Lake-Effect Snowfall over Lake Michigan

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ABSTRACT

Aircraft measurements of snow particle size spectra from 36 flights on 26 snowy days are used to estimate snow precipitation rates over Lake Michigan. Results show that average rates during 14 wind-parallel-type lake-effect storms increased from the upwind shore to about midlake and then were essentially uniform (1.5–2 mm day^{-1}, liquid water equivalent) to the downwind shore. Snow from midlake bands and shoreline bands maximized over the lake. The position of the maximum during these types of lake-effect storms depends on meteorological conditions. In any given case it may be near either shore or anywhere between them. This study combines 12 cases of midlake and shoreline bands. The resulting cross-lake snow profile shows a broad maximum reaching over 4 mm day^{-1} near midlake. The single sample maximum snow precipitation rate encountered in this study was 77.7 mm day^{-1}. The average cross-lake profile from combining 26 cases of lake-effect storms shows that snowfall into the lake is considerably greater than one would expect from a linear interpolation between values measured along either shore.

An attempt is made to estimate the average increase in snow over lake Michigan resulting from combined lake-effect and large-scale cyclonic storms. The result is interesting but not considered very reliable because it depends upon the relative frequencies of different types of lake-effect storms as well as overlake snow rates from large-scale cyclonic storms; neither is well known.

1. Introduction

The surfaces of the Great Lakes are data-void areas for weather observations during the winter months. During the summer, weather-reporting buoys and commercial ships provide considerable data for the open waters of the lakes. But in winter the buoys are picked up and commercial shipping is reduced substantially, resulting in a virtual absence of surface weather reports from over the lakes. This is especially serious for determination of winter precipitation amounts. As yet, satellite observations are of little value for this purpose. During winter, most of the precipitation in the upper Great Lakes region occurs as snow. The belts of enhanced snow along the downwind shores of the Great Lakes are easily observed and are well known. Much less is known about the amounts and distribution of snow over the lake surface where snow from midlatitude cyclonic storms is augmented by snow from lake-induced (also called lake-effect, LE) mesoscale systems. The frequency, location, and intensity of the LE mesoscale systems combine to determine the amounts and locations of LE snow over the lake.

This study is concerned with snowfall into Lake Michigan. In the northern, narrower end of Lake Michigan there are several islands on which precipitation gauges are located. Data from these have been used in conjunction with shore-based gauges to estimate annual and seasonal average snowfall for Lake Michigan (Changnon 1968; Bolsenga 1977). There are no islands in the southern two-thirds of Lake Michigan where it reaches a width of almost 130 km. This width and the consequent long fetches along wind directions common in cold-air outbreaks allow lake-induced mesoscale circulations to develop. Previous estimates of snowfall over the southern two-thirds of Lake Michigan have been based almost entirely on interpolations between amounts measured in near-shore regions on either side of the lake. Bolsenga (1979) called attention to the need for verification of these techniques and for "alternative methods for estimating overwater precipitation." Changnon (1968) concluded that winter season precipitation "exhibits a general increase across the lake with an abrupt increase in the last 10 miles" and that "lake-effect snows that develop over the lake Michigan occur as areas parallel (nearly north–south) and relatively close (1 to 20 miles) to the eastern shore."

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The University of Chicago Cloud Physics Group conducted coordinated aircraft and radar measurements of LE snowstorms over Lake Michigan during December 1980, January 1981, December 1983, and January 1984. These operations were based in Muskegon, Michigan (MKG) (Fig. 1). In a study of the water budget of lake-effect snow storms, a need arose for estimates of snowfall over the lake. Therefore we decided to examine the broader question of the amount and distribution of lake-effect snowfall over the southern basin of Lake Michigan, recognizing that the data were not obtained with this objective in mind. In this paper, aircraft measurements of snow particle size spectra are used to estimate snow precipitation rates, hereafter called snow flux (SF), thus providing the first quantitative estimates of snowfall over Lake Michigan to be based on overlake measurements.

2. Mesoscale organizations of lake-induced snowstorms

Several different patterns of mesoscale convection have been identified in LE storms over Lake Michigan. The most common are wind-parallel (WP) bands associated with horizontal roll convection. Typically, these occur when the cross-lake component of the gradient wind is stronger than about 10 m s^{-1} and lake-air temperature differences are greater than about 10°C. With bandwidths of 2–4 km and spacings of 8–20 km, WP convection results in widespread, low-intensity snow showers (usually less than 4 mm of precipitation per day). Wind-parallel bands are not always of equal size. Not infrequently a WP pattern blends into a cellular, or irregular, pattern. Observational studies of WP convection on Lake Michigan have been carried out by Holroyd (1971), Braham and Kelly (1982), Kelly (1984), Kristovich (1991, 1992), and others.

When the cross-lake component of the gradient winds is less than about 10 m s^{-1} and/or surface temperature differences are greater than about 10°C, the boundary layer over Lake Michigan begins to be noticeably affected by the cold land surfaces on either side. When the land–lake circulation becomes fully developed, a density current originates well inland over lower Michigan. It moves westward, or southwestward, across the shore as a land breeze and focuses convection into a band aligned roughly parallel to the long axis of the lake (Passarelli and Braham 1981; Schoenberger 1984, 1986; Hjelmfelt 1990). More commonly the low-level winds along the Michigan shore are reduced in speed but not completely reversed in direction, resulting in enhanced convection over the downwind half of the lake. Bands produced in this manner have been called midlake (ML) or shoreline (SL) bands depending on their position over the lake. Under certain conditions SL bands may form on both sides of the lake (Hjelmfelt 1990). Since there seems to be no fundamental difference between ML and SL bands, and because of the small sample available, here they are combined under the label of ML bands.

