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# Snowfall From Lake-Effect Storms

**JAMES E. JIUSTO and MICHAEL L. KAPLAN**—*State University of New York, Albany, N.Y.*

**ABSTRACT**—Three yr of winter lake-storm data were analyzed to determine snowfall distribution patterns downwind of Lake Erie and Lake Ontario. The total amount of snowfall and the area of ground cover in each of 23 lake-effect storms were determined for both lakes. Total snowfall mass was highly dependent on time of year; November and early December storms were two to five times more productive than January storms. A considerable variation in snow density (snowfall depth to melt water ratio) could be attributed mainly to differences in snow crystal type.

## 1. INTRODUCTION

Great Lakes snowstorms can be as intense as those found almost anywhere in this country, on occasion depositing as much as 2–3 ft of snow in a single day. Their discrete lateral boundaries and relatively shallow vertical dimensions indicate a high degree of mesoscale organization. It is known that pronounced lake-effect snowfalls can occur with outbreaks of arctic air during early winter.[1] Such an occurrence, as suggested by Sheridan (1941) and Wiggin (1950), leads to large air-water temperature differences which, when combined with long lake fetch, can produce locally heavy snow to the lee of such lakes as Erie and Ontario. McVehil and Peace (1966) have amplified on the criteria for single and multiple snowbands, and Lavoie (1968) used a numerical model to simulate their formulation. The most intense snow situations are spawned when a secondary trough forms and couples with the lake-induced vertical fluxes of momentum, heat, and water vapor (Paine and Jiusto 1970).

A climatological study was undertaken to better define the snowfall patterns associated with these bands and to attempt to correlate snowfall depth and density with relevant variables. The former information is particularly useful in the evaluation of numerical models, weather modification potential, and water budget studies of the particular lakes—activities that currently are being pursued by several agencies.

## 2. METHODS

A total of 75 stations (primarily class C Cooperative, National Weather Service) provided daily data for the Lake Erie and Lake Ontario snow analysis: 42 stations in New York State, 17 in Pennsylvania, and 16 in Ohio. Eleven well-defined storm periods from November 1966 to January 1968 were initially selected for study (dates shown in table 4); thereafter, 12 additional storms of generally lesser severity occurring during the 1968–69 winter season were incorporated into the study.

In brief, the research effort involved four phases: (1) the areal plotting of storm-period snowfall depth and of meltwater depths, (2) the calculation and plotting of storm period snowfall-to-meltwater ratios and an estimation of dominant snow crystal types based on these ratios, (3) a statistical analysis designed to examine certain possible snowfall correlations, and (4) the integration of the snowfall patterns to yield total storm water and areal coverage.

We found that the original 11 storms studied could be partitioned into three categories depending upon storm intensity (total snowfall), areal extent of heavy snow, and wind direction. The categories were defined as follows:

Intense storms—SW to W air flow, heavy snowfall exceeding 20 in. in spots, and concentrated snowfall area.

Moderate storms—SW to W winds, snowfall less than 20 in. and more widespread.

NW storms—Snowfall less than 15 in. and widespread.

## 3. SNOWFALL DISTRIBUTIONS

The intense storm situations of Dec. 2, 1966, Nov. 4–7, 1967, and Nov. 27–29, 1967, all exhibited highly localized snowfall patterns and west to southwest winds at 5,000 ft. In all three cases (one of which is shown in fig. 1), elongated areas of heavy snowfall lay nearly parallel to the 5,000-ft wind flow with snowfall maxima oriented along east–west lines to the lee of the lakes. All three situations showed a rapid decrease of snowfall with lateral distance from the aforementioned concentrated axes in a fashion which would suggest a high degree of storm organization and a relatively stationary convergence line.

On four occasions (NW storms), the winds between 5,000 and 10,000 ft were from a direction of 300° or more northerly. Figure 2 shows one case. The reasons for the NW flow cases producing less snowfall over broader areas appear to be threefold: a shorter trajectory of the air mass over the lakes, colder lake temperatures tending to reduce the available energy and moisture, and weaker patterns of positive vorticity advection.

