PICTURE OF THE MONTH

Mesoscale Vortices over the Great Lakes in Wintertime

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ABSTRACT

The occasional occurrence of wintertime mesoscale lake vortices is documented. The vortices are readily discernible in satellite imagery, in which they take one of three forms: a miniature comma cloud, a swirl of cloud bands (resembling a miniature tropical storm) or a swirl of cloud streets. Despite their impressive appearance in satellite imagery, these vortices are usually relatively mild in comparison with other lake-effect storms and produce only gusty winds and brief snow squalls as they move onshore. The vortices are accompanied by a slightly lowered surface pressure and a weak cyclonic low-level wind circulation.

Fourteen vortices were detected over the Great Lakes in the years 1978–82; they occurred under conditions of relatively weak surface pressure gradient, with a ridge of high pressure usually found over or west of the region. Convergence was generally detected in the surface winds prior to vortex development, apparently related to land breeze circulations. Comparisons are made between the conditions favoring the occurrence of shoreline-parallel cloud bands and lake vortices. Comparisons are also made between lake vortices and polar vortices, i.e., mesoscale vortices occurring in polar airstreams over oceans.

1. Introduction

The existence of mesoscale phenomena and mesoscale weather regimes over and adjacent to lakes is well-known. In the summertime, the lake breeze, the lake breeze front and the lake mesohigh are practically daily occurrences (e.g. Lyons, 1972). In the wintertime, lake-effect snowstorms (e.g. Holroyd, 1971) are common and there is a marked tendency for troughing of the surface isobars over the warm Great Lakes (e.g. Petterssen and Calabrese, 1959). Signatures of lake-effect snowstorms have been identified in satellite imagery as multiple cloud streets roughly parallel to the low-level wind and enhanced shoreline-parallel cloud bands (e.g. Peace and Sykes, 1966; Holroyd, 1971; Passarelli and Braham, 1981).

One type of wintertime mesoscale cloud configuration which occasionally occurs over the Great Lakes has apparently not been previously reported in the literature and is referred to here as the *wintertime mesoscale lake vortex.* Such lake vortices often appear rather spectacular in satellite imagery, as can be seen from Fig. 1.

2. Characteristics of the wintertime mesoscale lake vortex

Fourteen lake vortices were identified during the winter months (October–April) of the years 1978–82 by inspection of the satellite photo archives of the Department of Meteorology, Pennsylvania State University. Table 1 summarizes the dates and locations of occurrence of these vortices. Inasmuch as this archive consists typically of only a few pictures per day, some vortices may have gone unnoticed. Synoptic-scale high-cloud overcast conditions may also have prevented vortex detection on some days.

Each of the vortices of Table 1 was most distinct during the period from midday to midafternoon. Some of the vortices appeared to form before sunrise and some persisted beyond sunset. There is, however, a considerable diurnal bias in the ability to detect a lake vortex. First, the Pennsylvania State University archive is predominantly a collection of daytime (visible and infrared) imagery. Further, recognition of the lake vortex is more difficult using infrared imagery, encouraging a daytime (visible imagery) reporting bias.

Vortices were most commonly observed over Lake Michigan (8 of the 14), although three each were observed over Lakes Huron and Superior. There were five occurrences in each of the months of January and February and one each in the months of November, December, March and April. Thus, the wintertime mesoscale lake vortex is not especially rare, occurring about three times per winter.

Vortices were observed in three types of configurations, as listed in Table 1: miniature comma clouds (3 of 14 cases), swirls of cloud bands (resembling a miniature tropical storm, 9 of 14 cases) and swirls of cloud streets (2 of 14 cases). Examples of the three types are shown in Figs. 1, 2, and 3. All vortices ap-