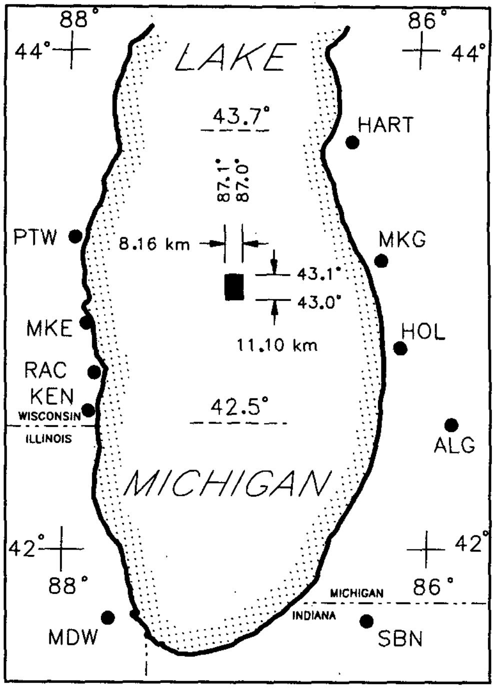

FIG. 1. The southern basin of Lake Michigan with important locations in Project Lake Snow and example of a cell used in analysis of snow flux. Michigan stations: Hart, Muskegon (MKG), Holland (HOL), and Allegan (ALG). Wisconsin stations: Port Washington (PTW), Kenosha (KEN), Milwaukee (MKE), and Racine (RAC). Midway Airport, Chicago (MDW), South Bend, Indiana (SBN).

Midlake bands are wider and more intense than the WP bands. Snow from them is deposited mainly over the lake and in the land area where they intersect the downwind shore. Midlake bands seem to account for most of the heavy LE snows around the southern end of Lake Michigan and on the downwind shores of Lakes Erie and Ontario. Satellite images show that ML and SL bands often have WP bands on their upwind side. Some ML bands exhibit a wavy structure along the bands. Studies of ML and SL snow bands have been carried out by Passarelli and Braham (1981), Braham and Kelly (1982), Braham (1983), Hjelmfelt and Braham (1983), Schoenberger (1984, 1986), Hjelmfelt (1990).

The wavy structure of some ML bands evolves into mesoscale vortices (Forbes and Merritt 1984; Schoenberger 1986). These structures seem to be favored by weak northerly or northwesterly winds and moderate to strong air–lake temperature differences. Snowfall from mesoscale vortices over Lake Michigan is almost entirely restricted to the lake surface.

The presence of the relatively warm lake surface undoubtedly enhances convection in large cyclonic systems. Data given by Kelly (1986) indicate the possibility for slight enhancement of cyclonic-system snow-

TABLE 1. Meteorological conditions on snow-sampling days.

		Temperature (°C), 1200 UTC					
			Surface				
Date	Mesoscale type	Lake (°C)	MKE	MKG	85 kPa (°C)	ΔT (°C)	Stability (K km^{-1})
3 Dec 80	ML	6.1	−10.0	−11.7	−7.5	16.1	11.9
11 Dec 80	WP	6.1	−13.3	−8.9	−13.0	19.4	10.1
13 Dec 80	ML	6.1	−5.0	−3.3	−9.0	11.1	6.7
7 Jan 81	WP	1.1	−16.1	−12.2	−20.0	17.2	6.6
10 Jan 81	WP	1.1	−18.3	−11.1	−17.7	19.4	10.5
11 Jan 81	ML	0.6	−17.2	−11.7	−22.0	17.8	6.1
16 Jan 81	ML	1.1	−6.1	−4.4	−14.0	7.2	3.4
17 Jan 81	WP	1.1	−15.0	−7.2	−8.0	16.1	15.6
1 Dec 83	WP	6.1	−10.0	−3.3	−8.0	16.1	11.8
7 Dec 83	WP	5.6	−11.7	−2.8	−11.0	17.2	10.6
16 Dec 83	ML	5.0	−10.0	−3.3	−17.0	15.0	4.0
17 Dec 83	WP	4.4	−14.4	−5.6	−16.0	18.9	8.8
18 Dec 83	WP	3.9	−21.7	−11.1	−18.0	25.6	13.0
19 Dec 83	ML	3.9	−26.1	−16.1	−21.0	30.0	14.1
20 Dec 83	ML	3.9	−16.1	−21.7	−18.0	20.0	8.5
29 Dec 83	WP	1.1	−19.2	−11.1	−23.0	20.3	6.7
30 Dec 83	WP	1.1	−19.4	−10.6	−13.0	20.6	15.2
7 Jan 84	ML	1.1	−5.6	−13.3	−6.4	6.7	9.2
10 Jan 84	ML	1.1	−10.6	−6.7	−17.0	11.7	4.8
14 Jan 84	ML	1.1	−7.2	−12.2	−14.1	8.3	4.7
15 Jan 84	ML	1.1	−12.2	−21.7	−14.4	13.3	8.3
17 Jan 84	WP	1.1	−13.3	−7.2	−15.4	14.4	8.3
18 Jan 84	ML	1.1	−17.8	−12.2	−19.5	18.9	8.6
20 Jan 84	WP	1.1	−22.8	−15.6	−27.0	23.9	6.5
21 Jan 84	WP	1.1	−26.7	−16.1	−20.0	27.8	15.6
27 Jan 84	WP	1.1	−4.4	−3.3	−7.9	5.6	7.2
Averages:		2.6	−14.2	−10.2	−15.3	16.9	9.10

fall along the east shore of Lake Michigan. Similar enhancement over the lake surface seems highly probable but has not been studied.