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[1] Lake-effect storms are herein defined as mesoscale systems, not directly associated with a primary Low or front, that develop largely because of the influence of water bodies on an over-riding airmass. Snowfall customarily exceeds 4 in.

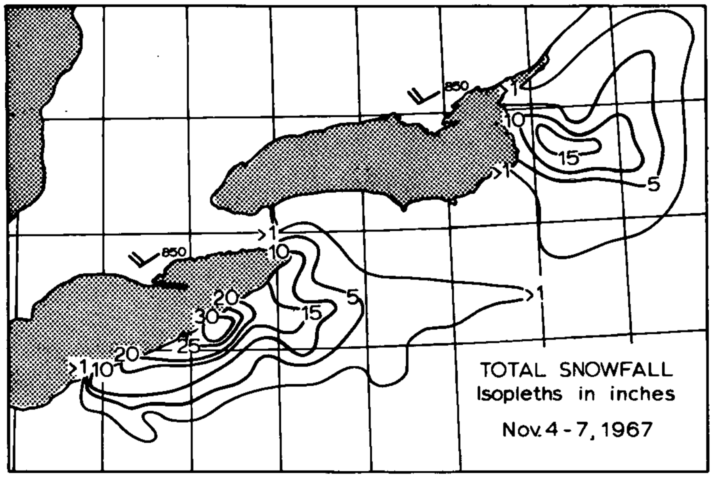

FIGURE 1.—Intense storm having west to southwest 850-mb flow.

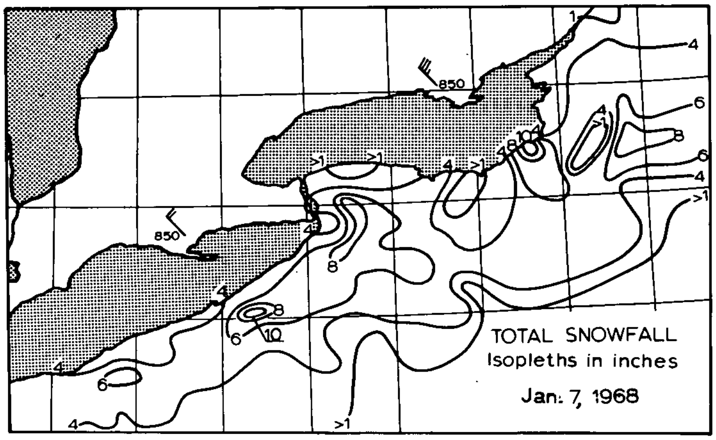

FIGURE 2.—Weak storm having northwesterly 850-mb flow.

The four remaining (moderate) storms; that is, Nov. 4–6, 1966, Dec. 29–30, 1966, Nov. 14–15, 1967, and Jan. 4–5, 1968, all exhibited rather strong west-southwest winds (30–40 mi/hr) at 5,000 ft and very broad snowfall distributions (see fig. 3). The more extensive but lesser snowfall accumulations in the intense storms presumably were associated with decreased convective organization and greater meandering of the convergence line, as well as stronger advecting winds.

A statistical study was made of the relationship between snowfall and inland distance, snowfall-meltwater ratios and inland distance, and snowfall and elevation. The method of analysis consisted of computing 33 linear correlation coefficients for the preceding three sets of variables for each of the 11 pronounced storms mentioned.

The overall correlation coefficients between examined variables are summarized in table 1. Little correlation exists between snowfall depth and inland distance or station elevation. The latter, however, is relevant in that it suggests a secondary role for orography in lake-storm snowfall, an inference also indicated in the Lavoie (1968) numerical model. The higher (but not overwhelming) positive correlation between snowfall-meltwater ratios and inland distance, reflects a frequently observed transition from dense coastal snow to lighter inland snowflakes (discussed in the next section). This partitioning of snow type is due to the increased fall velocity of rimed crystals and graupel relative to the less dense snowflakes and dendritic crystals (Jiusto 1968).