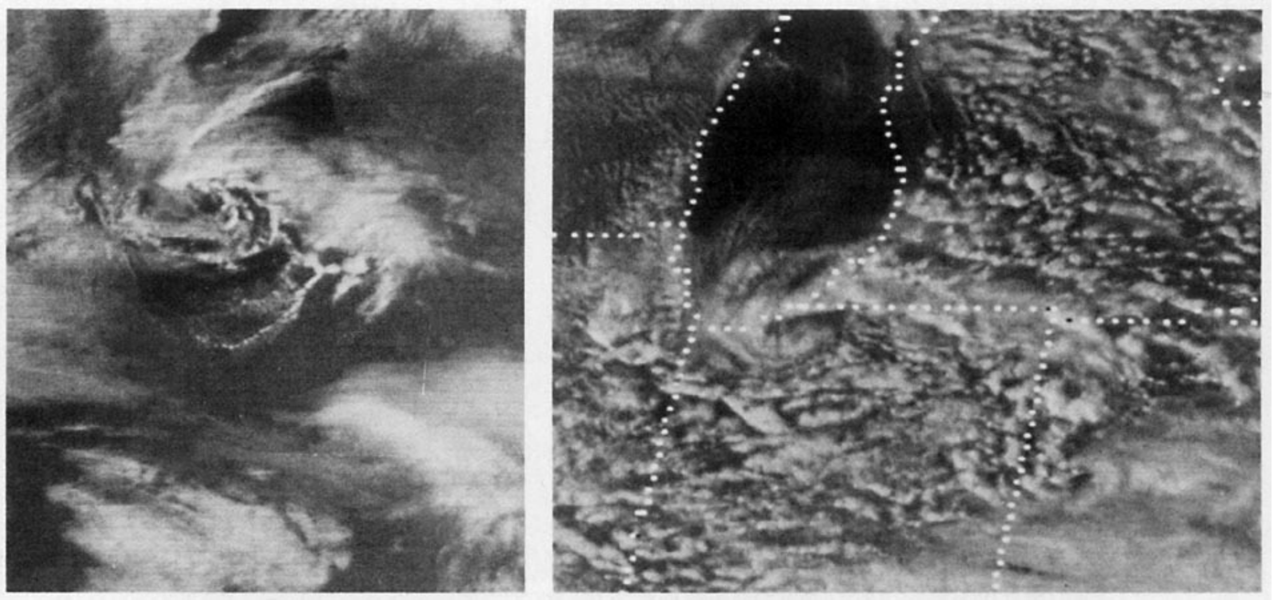

FIG. 1. Evolution of the lake vortex, miniature comma type, on 6 March 1981 over Lake Michigan at 1600 GMT (left) and 2100 GMT (right).

peared to be cyclonic. Vortex diameters ranged from ~50 to 120 km.

Cloud tops accompanying the lake vortices were considerably lower than those of synoptic-scale cyclones elsewhere over North America. Cloud top temperatures, estimated from infrared satellite imagery, were typically −25°C and ranged from about −10 to −32°C. The associated cloud top heights, estimated from nearby soundings, were typically ~5 km and ranged from ~3.5 to 5.5 km. Much of the cloud appeared to be convective in origin.

Despite their impressive appearance in satellite imagery, the lake vortices in this study were insignificant weatherwise.[1] In some instances, bands or other portions of the cloud patterns extended outward from the lake over adjacent shorelines, and in many instances (as shown in Figs. 1 and 2) the vortices translated inland. Inspection of hourly precipitation data at climatological stations (spaced ~30–40 km apart) for several such cases failed to reveal any major mesoscale snowbands associated with the lake vortices.

Inspection of hourly and special reports at airport stations showed that the lake vortices did exert minor influences on the local weather as they translated inland. Snow showers were often suppressed over adjacent land regions while the vortex was over the lake nearby. Brief snow showers and squalls, accumulating to a snow depth of generally less than 2 cm, resumed as the bands of the vortex passed overhead. Winds generally shifted and became gusty and sea level pressures fell slightly (~1 mb) as the vortex approached. No ship reports were available to determine the weather accompanying the vortices over the lakes. It seems likely that gusty, showery weather accompanied the cloud bands there.

3. Conditions favoring lake vortex development

Lake vortices developed under conditions of weak surface pressure gradient and entrenched cold polar air. Air temperatures over adjacent land regions averaged about −12°C while the vortices developed and, depending upon the case, ranged from −27 to 5°C.

TABLE 1. List of mesoscale lake vortices 1978–82.