3. Statement of the problem

In its simplest terms, the problem addressed in this paper is the following: what was the amount and areal distribution of snowfall over Lake Michigan in the University of Chicago's observations? Can these data provide guidance for interpolating between measurements on opposite shores to estimate patterns of snowfall over the lower part of Lake Michigan? These questions are addressed by using aircraft measurements of snow particle size spectra to estimate snow precipitation rates. Several authors have estimated SF from particle size spectra (e.g., Heymsfield 1977; Houze et al. 1981; Super and Boe 1988; Holroyd 1987; Black 1990). Braham et al. (1991) showed that during LE conditions, values of SF estimated from Particle Measuring Systems (PMS) 200Y probes were within ±20% of values calculated from ground-based measurements of radar reflectivity. In this paper the same technique is applied to estimate SF over and near Lake Michigan during LE snowstorms.

4. Data and calculations

Thirty-six aircraft flights, from 26 days having LE snow storms over Lake Michigan, were used in this analysis. Of these, 14 were classified as WP and 12 were ML or SL. All LE flights that encountered measurable snow within 500 m of the surface (lake or land), and on which the measured air temperature was less than 0°C, were used in this analysis. For each of these flights, all time periods during which the planes were taking measurements at or below 500 m, *whether or not in snow,* were included. The restriction to data taken within 500 m of the surface allows the assumption that snow sampled by the airplanes reached the surface reasonably close to the point of measurement.

Meteorological conditions associated with the flight days are summarized in Table 1. Days were classified as to type of mesoscale organization on the basis of data available at the times of the flights. Lake temperatures were obtained from Coast Guard observations at MKG. Surface air temperatures at 1200 UTC are given for Milwaukee, Wisconsin (MKE), and MKG. The magnitudes of surface thermal forcing (ΔT) were measured by the aircraft on every flight. However, those measurements were at a variety of heights, locations, and times. To allow for a more uniform summary of flight days, values given in Table 1 are the differences

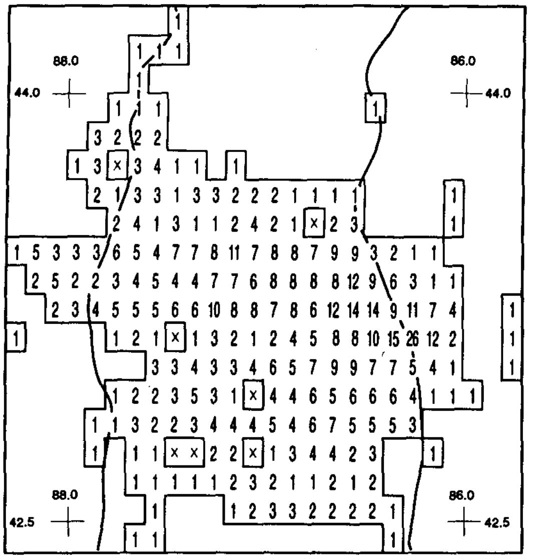

FIG. 2. Number of days contributing data to each analysis cell.

between the 1200 UTC air temperatures at MKE and the lake surface temperatures. Estimates of airmass stability upstream of the lake (K km^{-1}) were obtained using the lake temperature and the height and temperature of the 1200 UTC 85-kPa surface over MKE and the MKE surface temperature at 1200 UTC.

A typical flight profile consisted of horizontal passes that were wind-parallel and crossing major fractions of the lake, combined with short crosswind legs flown at several levels. A deliberate effort was made to obtain measurements well beyond the upwind edge of the lake-induced clouds. By special arrangement with the Federal Aviation Administration, flights usually were restricted to the area north of 42.5°N. In addition, there were clearance restrictions and flight delays, which reduced the amount of data obtained at low levels within 8 km of either shore.

Over 48.5 h of samples (about 13 100 km of aircraft track below 500 m) met the foregoing criteria and are included in this study. The daily average duration of aircraft sampling used in this study was 1.87 h; it ranged from 29 min to 4.9 h. These sampling periods were embedded within total flights that averaged 3.34 h per day and ranged from 0.8 to 5.9 h.

Snow particle size spectra were measured by PMS 200Y probes. The size calibration was based upon Knollenberg (1975, Fig. 17). The maximum particle size that could be determined by the PMS 200Y probes was 5.4-mm diameter. With the 200Y probe, sample volume varies with particle size and is allowed for in the data reduction. At our flight speeds of about 75 m s^{-1}, the sample volume for 1-mm particles was about 7.2 m^3 s^{-1} and for 3-mm particles about 4.8 m^3 s^{-1}. Other details of the 200Y calibration are given in Braham et al. (1991). Examples of lake-snow particle size spectra and PMS 2D-C images of typical particles are given in Braham (1990). Particle counts in each size interval were summed over each minute of flight, corresponding to about 4.5 km of flight path. Each of the resulting 2912 snow particle spectra were used to calculate values of snow flux.

Snow flux values from individual 1-min samples were grouped into 0.1° × 0.1° latitude–longitude cells. One of these cells is indicated as an example in Fig. 1. These cells are approximately 11.1 km × 8.2 km. Figure 2 gives the number of days that contributed data to each cell. Figure 3 gives the number of 1-min samples in each cell. Interior cells that were not sampled are marked by a cross. One should note that samples available for this study are concentrated in a band between about 42.7° and 43.5°N.

