), and Portland, Me., suggest that the cloud band between these two stations is not part of the lakestorm; it may be a cirrus band instead.

convergence from passing over the bay-like west end of the lake, and finally receive a strong boost from friction generated convergence along the south shore; such an example is illustrated in Fig. 5 where the 20 km-wide line thus generated continues intact for a distance of 400 km.

In Fig. 6 the two friction zones of Lake Huron are aligned with the wind to produce an enlarged lake storm 18 km wide and about 750 km long, while adjacent lake-effect cloud streets measure 7 km by 250 km and the fused cloud masses extend 150 km. Two other lines of interest in this figure stem from the thermal pollution sources of Detroit and Hamilton; both begin over land before crossing Lake Erie. Fig. 7 shows a storm on Lake Ontario that originated along the south shore with its friction convergence mechanism and then moved to a center position on the lake, possibly in response to the thermal mechanism. Adjacent small fused clouds or unresolved cloud streets make the 15 km by 300 km storm seem even wider. Friction generated clouds from both sources appear on Lake Huron while a center line storm extends along Lake

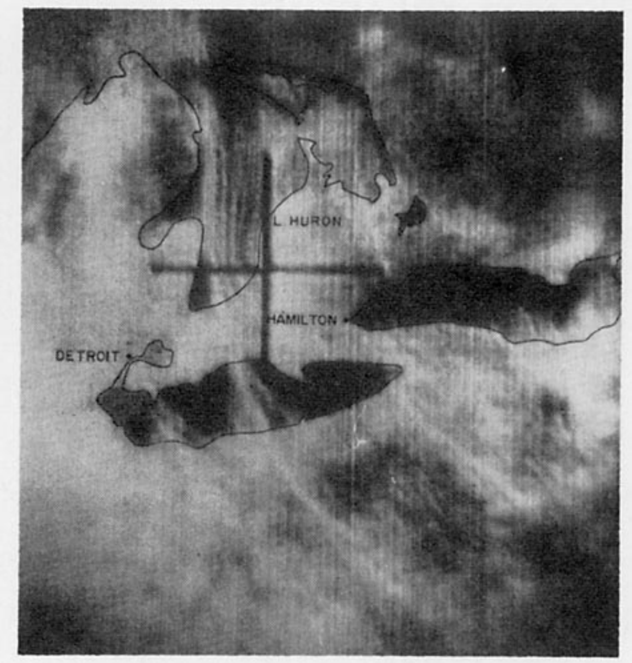

Fig. 6. Enlarged lake storms from the west shores of Lake Huron, Detroit, and Hamilton (1505 GMT 14 December 1962).

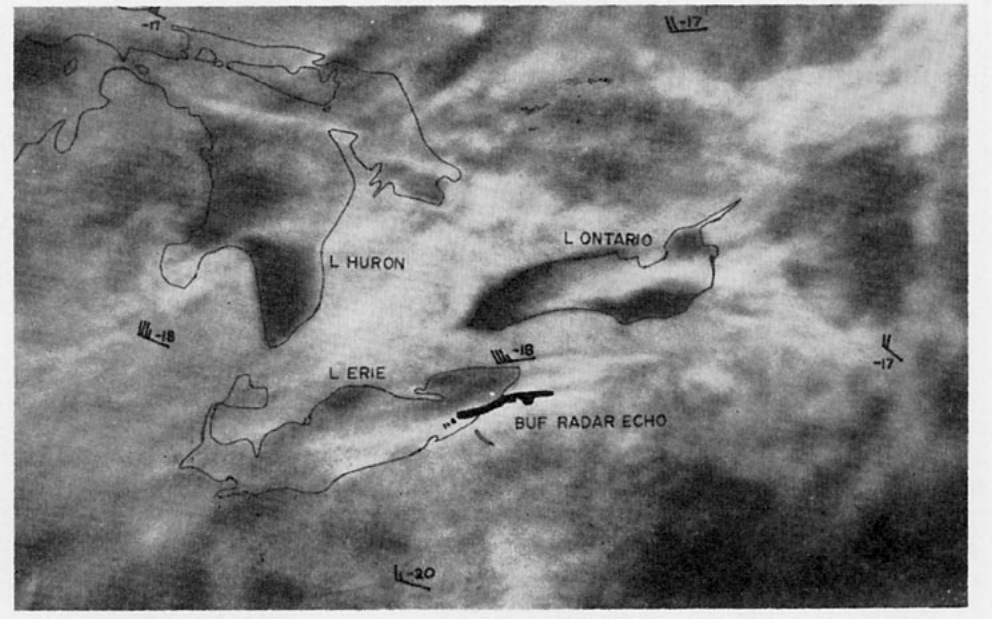

Fig. 7. "Enlarged lake storms" over Lakes Huron, Erie and Ontario (1510 GMT 4 January 1969). The 850-mb winds and temperatures at 1200 GMT have been plotted.

Erie. The Buffalo radar position of this latter storm is shown in black. A 10 km by 170 km cloud line appears to originate at the Lackawanna area at the eastern tip of Lake Erie (a region of several steel mills), but it did not produce a radar echo.

5. Conclusions

Winter lake-effects clouds are generated primarily by the instability resulting from the movement of cold air over warm water, and the resultant vertical fluxes of heat, momentum and water vapor. Usually such clouds are present only when the 850-mb temperature is more than 13C colder than the lake surface temperature. The normal lake-effect clouds resemble cloud streets but have larger dimensions.

An "enlarged lake-storm" cloud band was found on numerous occasions which was about 2.5 times larger than other lake-effect cloud bands. Most of these enlarged lake storms have preferred origins and are apparently generated by one or more of the three following mechanisms:

1) Frictional differences between water and land surfaces which cause convergence and downwind storms when the wind is blowing parallel to the lakeshore with the land to the right of the direction of air movement.

2) Thermally induced convection from bays or along the center lines of bays.

3) Thermal pollution from urban areas which initiates convection and/or cloud formation.

Synoptic-scale systems with varying horizontal pressure gradients may account for enlarged lake storms without preferred geographic origins. The effects of thermal pollution may be greater than indicated. Industrial areas are frequently located around bays and at the tips of lakes, and thus may be aiding in the production of lake-storm bands attributed to the bay type of thermally induced convergence.

It was found that the frictional convergence mechanism was dominant on Lakes Huron and Superior, and the thermal mechanism on Lake Erie; on Lake Ontario they are about of equal importance.

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