Date	Lake	Classification
2 Feb 1978	Huron	Well-defined swirl of bands
2 Feb 1979	Michigan	Weak swirl of bands
1 Dec 1979	Michigan	Well-defined swirl of bands
29 Jan 1980	Michigan	Weak swirl of bands
1 Feb 1980	Michigan	Well-defined swirl of bands
28 Feb 1980	Michigan	Well-defined swirl of bands
16 Nov 1980	Michigan	Weak miniature comma
8 Jan 1981	Michigan	Well-defined swirl of bands
14 Jan 1981	Huron	Weak swirl of bands
28 Jan 1981	Huron	Weak swirl of bands
6 Mar 1981	Michigan	Well-defined miniature comma
14 Jan 1982	Superior	Well-defined miniature comma
3 Feb 1982	Superior	Well-defined swirl of cloud streets
6 Apr 1982	Superior	Well-defined swirl of cloud streets

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[1] In other instances, however, lake vortices appear to have produced strong winds and up to 20 cm of snowfall, as reported by W. A. Lyons (personal communication, 1983), Braham (1983) and M. R. Hjelmfelt, W. A. Lyons and R. A. Pielke, 1983: Mesoscale spiral vortex embedded within a Lake Michigan snow squall band: Observations and model simulation. Oral presentation, 1st Conf. Mesoscale Meteor., Norman, OK.

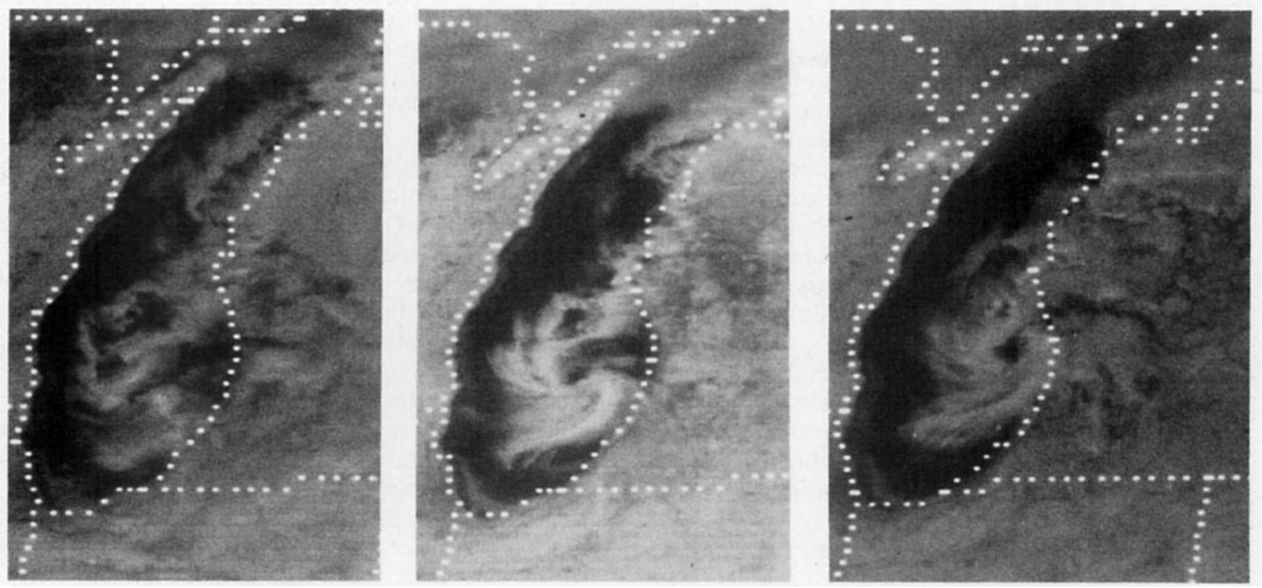

FIG. 2. Evolution of the lake vortex, swirl of bands type, on 8 January 1981 over Lake Michigan at 1600 GMT (left), 1800 GMT (center) and 2000 GMT (right).

In each case, the air temperature was colder than that of the lake surface, suggesting the importance of diabatic heating in lake vortex generation. The lakes were not frozen at these times, and lake vortices would appear to be unlikely under such conditions. Air temperatures above land were generally fairly uniform spatially on a given day, especially when winds were weak. On days with an appreciable synoptic-scale wind flow (which was generally from the northwest) there was, of course, an air temperature difference between the windward and leeward regions, as a result of heating during the trajectory over the lake.