5. Calculation of snow flux values

Snow flux was calculated using

$$\mathrm{SF} = N(D)M(D)V(D), \qquad (1)$$

where N is the concentration of flakes of size D in a 1-min sample, M is their mass, and V is their fall speed. Particle masses were obtained from 200Y spectra using a relation derived from Knollenberg (1975):

$$M(D) = 0.0423D^{2.712}, \qquad (2)$$

where M is in milligrams and D is in millimeters. [For a general discussion of snow size–mass relations, see Braham et al. (1991).] For $V(D)$ the Locatelli and Hobbs (1974) relation for aggregates of unrimed radiating assemblages and dendrites was used:

$$V(D) = 115.6D^{0.16}, \qquad (3)$$

where D is in centimeters and V is in centimeters per second. In this study SF is expressed in units of mil-

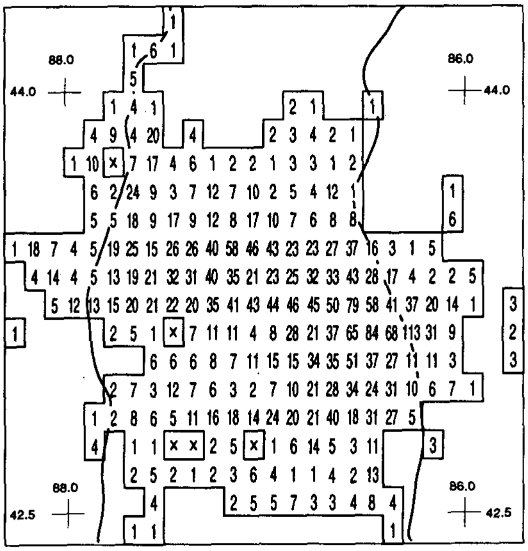

FIG. 3. Number of 1-min samples in each analysis cell.

limeters per day to facilitate comparison with land-based surface observations, many of which are available only for 24-h periods.

6. Results

Table 2 gives the number of samples, the average SF, and the predominant category of mesoscale organization for each of the 26 days that make up the total dataset. Also given for each day is the average 24-h snow precipitation at four climatological network stations on each side of the lake. Data from these stations are used in a later section for comparison with SF estimated from aircraft data. Stations used for this purpose were Port Washington, Kenosha, Milwaukee, and Racine, Wisconsin, and Hart, Muskegon, Holland, and Allegan, Michigan. Their locations are shown in Fig. 1.

The flights provide 2912 1-min samples of snow particle spectra. Of these, 2385 (82%) were obtained in snow and 527 (18%) were in snow-free regions. The overall sample average SF calculated from aircraft data was 1.93 mm day^{-1}. Within the mesoscale groups the overall average rates were 1.40 mm day^{-1} for WP, and 2.24 mm day^{-1} for ML cases. Average rates for individual days ranged from 0.002 to 5.52 mm day^{-1}.

For each of several categories of SF intensity and the corresponding values of effective radar reflectivity, Table 3 gives the number of observations and their contribution to total snowfall, as well as their cumulative contribution to the total number of observations and total snowfall. Not unexpectedly, lake-effect snowfall is dominated by a high frequency of low intensities that contribute a relatively small fraction of the total snowfall. For example, SF less than 2 mm

TABLE 2. Summary of numbers of observations and average snow flux values for each day grouped by category of mesoscale organization.

	Number of aircraft observations			Average snow flux		
Date	In snow	Not in snow	Total	Aircraft (mm day^{-1})	West shore (mm day^{-1})	East shore (mm day^{-1})
Wind parallel						
11 Dec 1980	30	10	40	0.29	0	0.19
7 Jan 1981	120	0	120	4.24	0.32	4.76
10 Jan 1981	76	1	77	1.38	0	1.84
17 Jan 1981	42	83	125	0.002	0	0.48
1 Dec 1983	55	0	55	0.95	0.25	0.60
7 Dec 1983	58	22	80	0.03	0.51	0.57
17 Dec 1983	186	0	186	2.94	0.06	1.30
18 Dec 1983	128	24	152	2.33	0.00	2.48
29 Dec 1983	89	0	89	2.38	0.19	2.48
30 Dec 1983	49	1	50	0.50	0	0.70
17 Jan 1984	105	53	158	0.15	0.06	2.29
20 Jan 1984	38	35	73	1.63	0.03	2.73
21 Jan 1984	29	0	29	3.01	0	3.24
27 Jan 1984	232	60	292	0.32	0.03	1.84
Totals	1237 (81%)	289	1526			
Mean daily average				1.44	0.10	1.82
Sample average				1.40	0.10	1.82
Midlake and shoreline						
3 Dec 1980	79	55	134	0.03	0.35	3.27
13 Dec 1980	46	0	46	0.73	0.03	0.03
11 Jan 1981	188	13	201	4.77	0	1.40
16 Jan 1981	132	10	142	5.52	0.44	4.19
16 Dec 1983	97	35	132	0.99	0.38	4.89
19 Dec 1983	177	2	179	3.17	0.86	1.49
20 Dec 1983	57	2	59	0.01	3.30	0.00
7 Jan 1984	74	81	155	0.15	0	0.06
10 Jan 1984	61	9	70	1.50	0.25	2.22
14 Jan 1984	114	25	139	1.65	5.18	0.95
15 Jan 1984	94	6	100	1.68	0.83	0.03
18 Jan 1984	29	0	29	3.06	0	0.89
Totals	1148 (83%)	238	1386			
Mean daily average				1.94	0.97	1.62
Sample average				2.23	0.97	1.62
Totals	2385 (82%)	527	2912			
Mean daily average				1.67	0.48	1.66
Sample average				1.93	0.50	1.73

day^{-1} ($Z_e < 2.1$ dBZ) accounted for about 74% of the observations but only about 13% of the total snowfall. Only about 1.5% of the samples gave rates in excess of 15 mm day^{-1}. The maximum SF rate encountered in this study was 77.7 mm day^{-1}.

Figure 4 gives a map of cell average SF based upon the total dataset (including samples with zero snow). The lake boundary is shown by the heavy line. The thin outer boundary delineates the area in which aircraft samples were obtained. Seven interior cells marked by crosses were not sampled. Cells that were sampled without encountering snow are marked by zeros. Snow flux rates are shown by the three patterns of diagonal lines. Areas within the outer (sampling) boundary that have no pattern of lines had average SF values less than 1.0 mm day^{-1}.