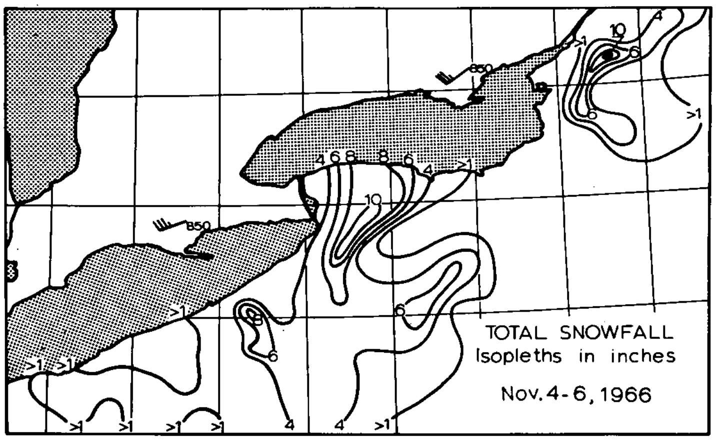

FIGURE 3.—Moderate storm having southwesterly 850-mb flow.

TABLE 1.—*Correlation statistics for 11 pronounced storms of table 4*

| Variables | Correlation r* | Data points |
|---|---|---|
| Snowfall depth vs. inland distance | −0. 23 | 691 |
| Snowfall depth vs. station elevation | −0. 15 | 693 |
| Snowfall-meltwater ratio vs. inland distance | 0. 42 | 550 |

*All r values significant at the 99-percent level as determined by F-value significance test

## 4. RATIOS OF SNOW DEPTH TO MELTWATER EQUIVALENT, *R*

It has become customary to assume that 10 in. of snow will, in general, melt down to about 1 in. of water. This ratio can vary, however, from values less than 2 to well over 100. We felt that some analysis of this variance was in order, and that a physical explanatory model might be useful in describing snow crystal character based on standard measurements of snow depth and meltwater equivalent.

Clearly, crystal type must be a major influence on the snow-to-water depth ratio, which we will refer to as $R$. Very wet snow or compact individual crystals might be expected to produce the lowest $R$ values, and snowflakes of light spatial aggregates, the highest. Other factors influence the ratio as well, such as:

1. Partial melting of snow in air or on the ground,
2. Wind action—(a) crystal breaking and packing and (b) turbulent fluffing of crystals, and
3. Normal gravitational stacking of crystals and snowflakes.

Melting, which tends to decrease $R$, should be relatively insignificant, at least in the classically cold lake storms.

TABLE 2.—*Snow crystal densities*

| | $\rho$ | $1/\rho$ |
|---|---|---|
| Plane dendrites | 0. 484 | 2. 1 |
| Stellars-solid | (0. 726)* | 1. 4 |
| Hexagonal plates | 0. 968 | 1. 1 |
| Columns | (0. 90)* | 1. 1 |
| Needles | 0. 230 | 4. 3 |
| Rimed crystals | 0. 172 | 5. 8 |
| Graupel | 0. 125 | 8. 0 |
| Snowflakes (compact) | 0. 050 | 20 |
| Snowflakes (dendritic) | 0. 010 | 100 |
| Spatial dendrites | 0. 00954–0. 00381 | 105–260 |

*Parentheses indicate interpolated values.

TABLE 3.—*Snow depth to meltwater ratio R versus crystal type*

| Class | Crystal type | *R* |
|---|---|---|
| I | Individual solid crystals | ≤5 |
| II | Rimed forms | 6–15 |
| III | Snowflakes | 16–50+ |
| IV | Spatial dendrites | >50 |

Wind action involving crystal fragmentation would tend to decrease *R*, but turbulent disruption of fallen crystals should generally increase *R* so that these air motion effects are partially self-compensating. Snow stacking can act in either direction, depending on whether the crystals are compact or dendritic in nature. Thus, *R* data obtained within 24 hr of a Great Lakes snowstorm conceivably could shed information on crystal composition, the presumably dominant variable.

With the aid of crystal size and mass relationships (Nakaya 1954), the densities of 10 basic crystal and snowflake forms were computed (Jiusto et al. 1970) and the results summarized in table 2. The inverse density values represent simple snow depth to meltwater ratios, exclusive of the ground packing factors mentioned.