The lake vortices generally occurred near or somewhat east of the synoptic-scale ridge of high pressure. Often the ridge was disrupted by a pressure trough associated with diabatic heating over the lakes—either individually or collectively (as discussed by Petterssen and Calabrese, 1959).

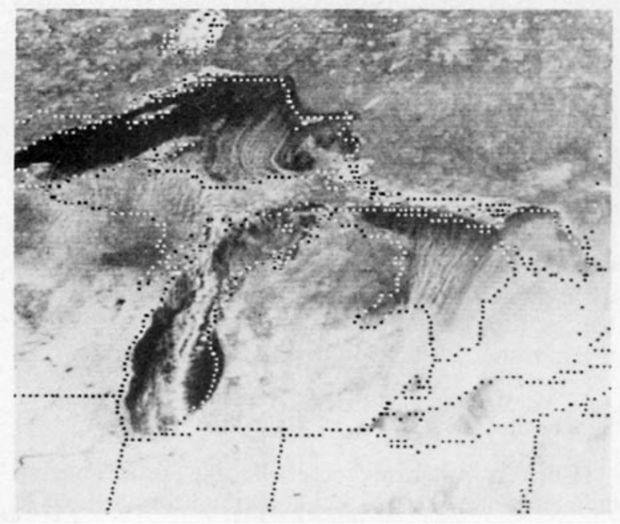

FIG. 3. Configuration of the lake vortex, cloud street swirl type, at 1531 GMT on 6 April 1982 over Lake Superior.

Even more common than well-defined troughs were organized convergences in the surface winds. In all, 79% of the cases showed convergence over the lake prior to vortex development, including 11 of the 12 cases of mini commas and swirls of cloud bands. Neither of the cloud street swirls exhibited such convergence. It appeared that the convergence was attributable to a lake-induced circulation, generating wind components of up to 3 or 4 m s^{-1} toward the lake. The synoptic-scale wind speeds varied considerably, from nearly zero to about 10 m s^{-1}. Synoptic-scale wind direction was generally between westerly and northerly.

Synoptic-scale forcing appeared rather weak and unimportant in the development of these vortices. Fifty-seven percent of the cases showed negative vorticity advection at 500 mb during vortex development, and only one case showed strong positive vorticity advection. Synoptic-scale advections of 1000–500 mb thickness were weak in 71% of the cases, with negative advection in 64% of the cases. Strong thickness advections were rather rare, with cold advection outnumbering warm advection 3 cases to 1.

4. Discussion of possible causal mechanisms of the lake vortices

The lake vortices (excluding the cloud street swirl type) appeared to form under conditions rather similar to those favoring shoreline-parallel cloud bands. Passarelli and Braham (1981) found that single, broad shoreline-parallel cloud bands form over Lake Michigan under conditions of relatively weak synoptic-scale gradient wind. On such days, heating of the air over the warm lake surface produces a large temperature gradient across the lake shorelines. Such conditions permit the development of land breeze circulations (of opposing direction) on opposite lake shores, resulting in marked convergence over the lake and the occurrence of a cloud band in the convergence zone. On days with increasing gradient winds, the land breeze convergence is disrupted and the cloud band deteriorates.

Pitts *et al.* (1977) presented an example of a shoreline-parallel band over Lake Superior which accompanied a thermally-induced pressure trough and convergence line. Loops or vortex structures developed along the band at intervals of approximately 15 km. Peace (1966) observed a similar type of vortex using radar. Similarly, a number of lake vortices of Table 1 originated as disturbances on shoreline-parallel cloud bands, though the scale of the subsequent vortices was considerably larger than those of the previous studies. In view of the low-level convergence and often significant low-level vertical wind shear, stretching and tilting of vorticity must be considered potential[2] contributors to lake vortex development.

