Lake-Land Precipitation Relationships Using Northern Lake Michigan Data

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ABSTRACT

Data from a network of recording precipitation gages, operated over a 5-year period on islands in Lake Michigan, provides the basis for the first monthly analysis of the relationship of lake to land precipitation conducted on the Great Lakes. Wide monthly fluctuations in lake to land relationships, previously masked by seasonal analysis using storage gages, are shown. An examination of the significance of the findings indicates that all but the largest differences are not statistically significant and that even the largest lake-land differences could possibly be attributed to gage errors.

1. Introduction

The relationship of lake to land precipitation has received much attention over the last several years. A survey of many studies (Phillips and McCulloch, 1972) reveals both conflicting and corroborative evidence on the variation of lake to land precipitation. The association of lake to land precipitation is critical in computation of the over lake precipitation which affects the basin water balance and therefore items such as computed lake water levels. Small errors in extrapolating overwater precipitation from overland data can result in serious errors in estimating total water volume collected in a large lake, thereby adversely affecting certain types of hydrologic models. On the other hand, inherent errors in the catch of standard precipitation gages are serious enough to sometimes overshadow the smaller lake-land differences which occur.

Definition of lake versus land precipitation in the Great Lakes requires placement of gages on only a small number of island groups or on man-made platforms such as towers or water intake cribs. The majority of previous work has used data from an island group in northeastern Lake Michigan. These investigators used data from only one regular gage at Beaver Island (Horton and Grunsky, 1927) and from storage gages (Changnon, 1967, 1968; Changnon and Jones, 1972; Blust and DeCooke, 1960; Hunt, 1959). The desirability of overwater data from recording gages was apparent from the previous analyses.

This report uses data from five recording gages, installed at the same sites used for the previous studies. The resulting island data set is the longest and most complete collected to date in the Great Lakes. After extensive analysis, it became increasingly apparent that, although additional detail was revealed by the Lake Michigan recording gages, many of the observed differences in lake versus land precipitation were not statistically significant nor were they greater than the gage errors which have been observed by other investigators.

The first portion of this paper analyzes the recording gage data, shows favorable comparisons to previous work and indicates apparent new detail in lake-to-land precipitation relationships. The second portion examines the significance of the analysis and indicates that problems due to instrumentation and exposure introduce errors that are in most cases larger than the differences noted in the first portion of the report.

2. Data collection

A network of recording precipitation gages was installed on the only island group in Lake Michigan (Fig. 1) located in the northeast portion of the lake. Data collection began in October 1963 and ended in October 1968. All but one of the island stations (St. James) were specifically established for this study. The St. James gage is a regular National Weather Service station with a long-term record. The islands vary in size from Ile aux Galets which is small (1–2 acres) in area, low and rocky, to Beaver Island which is about 70 mi² in area with abundant trees and vegetation.

Each island precipitation gage, except St. James, was equipped with a Fischer and Porter recording unit with output generated each hour on punched paper tape. The tapes were subsequently processed and the data transferred to punched cards for computer analysis. Gages were periodically checked and serviced by National Weather Service personnel. When missing data occurred during a month, that total was not included in any computations. All island gages, except