The effect of crystal stacking of fallen snow would generally be to increase the inverse density values of compact individual crystals and rimed forms while a decrease would be likely for intertwining spatial dendrites and dendritic snowflakes. Applying such physical arguments, the above data were adjusted and classified into the four tentative *R* categories of table 3.

In nature, an endless variety of crystal forms exists that cannot be represented completely with 10 somewhat idealized types. However, the rather extensive spread of computed *R* values was encouraging in terms of developing characteristic categories for different types of snow. Further, the interpretive trend of the values seems unquestionably valid—namely, low ratios of snow depth to meltwater equivalent for individual compact crystals, very large values for fluffy snowflakes and spatial dendrites, with rimed forms lying somewhere between. This analytical observation, in itself, helps to clarify some of the diverse field measurements of *R*.

The subsequent mapping of snow crystal type in 23 storms, using the criteria of table 3, indicated that rimed snow crystals occurred close to Lakes Erie and Ontario while snowflakes became dominant further inland. Also, values of *R* corresponding to graupel and rimed crystals were more common early in the winter season and when 850-mb temperatures were relatively warm. Although these trends are consistent with actual field observations in the vicinity of the two lakes, more data are needed to determine the validity of inferring general snow crystal type from snow density data.

## 5. TOTAL PRECIPITATION OVER LAND FROM LAKE STORMS

A comparison was made of the total precipitation and snowfall area associated with storms of Lake Erie and of Lake Ontario. Table 4 presents the results obtained for the 11 well-defined storms previously described—the intense (I) and moderate (M) SW flow cases and NW flow cases. A number of useful observations can be made:

1. The total mass of snowfall over land for both lakes combined averages approximately 0.9–1.6 × $10^{12}$ kg per storm type. The higher values were associated with storms possessing SW–W winds (long lake-axis fetch), while the 50-percent lower values were associated with NW flow situations.
2. The total area of land snowfall was a more conservative property of the three storm types, being least in the highly organized intense bands (170,718 $km^2$), slightly more in the moderate cases (176,640 $km^2$), and some 14 percent greater in the NW flow cases (194,090 $km^2$).
3. Comparing the influence of each lake, it is apparent that the average snowfall figures are quite similar, while Lake Erie storms cover a somewhat greater land area.

In table 5, similar data are presented for virtually all lake-effect storms that occurred within the three winter seasons, 1966–69. Thus, in addition to the 11 "classic" cases, a number of weaker storms of both the SW and NW flow types are listed.

We see that the overall snowfall mass and area per storm averaged approximately $0.9 \times 10^{12}$ kg and 141,000 $km^2$, respectively. The snowfall contributions of each lake were almost identical (about $0.45 \times 10^{12}$ kg) while the greater area coverage of Lake Erie storms was quite pronounced (30 percent more). The latter indicates that Lake Ontario storm clouds have their precipitation more efficiently removed than do Lake Erie cloud bands. A likely explanation is a more presistent wind direction (west), matching the long axis of Lake Ontario, coupled with a more pronounced orographic effect just to the lee of this lake.

Values of total water output per storm for both lakes were plotted as a function of time of year, as shown in figure 4. Clearly, November and early December storms were two to five times more productive than January storms. The trend of the data is distinct, with the resultant curve resembling a plot of either seasonal lake temperature (or corresponding saturation vapor pressure) or air-water