Cyclogenesis due to spatially variable diabatic heating must also be considered. Petterssen (1955, 1956) showed that a pocket of diabatic heating, associated with a negative extreme of the Laplacian of the heating rate, contributes to cyclogenesis. There is considerable evidence that this mechanism operates on the scale of individual lakes and of the Great Lakes as a whole (e.g., Petterssen and Calabrese, 1959). Weak vortices developed over Lake Erie in the numerical model experiments of Lavoie (1968) and the position of the vortex changed when the ambient wind direction changed. For individual lakes, the Laplacian of the heating rate is most negative in the vicinity of rounded shorelines, generally favoring development there. Of the cases of Lake Michigan vortices, 7 of the 8 formed over the southern third of the lake where shoreline curvature was most pronounced. Of course, this configuration also maximizes convergence between land breezes normal to the shoreline, thereby maximizing the generation of vorticity through stretching.

The lake vortex would also appear to be possibly related to the polar vortex, which occurs over oceans within polar airstreams. Weak polar vortices are accompanied by a trough in the surface pressure field, whereas intense vortices are accompanied by closed isobars and are often called polar lows. Most of the cases in the literature are of the latter type, undergoing intense cyclogenesis and possessing deep cloud systems which produce considerable precipitation (e.g., Harrold and Browning, 1969; Monteverdi, 1976; Rasmussen, 1979, 1981; Reed, 1979). Many of the lesser disturbances exist in polar airstreams, however, and it is probably these which more closely resemble the lake vortex. Oerlemans (1980) studied a vortex disturbance which moved inland from the North Sea, producing a pressure decrease of only 1 mb. Unlike the lake vortices, however, this disturbance brought significant (20 mm) precipitation to the coastal regions (of the Netherlands).

Forbes and Lottes (1982) studied a number of polar vortices and found that those which were small in diameter and contained small, shallow convective elements were unlikely to be significant in terms of pressure perturbation. By analogy with these polar vortex studies, lake vortices are unlikely to be significant for three reasons. First, their diameters are small, typical of insignificant polar vortices. Second, the convection is relatively shallow and of small diameter; cloud tops in significant polar vortices generally approached 7 km. Third, with regard to the contribution from diabatic heating, polar airstreams and traveling polar vortices can have considerable (i.e., several days) residence time over a warm ocean, whereas the residence time of polar flow and lake vortices over lake surfaces is considerably less. However, the pattern of diabatic heating favors development near coastlines, so initiation of polar vortices may be favored there. Indeed, many polar vortices form just off the coasts of Greenland, Iceland and Norway.

There has been considerable observational and theoretical discussion of the mechanism(s) causing polar cyclogenesis (refer to Sardie and Warner, 1983, for a review). Basically, baroclinic instability and conditional instability of the second kind (CISK) have been proposed as mechanisms. Recently, Mullen (1982) has shown that cyclogenesis can occur in polar airstreams over continental regions, where CISK cannot contribute. However, observations by Forbes and Lottes (1982), which show that a number of initial cloud configurations can evolve into polar lows, may interject an element of caution into arguments which advocate either baroclinic instability or CISK as the sole mechanism for development. The existence of lake vortices would suggest that, at minimum, diabatic heating and its feedback processes can initiate cyclonic disturbances. Further studies of mesoscale vortices and their mechanisms for development are needed.

5. Conclusions

Fourteen wintertime mesoscale lake vortices having diameters of 50 to 120 km and cloud tops as high as 5.5 km were studied. These vortices were rather in-

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[2] Due to the lack of mesoscale data available for this study, it is only possible to qualitatively discuss the processes potentially contributing to lake vortex development.

nocuous, associated only with weak cyclonic wind circulations and brief snow showers, though there are reports (see footnote 1) that more extreme cases occasionally occur.

Shoreline-parallel cloud bands occurred over the lake during many of the vortex developments and some of the vortices were initiated as small disturbances along these bands. These initial disturbances were of rather small scale, however, and the developing lake vortices quickly grew to diameters approaching the width of the lakes. This suggests that vorticity production associated with diabatic heating over the lake was more important for lake vortex development than the vorticity-generation processes operating on the scale of the shoreline-parallel cloud band.

Lake vortices occurred in specific synoptic-scale weather regimes (in cold air masses and near or just east of the axis of the pressure ridge) but synoptic-scale processes otherwise did not appear to contribute to lake vortex development. Positive vorticity advection and positive (warm) thermal advection, favoring synoptic-scale cyclogenesis, were not normally present.