Because of the small number of samples and their uneven distribution across the lake, one must be very cautious in interpreting Fig. 4. Even so, it is interesting to note several features. Average SF values greater than 2 mm day^{-1} were found over a large fraction of the eastern half of the lake and offshore from Milwaukee. There is some evidence for a maximum inland along the eastern shore, suggesting the Michigan snowbelt. Areas with SF > 5 mm day^{-1} were scattered across the sampled area, with a preponderance in the eastern half of the lake. The areas of heaviest snow east and northeast of MKE seem to be separated from the general area of heavier snow over the eastern half of the lake. This may be due entirely to sampling; however, it bears little resemblance to the patterns of sample days or sample numbers, suggesting that the SF pattern was not due solely to sampling vagaries. This pattern may reflect a tendency for northeast–southwest-trending midlake bands to terminate near MKE in northerly wind situations.

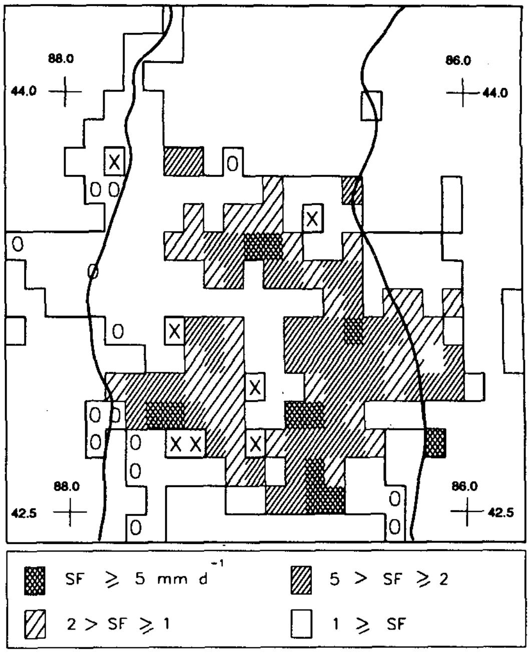

FIG. 4. Cell average snow flux based on total dataset.

Since the main objective of this paper is to examine possible west–east variations of snow over the lake, a more reliable way to view the data is in the form of longitudinal profiles. For this purpose, the data were grouped into 0.1° intervals of longitude. Values are given in Table 4.

7. Longitudinal profiles

a. Wind-parallel bands

Figure 5 gives the longitudinal profile of SF across the southern basin of Lake Michigan, averaged over

TABLE 3. Frequency of various categories of snow flux rates and their contributions to the total snow over Lake Michigan for combined midlake and wind-parallel cases.

Snow flux (mm day^{-1})		Effective reflectivity factor dBZ*	Category contributions		Cumulative contributions (%)	
From	To		Obs.	Snow	Obs.	Snow
<0.01	0.009	−49.7	987	1.2	33.9	0.0
0.01	0.99	−27.6	857	263.7	63.3	5.0
1.00	1.99	2.1	301	433.6	73.7	13.2
2.00	2.99	6.0	198	492.6	80.5	22.5
3.00	3.99	8.8	163	562.7	86.1	33.1
4.00	4.99	10.9	109	486.3	89.8	42.3
5.00	9.99	17.6	203	1337.7	96.8	67.5
10.00	14.99	21.5	50	604.5	98.5	78.9
15.00	19.99	24.2	22	393.2	99.2	86.3
20.00	29.99	28.1	12	279.0	99.7	91.6
30.00	49.99	33.0	8	301.2	99.9	97.3
50.00	77.99	37.3	2	143.5	100.0	100.0
Totals			2912	5299.2		

* Calculated using the Z–R relation for snow from Sekhon and Srivastava (1970); corresponds to the upper end of each snowflake category.

TABLE 4. Numbers of observations and average snowflux in various longitudinal intervals, grouped by type of mesoscale cloud organization. Here N is the number of days, and n is the number of samples in each longitudinal interval.

Longitude interval (°N)	WP			ML			Combined		
	N	n	Average (mm day^{-1})	N	n	Average (mm day^{-1})	N	n	Average (mm day^{-1})
85.7°-85.8°	0	0	—	1	8	0.252	1	8	0.252
85.8°-85.9°	0	0	—	0	0	—	0	0	—
85.9°-86.0°	0	0	—	1	1	0.508	1	1	0.508
86.0°-86.1°	2	7	2.429	4	32	1.188	6	39	1.411
86.1°-86.2°	7	28	3.042	7	36	1.596	14	64	2.229
86.2°-86.3°	14	90	1.380	12	82	1.084	26	172	1.239
86.3°-86.4°	12	91	1.322	10	100	1.474	22	191	1.402
86.4°-86.5°	12	144	1.626	11	108	2.216	23	252	1.878
86.5°-86.6°	12	152	2.495	12	141	4.100	24	293	3.268
86.6°-86.7°	12	139	2.041	12	88	2.978	24	227	2.404
86.7°-86.8°	11	116	1.658	11	70	3.678	22	186	2.418
86.8°-86.9°	10	85	1.825	10	72	2.963	20	157	2.347
86.9°-87.0°	10	73	2.118	11	82	4.066	21	155	3.149
87.0°-87.1°	8	70	1.071	10	87	3.432	18	157	2.380
87.1°-87.2°	10	87	1.549	10	89	1.975	20	176	1.764
87.2°-87.3°	9	77	2.188	10	84	1.250	19	161	1.699
87.3°-87.4°	8	52	0.932	10	48	1.301	18	100	1.109
87.4°-87.5°	8	54	0.471	10	49	2.081	18	103	1.237
87.5°-87.6°	8	76	0.019	9	54	1.309	17	130	0.555
87.6°-87.7°	7	86	0.002	9	65	0.859	16	151	0.371
87.7°-87.8°	7	41	0.001	8	29	0.356	15	70	0.148
87.8°-87.9°	6	26	0.001	4	22	0.027	10	48	0.013
87.9°-88.0°	4	9	0.001	3	12	0.017	7	21	0.010
88.0°-88.1°	4	9	0.001	3	17	0.004	7	26	0.003
88.1°-88.2°	3	12	0.001	2	10	0.00005	5	22	0.001
88.2°-88.3°	2	2	0.017	0	0	—	2	2	0.017
Totals		1526			1386			2912	