TABLE 4.—*Total mass and area of snowfall in classic lake storms*

| Storm | | Lake Erie | | Lake Ontario | | Total—two lakes | |
|---|---|---|---|---|---|---|---|
| | | Precip. | Area | Precip. | Area | Precip. | Area |
| | | ($10^{12}$ kg) | (km$^2$) | ($10^{12}$ kg) | (km$^2$) | ($10^{12}$ kg) | (km$^2$) |
| I | Dec. 2, 1966 | 0. 531 | 79, 985 | 0. 358 | 85, 885 | 0. 889 | 165, 870 |
| I | Nov. 4, 1967 | 1. 238 | 59, 543 | 1. 070 | 55, 050 | 2. 308 | 114, 593 |
| I | Nov. 27, 1967 | 0. 531 | 149, 132 | 0. 540 | 82, 558 | 1. 071 | 231, 690 |
| | Average | | | | | 1. 42 | 170, 718 |
| M | Nov. 4, 1966 | 1. 034 | 93, 945 | 0. 721 | 32, 241 | 1. 755 | 126, 186 |
| M | Dec. 29, 1966 | 0. 721 | 102, 622 | 1. 424 | 100, 462 | 2. 145 | 203, 084 |
| M | Nov. 14, 1967 | 0. 925 | 107, 218 | 0. 608 | 99, 227 | 1. 533 | 206, 445 |
| M | Jan. 4, 1968 | 0. 172 | 81, 769 | 0. 549 | 89, 075 | 0. 721 | 170, 844 |
| | Average | | | | | 1. 538 | 176, 640 |
| NW | Jan. 10, 1967 | 0. 159 | 94, 425 | 0. 240 | 90, 378 | 0. 399 | 184, 803 |
| NW | Jan. 16, 1967 | 0. 231 | 92, 710 | 0. 267 | 76, 658 | 0. 498 | 169, 368 |
| NW | Nov. 18, 1967 | 1. 610 | 106, 361 | 0. 472 | 94, 734 | 2. 082 | 201, 095 |
| NW | Jan. 7, 1968 | 0. 476 | 118, 915 | 0. 372 | 102, 177 | 0. 848 | 221, 092 |
| | Average | | | | | 0. 957 | 194, 090 |
| | Over all averages | 0. 694 | 98, 781 | 0. 603 | 82, 586 | 1. 295 | 181, 370 |
| | Standard deviations ($\sigma$) | 0. 445 | 21, 951 | 0. 340 | 21, 265 | 0. 288 | 36, 699 |

Table 5.—*Total mass and area of snowfall in "all" lake storms (three winter seasons—1966–69)*

| Date | Lake Erie | | Lake Ontario | | Both lakes | |
|---|---|---|---|---|---|---|
| | Precip. | Area | Precip. | Area | Precip. | Area |
| | ($10^{12}$ kg) | (km$^2$) | ($10^{12}$ kg) | (km$^2$) | ($10^{12}$ kg) | (km$^2$) |
| Nov. 4, 1966 | 1. 036 | 93, 945 | 0. 721 | 32, 241 | 1. 757 | 126, 186 |
| Dec. 2, 1966 | 0. 529 | 79, 985 | 0. 358 | 85, 885 | 0. 887 | 165, 870 |
| Dec. 29, 1966 | 0. 721 | 102, 623 | 1. 426 | 100, 428 | 2. 147 | 203, 051 |
| Jan. 10, 1967 | 0. 160 | 94, 391 | 0. 240 | 90, 378 | 0. 400 | 184, 769 |
| Jan. 16, 1967 | 0. 234 | 92, 676 | 0. 269 | 76, 658 | 0. 503 | 169, 334 |
| Nov. 4, 1967 | 1. 240 | 59, 509 | 1. 068 | 55, 016 | 2. 308 | 114, 525 |
| Nov. 14, 1967 | 0. 924 | 107, 184 | 0. 608 | 99, 193 | 1. 532 | 206, 377 |
| Nov. 18, 1967 | 1. 611 | 106, 327 | 0. 471 | 94, 700 | 2. 082 | 201, 027 |
| Nov. 27, 1967 | 0. 533 | 149, 132 | 0. 542 | 82, 523 | 1. 075 | 231, 655 |
| Jan. 4, 1968 | 0. 171 | 81, 769 | 0. 547 | 89, 040 | 0. 718 | 170, 809 |
| Jan. 7, 1968 | 0. 475 | 118, 880 | 0. 372 | 102, 143 | 0. 847 | 221, 023 |
| Nov. 11, 1968 | 0. 046 | 58, 274 | 0. 053 | 11, 559 | 0. 099 | 69, 833 |
| Nov. 19, 1968 | 0. 537 | 68, 598 | 0. 839 | 22, 775 | 1. 376 | 91, 373 |
| Dec. 3, 1968 | 0. 162 | 95, 317 | 0. 152 | 73, 469 | 0. 314 | 168, 786 |
| Dec. 5, 1968 | 0. 503 | 61, 052 | 0. 834 | 58, 514 | 1. 337 | 119, 566 |
| Dec. 6, 1968 | 0. 378 | 53, 849 | 0. 487 | 39, 375 | 0. 865 | 93, 224 |
| Dec. 7, 1968 | 0. 149 | 59, 989 | 0. 191 | 7, 374 | 0. 340 | 67, 363 |
| Dec. 14, 1968 | 0. 033 | 111, 232 | 0. 057 | 69, 901 | 0. 090 | 181, 133 |
| Dec. 24, 1968 | 0. 293 | 18, 453 | 0. 234 | 18, 762 | 0. 527 | 37, 215 |
| Jan. 1, 1969 | 0. 109 | 54, 398 | 0. 159 | 42, 771 | 0. 268 | 97, 169 |
| Jan. 2, 1969 | 0. 205 | 83, 175 | 0. 111 | 26, 445 | 0. 316 | 109, 620 |
| Jan. 10, 1969 | 0. 141 | 80, 054 | 0. 193 | 24, 112 | 0. 334 | 104, 166 |
| Jan. 25, 1969 | 0. 196 | 54, 947 | 0. 198 | 59, 509 | 0. 394 | 114, 456 |
| Average | 0. 451 | 81, 975 | 0. 440 | 59, 234 | 0. 892 | 141, 243 |
| Standard deviations ($\sigma$) | 0. 403 | 28, 743 | 0. 345 | 30, 629 | 0. 653 | 57, 931 |