Though many of the vortices showed little systematic movement, three of the vortices (on 28 February 1980, 8 January 1981 and 6 March 1981) translated not only over portions of Lake Michigan but also moved inland. Whereas this might suggest some connection to a traveling synoptic-scale feature, other explanations are possible. Lavoie (1968) showed that the vortex changes position on the lake as the synoptic-scale wind direction shifts; this may have played a role in one of the cases. In the other two cases, warming of the air over land in the afternoon (resulting from insolation) reduced the air–water temperature difference. It is suggested that the vortices were generated and maintained over the lake during the morning by the stationary pattern of diabatic heating and were steered inland by the synoptic-scale flow in the mid-to-late afternoon when this forcing weakened. Indeed, the vortices themselves weakened rapidly during their movement inland.

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REFERENCES

Braham, R. R., Jr., 1983: The midwest snow storm of 8–11 December 1977. *Mon. Wea. Rev.*, **111**, 253–272.

Forbes, G. S., and W. D. Lottes, 1982: Characteristics and evolution of mesoscale cloud vortices occurring in polar airstreams. *Preprints Conf. Cloud Phys.*, Chicago, Amer. Meteor. Soc., 310–313.

Harrold, T. W., and K. A. Browning, 1969: The polar low as a baroclinic disturbance. *Quart. J. Roy. Meteor. Soc.*, **95**, 719–730.

Holroyd, E. W., 1971: Lake-effect cloud bands as seen from weather satellites. *J. Atmos. Sci.*, **28**, 1165–1170.

Lavoie, R. L., 1968: A mesoscale numerical model and lake effect storms. Ph.D. thesis, The Pennsylvania State University, University Park, 102 pp.

Lyons, W. A., 1972: The climatology and prediction of the Chicago lake breeze. *J. Appl. Meteor.*, **11**, 1259–1270.

Monteverdi, J. P., 1976: The single air mass disturbance and precipitation characteristics at San Francisco. *Mon. Wea. Rev.*, **104**, 1289–1296.

Mullen, S. L., 1982: Cyclone development in polar air streams over the wintertime continent. *Mon. Wea. Rev.*, **110**, 1664–1676.

Oerlemans, J., 1980: A case study of small synoptic-scale cyclones in polar airstreams. *Mon. Wea. Rev.*, **107**, 1636–1647.

Passarelli, R. E., Jr., and R. R. Braham, Jr., 1981: The role of the winter land breeze in the formation of Great Lakes snow storms. *Bull. Amer. Meteor. Soc.*, **62**, 482–491.

Peace, R. L., Jr., 1966: Radar characteristics of lake effect storms. *Proc. 12th Conf. Radar Meteor.*, Norman, Amer. Meteor. Soc., 454–460.

——, and R. B. Sykes, Jr., 1966: Mesoscale study of a lake effect snow storm. *Mon. Wea. Rev.*, **94**, 495–507.

Petterssen, S., 1955: A general survey of factors influencing development at sea level. *J. Meteor.*, **12**, 36–42.

——, 1956: *Weather Analysis and Forecasting, Vol. I,* 2nd ed., McGraw Hill, 257–277.

——, and P. A. Calabrese, 1959: On some weather influences due to warming of the air by the Great Lakes in winter. *J. Meteor.*, **16**, 646–652.

Pitts, D. E., J. T. Lee, J. Fein, Y. Sasaki, K. Wagner and R. Johnson, 1977: Mesoscale cloud features observed from Skylab. *Skylab Explores the Earth,* NASA-SP-80, 479–501. [Superintendent of Documents, Government Printing Office, Washington, DC 20402, Stock 033-000-00674-8.]

Rasmussen, E., 1979: The polar low as an extratropical CISK disturbance. *Quart. J. Roy. Meteor. Soc.*, **105**, 531–549.

——, 1981: An investigation of a polar low with a spiral cloud structure. *J. Atmos. Sci.*, **38**, 1785–1792.

Reed, R. J., 1979: Cyclogenesis in polar airstreams. *Mon. Wea. Rev.*, **107**, 38–52.

Sardie, J. M., and T. T. Warner, 1983: On the mechanism for the development of polar lows. *J. Atmos. Sci.*, **40**, 869–881.