the 14 cases of WP bands. Across the top are given the numbers of days and samples contributing to each longitudinal interval. The solid bars along the horizontal axis show the range in longitude of the Wisconsin and Michigan shorelines within the latitudes included in our dataset. Figure 5 shows a systematic increase in average SF beginning about 25 km from the Wisconsin shore and increasing to a fairly uniform level over the downwind two-thirds of the lake where average values are between 2 and 3 mm day^{-1}. The slight maxima near 87.2°, 86.9°, and 86.5°W are likely due to sampling vagaries. The peak near 86.1°W may reflect the Michigan snowbelt, which is thought to reach its maximum slightly inland from the shore (Changnon 1968, Fig. 20).

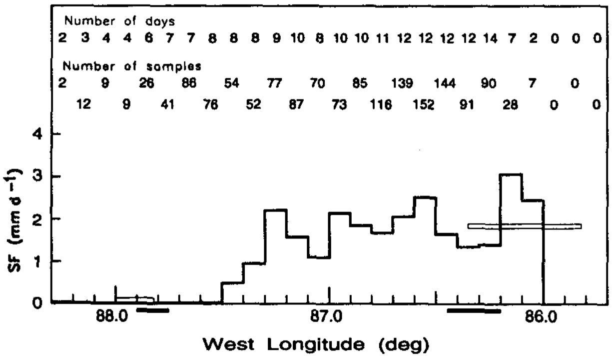

FIG. 5. Longitudinal profile of average snow precipitation rates, the southern basin of Lake Michigan, during 14 wind-parallel-type storms. Numbers of days and 1-min samples shown across the top. Wisconsin and Michigan shores shown by solid horizontal bars. Precipitation measured at nearshore land stations on the same days given by open horizontal bars.

Figure 5 also gives the average 24-h snow amounts measured on the same 14 days at four near-shore land-based stations on either side of the lake. This is shown by the open bars, the lateral extent of which indicates the ranges in longitude of these stations. As expected, snow over the western shore was essentially zero during the 14 WP days. If WP snow patterns over the lake advect across the downwind shore with little change, and if the 1.9-h average daily aircraft samples are representative of 24-h snow periods (a rather large assumption), then aircraft-measured SF over the downwind part of the lake would approximately equal 24-h snow measured at nearshore land stations. In the case of the 14-day averages (Fig. 5), the correspondence between aircraft and land-based measurements is surprisingly good. However, on individual days we find much less agreement in these two quantities.

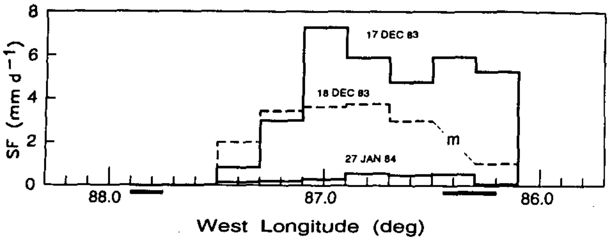

FIG. 6. Same as Fig. 5 except for three individual wind-parallel-type storms.

Longitudinal SF profiles for three individual WP days are shown in Fig. 6. These were selected because of their above-average number of samples and their wide range in SF intensities. We note that in all three cases snow begins about 0.3° (33 km) from the Wisconsin shore and builds up to approximately uniform amounts, the magnitude of which depends on the day. A similar profile for the case of 20 January 1984 can be seen in data presented by Chang and Braham (1991).

The general form for the average longitudinal profile for SF during WP situations is not particularly surprising. Over the southern basin, where fetches are adequate, horizontal-roll convection reaches a quasi-steady state after an initial "spinup" along the western shore. Thus, when SF is averaged across several rolls at similar fetch distances, one might expect a quasi-uniform result. However, on scales of about 10 km and less, order-of-magnitude variations in SF are found (Braham and Kelly 1982; Kristovich 1991, 1992).

The quasi-steady and widespread nature of WP band convection, plus the fact that WP storm intensities are determined by lake temperatures and regional meteorological conditions, suggests that Fig. 5 may be fairly representative of WP cases in general, even though it was obtained from only 14 cases.

b. *Midlake band cases*

Figure 7 gives the average cross-lake SF profile for the 12 days having ML convection. It shows a broad maximum covering the eastern half of the lake where average values exceeded 4 mm day^{-1}. The average land-station values along the Michigan shore are comparable to those measured by aircraft over and near the shore but well-below values measured over the lake. The average aircraft-measured SF along the western shore was substantially less than that measured at the nearby land stations. This may be due in part to undersampling because of flight clearance delays when bands were close to the Wisconsin shore, but it is more likely that one of the midlake bands sampled over the lake by the aircraft subsequently moved westward across the shoreline.

Although most of the snow from ML bands is deposited into the lake, on occasion these bands result in significant amounts of snow along the lake shores. Kelly (1986) found that most of the lake-effect snow along the Wisconsin shore resulted from midlake bands. Braham (1983) discusses a case in which a band along the Michigan shore moved inland, producing heavy snow at Muskegon, which then came to an end as the band reformed over the lake.

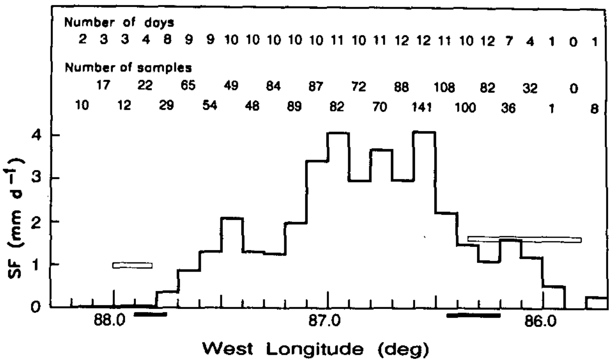

FIG. 7. Same as Fig. 5 except for 12 midlake band-type storms.