TABLE 1. Monthly precipitation (inches) for island stations.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
South Manitou	1968	1.16	1.29	0.54	3.38	2.32	5.02	1.33	0.98	3.03	—	—	—
	1967	1.55	1.37	1.53	3.31	2.07	4.00	1.07	3.28	1.40	3.22	2.61	1.69
	1966	1.68	2.65	3.97	1.69	1.09	0.67	1.67	1.70	3.03	1.52	4.55	1.46
	1965	1.70	1.44	1.21	3.70	2.10	2.37	3.25	1.96	8.24	1.29	2.32	2.24
	1964	1.64	0.64	2.75	2.86	2.86	0.81	2.11	1.80	3.78	1.09	2.42	1.05
	1963	—	—	—	—	—	—	—	—	—	—	—	0.97
S. Fox	1968	1.00	1.50	0.70	3.70	2.70	3.90	3.30	4.70	3.90	—	—	—
	1967	1.80	1.70	1.80	3.90	2.60	3.60	0.80	4.00	1.50	—	—	—
	1966	1.30	1.90	3.90	1.30	1.10	1.60	2.10	2.00	2.20	1.80	5.40	1.80
	1965	1.50	1.00	0.90	3.60	3.40	1.10	1.60	1.10	10.10	0.90	3.70	2.10
	1964	1.50	0.40	2.40	3.00	2.30	0.70	1.80	1.80	4.00	0.50	2.60	1.10
	1963	—	—	—	—	—	—	—	—	—	—	2.80	1.20
North Manitou	1968	1.30	1.30	0.50	3.40	2.30	4.50	2.70	1.10	3.70	—	—	—
	1967	3.10	2.20	1.60	3.50	2.20	3.60	1.30	4.00	1.70	—	—	—
	1966	4.60	2.60	4.20	2.20	1.20	0.40	1.40	1.60	2.20	2.70	5.00	2.40
	1965	—	—	—	—	3.00	1.40	2.80	2.30	10.40	1.30	3.80	2.80
	1964	2.00	0.50	3.10	3.80	3.20	—	—	—	—	—	3.00	1.40
	1963	—	—	—	—	—	—	—	—	—	—	3.80	2.00
Ile aux Galets	1968	—	—	—	—	—	—	—	—	—	—	—	—
	1967	1.80	1.30	1.00	2.90	1.60	3.10	0.90	3.00	1.40	—	—	—
	1966	2.80	3.30	—	—	—	—	—	—	—	—	4.30	1.40
	1965	—	1.50	0.90	3.90	4.00	3.40	—	0.80	8.50	—	2.90	1.90
	1964	1.30	0.50	1.70	3.10	4.60	1.70	2.60	2.50	3.60	0.90	—	—
	1963	—	—	—	—	—	—	—	—	—	—	2.40	0.90
St. James (NWS)	1968	1.07	1.81	0.62	4.29	3.98	3.92	2.83	8.10	4.42	—	—	—
	1967	2.06	0.93	1.37	2.52	2.50	3.27	0.87	2.83	2.04	2.92	2.68	1.89
	1966	0.98	1.19	3.00	1.51	1.51	1.85	1.59	2.21	2.27	2.49	5.88	1.53
	1965	—	1.50	0.80	2.27	5.51	2.14	2.01	1.31	9.38	2.17	4.23	1.35
	1964	1.77	0.12	1.29	3.06	5.91	1.14	3.02	3.44	5.55	1.19	2.46	2.62
	1963	—	—	—	—	—	—	—	—	—	—	3.61	—
Beaver (GLERL)	1968	1.50	2.30	0.80	4.10	4.20	4.40	—	—	—	—	—	—
	1967	3.10	2.00	2.20	—	—	—	—	—	—	—	—	—
	1966	1.80	—	4.60	1.80	1.00	1.30	1.60	1.80	2.60	2.70	6.50	2.80
	1965	—	—	—	—	3.20	1.80	—	0.60	8.60	—	3.90	2.50
	1964	2.40	0.80	3.20	3.90	3.20	2.30	2.50	3.30	3.70	1.20	3.00	3.00
	1963	—	—	—	—	—	—	—	—	—	—	4.10	2.80

St. James, were equipped with Alter wind shields and mounted on 5 ft steel towers.

Land station data were from the existing National Weather Service stations at Sturgeon Bay and Washington Island, Wis.; and Manistique, Port Inland, Brevort, Mackinaw City, Cross Village, Petoskey and Charlevoix, Mich. Standard NWS type raingages were used at all land stations and at the St. James island station. The Brevort, Cross Village and Port Inland stations were equipped with Alter wind shields.

Exposure at the sites varied from extremely poor at Ile aux Galets to very good at Beaver (GLERL). The quality of exposure for island precipitation gages in the Great Lakes is often a function of the available sites and associated vegetation. Site selection was conducted with considerable care for the island gages and where proper sites were available, proper exposure was achieved. Notwithstanding these efforts, gage protection varied from site to site due to topography and vegetation variation. The Ile aux Galets site was nearly unprotected. Existing National Weather Service gages were not relocated to provide exposures more suitable than those existing at the time. The effects of gage exposure on the data are apparent and are further discussed in a later section of this paper.