temperature difference. Thus, this snowfall figure also illustrates the role of the lakes in generating moisture and thermal energy to sustain lake-effect snowstorms.

## 6. SUMMARY

A climatological study of 3 yr of lake-storm precipitation data confirmed previous indications that snowfall distributions in the vicinity of Lake Erie and Lake Ontario are dependent on air trajectory, with the greatest snowfall amounts being associated with southwest to westerly winds and a single intense snow band. Each of these intense storms generates an average of approximately $1.4 \times 10^{12}$ kg of water and covers a corresponding land snowfall area of approximately 170,000 km$^2$ (both lake regions combined). Storms associated with northwesterly

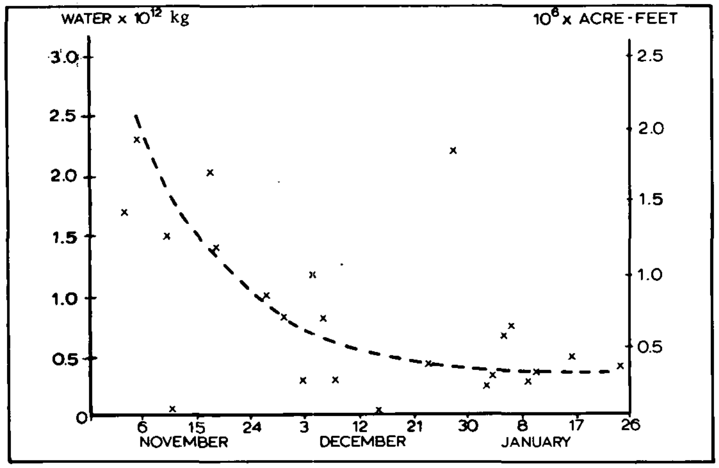

FIGURE 4.—Total lake-storm (Erie and Ontario) snowfall versus time of occurrence during three winter seasons (1966–69).

winds, consisting of multiple bands of less intensity, produce some 50 percent less total precipitation on the average, with the snowfall spread over a somewhat greater area. Orographic effects, while a factor in snowfall accumulation, generally appear less important than lake-induced and synoptic scale influences. Snowfall density (snow depth to meltwater ratio) is highly variable but seemingly consistent with the inland and seasonal variations in snow crystal types.

Water budget analyses show a strong correlation between amount of snowfall and time of year, with January lake-effect storms yielding two to five times less snow than early season storms. A steady decline in lake temperature and in air-water temperature difference are largely responsible and obviously result in reduced vertical fluxes of momentum, heat, and moisture over the water.

## ACKNOWLEDGMENTS

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