Figure 8 gives longitudinal SF profiles for three individual ML cases. These were selected to show the most intense band sampled (16 January 1981), a strong band along the Michigan shore (11 January 1981), and a case having weak bands along both shores (10 January 1984). In these and other cases not shown, the bands of heavy snow are sharply defined and about 15–30 km wide. Of the 11 ML bands that occurred on days having only a single major band, two were over the western half of the lake, one was very near to midlake, and nine were over the eastern half of the lake. This preponderance of ML bands over the eastern half of the lake reflects the frequent involvement of an eastern-shore land breeze in their formation.

c. *Total sample*

The average longitudinal (cross-lake) profile of SF for the 26 LE storms is given in Fig. 9. We note that the numbers of samples and sample days are fairly well distributed across most of the lake. As seen in this fig-

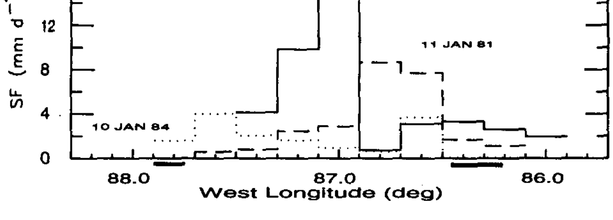

FIG. 8. Same as Fig. 5 except for three individual midlake band-type storms.

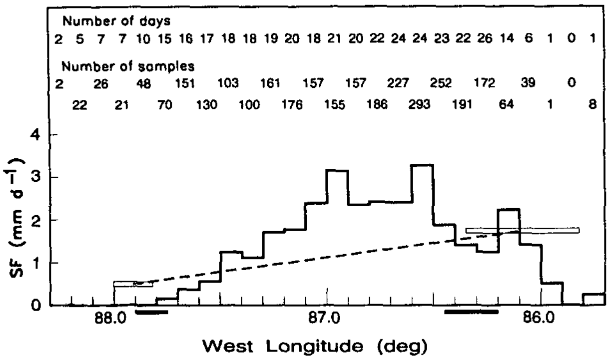

FIG. 9. Same as Fig. 5 except for all 26 lake-effect storms for which measurements were made in this study.

ure, the overall average LE snowfall increased in amount from west to east over the western half of the lake, remained high over the eastern half, and then decreased near the Michigan shore. Values deduced from aircraft data near the shore are in remarkable agreement with the average measured at the four land stations on the same 26 days. The average SF over the lake was 1.8 times that implied by a linear interpolation between values measured on opposite sides of the lake (dashed line in Fig. 9).

This result is strongly influenced by details of the ML sample which may or may not be representative of long-term averages for ML storms. However, there seems to be no question that LE snow maximizes over the lake.

8. Conclusions and discussion

This study is the first to report quantitative, in situ observations of the amounts and distribution of snow over the southern basin of Lake Michigan. Based on aircraft data from 26 days having LE snow storms, during four winter months (December 1980, January 1981, December 1983, and January 1984), it shows that snow over the southern basin of the lake was greater than that in the snowbelt along the Michigan shore and 1.8 times that which would have been estimated by interpolation between amounts measured at land stations on either side of the lake. This enhancement of overlake snow was most marked during midlake-type storms, which are characterized by strong snow bands over the lake and relatively less snow over the land (except where the bands make landfall, typically along the southern end of the lake). As far as we know there are no other overlake measurements for comparison.

One must be cautious in generalizing these findings to long-term LE snow conditions and to larger issues such as total winter precipitation over the lake.

The general applicability of these results depends on several factors. Temperatures and precipitation in the midwest during three of the four flight months were fairly normal; however, December 1983 was abnormally cold. One-third of the days in this study came from that month. Cold air temperatures enhance lake-induced convection (Hjelmfelt 1990; Braham and Dungey 1984). The calculation of SF from aircraft data, discussed earlier, is thought to be accurate within a factor of two, perhaps better. Even if errors arise from use of less than optimal size–mass and terminal-speed relations, there seems to be no reason why they would seriously depend upon position over the lake or on type of mesoscale organization; hence they should not alter the general shape of the SF profiles. Figure 5 is thought to be fairly representative of the average SF profile for WP storms for reasons previously discussed. Figure 7 may be a poor representation of ML storms; the sample of 12 ML storms is obviously too small in view of their variability in location and intensity. On the other hand, there is considerable evidence that these storms occur most frequently over the eastern half of the southern basin, supporting the conclusion that LE snow maximizes over the lake. Data presented here do not permit a discussion of the contribution of LE storms to snow along the shores of northern Indiana, southwestern Michigan, and northeastern Illinois.

The overall effect of LE storms on snow over the lake is strongly dependent on the frequency, location, and intensity of midlake band storms. If we knew the long-term relative frequency of WP and ML storm types, the profiles given in Figs. 5 and 7 could be appropriately weighted to give an estimate of long-term average LE snow over the southern basin of Lake Michigan. The only published study to systematically examine the relative frequency of LE storm types over Lake Michigan appears to be that of Kelly (1986). Using satellite images for the winters of 1978/79 and 1979/80 (November–March), he classified each of 176 days, when snow was reported at one or more 24-h observing stations around the southern half of the lake, as having LE or non-LE cloud patterns. A LE day was defined as one having a cloud-free zone along the upwind lake shore and separation of lake-induced clouds from clouds accompanying large-scale weather systems. Of 176 snowy days, 84 were classified as LE and 92 as non-LE. Each LE day was further classified as to type of mesoscale organization, that is, wind-parallel bands, midlake bands, shoreline bands, or an undetermined type including disorganized stratiform or cellular convection and days on which the mesoscale convection patterns were obscured by LE cloud cover, most probably WP days. Of the LE days, 43 were classified WP, 18 ML, 2 SL, and 21 were placed in the undetermined category.

The fact that Kelly found it impossible to classify almost 25% of the LE cases highlights the fact that a substantial fraction of LE storms over Lake Michigan does not fit neatly into either the WP or ML classification, instead having characteristics of both.

For purposes of this study, Kelly's frequencies for SL and ML days are combined and denoted ML. The resulting ratio of 43 WP to 20 ML is quite different from the 14 to 12 ratio obtained in the present study, thus indicating that Fig. 9 may exaggerate the relative amount of LE snow over the lake. A "worst case scenario" for estimating long-term cross-lake profiles of LE snow is obtained by combining Kelly's "undetermined" and WP cases since WP storms tend not to produce a maximum in SF over the lake. This would give 64 WP and 20 ML in the total of 84 LE storms. These relative frequencies are used to weight the cross-lake snow profiles to obtain Fig. 10.

This profile most likely underestimates the LE snow over the lake because it is highly likely that some of the Kelly's "undetermined" days contained ML bands. Since Fig. 10 gives a hypothetical SF profile, there are no land-based measurements for comparison. However, recalling the results of the previous comparisons between aircraft and land-based measurements, the average frequency-weighted SF over the shoreline intervals (86.0°–86.4°W and 87.7°–88.0°W) are used to estimate near-shore SF. The linear trend between these values, the dashed line in Fig. 10, indicates that even this worst case scenario predicts about 1.5 times as much snow over the lake as would be estimated from linear interpolation between shore-based measurements.

Extension of these results to total winter precipitation requires data on the cross-lake snow profiles for non-LE days, a subject that has attracted very little attention among researchers. The presence of mesoscale snow bands within large-scale cyclonic storms is well documented (e.g., see Houze and Hobbs 1982; Emanuel 1990; Kreitzburg 1991). Their locations and orientations usually are governed mainly by mid- and upper-tropospheric conditions. Therefore, one would expect wide variations in the cross-lake snow profiles among large-scale storms. But, given a sufficiently large sample, one might expect a relatively flat average snow profile, perhaps with a slight west–east increase since the main moisture sources in winter storms are south and east of the Great Lakes.

Estimates of the contribution of lake-effect storms to the total precipitation in the snowbelt of southwestern lower Michigan vary considerably, perhaps in part because of different time periods, analysis techniques, and reporting methods used by different authors. Changnon (1968) found that the December average snowfall, in the Michigan snowbelt, ranged up to 100% greater than that at locations of comparable latitudes in Wisconsin and Illinois. The comparative value for January–February was 33%. Dewey (1970) concluded that some areas in western lower Michigan receive about ". . . 200% more snow than stations at the same latitude in the interior of the state." Eichenlaub (1970) found that ". . . at least 30% of the seasonal snowfall in lee areas [from the lake] was derived from lake–atmospheric interactions." Gatz and Changnon (1976) give cross sections for annual average snowfall extending across Lake Michigan at three different latitudes. These suggest about 100% more snow along the Michigan shore than along the Wisconsin shore of Lake Michigan. Strommen (1974) compared annual average snow totals at locations in western lower Michigan with those at Minneapolis and St. Cloud, Minnesota. From these one would conclude an LE between 50% and 300% in western lower Michigan. Braham and Dungey (1984) found that the ratio of snowfall in the snowbelts of southwestern lower Michigan to that obtained by linear interpolation between values measured at interior stations at comparable latitudes ranged from 1.31 in the 1920s to 2.20 in the 1970s, with an average of 1.64 for the period 1910–80.

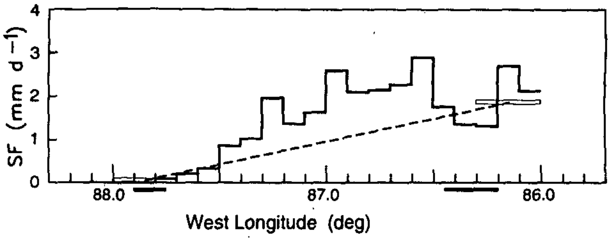

FIG. 10. Longitudinal profile of average snow precipitation over the southern basin of Lake Michigan obtained by combining cross-lake SF profiles, obtained in this study, with storm-type frequencies given by Kelly (1986) and other assumptions.

If we assume that one-half of the total winter precipitation in the snowbelt of southwestern lower Michigan is derived from LE storms, the estimates derived from Fig. 10 should be cut in half, resulting in an estimate that LE storms increase total snow over the southern basin of Lake Michigan by about 25%. This value is two to four times greater than had been obtained in evaluations based on data from the islands in the northern part of the lake (Changnon 1968; Bolsenga 1977).

Even though the sample in this study is smaller than one would like, it is a first step toward "alternative methods for estimating overwater precipitation . . ." as proposed by Bolsenga (1979). Additional studies will be required to check the representativeness of SF profiles and mesoscale frequencies found in this study and to extend the study to other winter months and other lakes in the Great Lakes chain. Perhaps the best way to do this would be through routine collection of data from one or more narrow-beam, low minimum-reflectivity-threshold radars located along the downwind shores of the lakes. How useful the NEXRAD radars will be for this purpose remains to be seen. However, because of the shallow depth, low average reflectivity, and wide horizontal extent of LE storms, land-based radars may not be entirely adequate. It may be necessary to supplement them with instrumented airplanes capable of measurements over major fractions of the lake area.

It also is important to establish the effect of the lakes on the amounts of snow deposited by large-scale cyclonic storms. The question remains: is it not reasonable to expect that a large, relatively warm lake would induce or modify mesoscale systems embedded in wintertime cyclonic storms, and thereby effect surface precipitation? If so, what would be the duration and subsequent evolution of such systems?

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