3. Analysis

Total monthly precipitation over the duration of this study for the island stations is given in Table 1. Daily and hourly values are available for the island stations and additional studies such as comparing island versus coastline precipitation intensity might prove useful. Analysis in this study is confined to the monthly values to fulfill a basic need in hydrologic modeling and other fields which require monthly information.

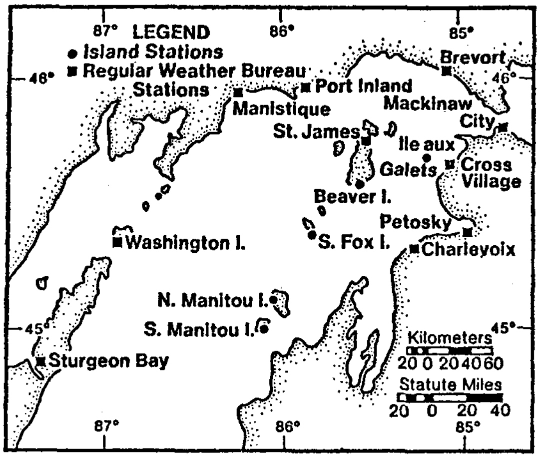

FIG. 1. Station network.

TABLE 2. Seasonal differences in average monthly lake-land precipitation (inches).

Dec–Feb	(Winter)
Lake	1.71
Land	1.78
Mar–May	(Spring)
Lake	2.57
Land	2.59
Jun–Aug	(Summer)
Lake	2.32
Land	2.79
Sep–Nov	(Fall)
Lake	3.21
Land	3.32

Lake versus land precipitation on a monthly basis is shown in Fig. 2. All land stations are included in the computations. During the warmer months, May through August, land precipitation exceeds that on the lake. Lake precipitation was significantly higher and lower than that on the land, in September and October, respectively. From November through April, lake and land precipitation were nearly equal. Accumulated differences show that 1.73 inches more precipitation fell on the land than on the lake during May through August. During September and October precipitation on the land was only slightly more than on the lake (0.29 inches) and during the period November through April lake and land precipitation were nearly equal. On a yearly basis, land precipitation exceeds the lake by 2.01 inches.

An examination of the data by seasons (Table 2) shows only slight differences in the average lake-land precipitation during winter, spring and fall with the most significant differences occurring in the summer.

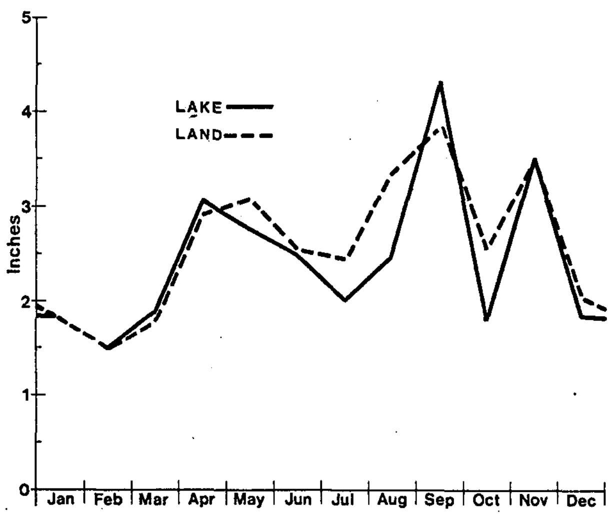

FIG. 2. Comparison of average monthly lake and land precipitation.

Changnon (1967) in a study of Lake Michigan precipitation used upwind and downwind land station data to compare with lake station data. He felt that upwind station data presented a comparison in which the land stations would be unaffected by the lake. It should be noted that wind direction was not measured in this or Changnon's study. The terms upwind and downwind are used only in a general sense based on the fact that predominant wind direction is from the north and west in this region (Phillips and McCulloch, 1972), placing upwind stations on the northern and western side and downwind stations on the eastern side of the lake. In this study, upwind and downwind stations were selected in a manner similar to that employed by Changnon. Upwind stations are Sturgeon Bay and Washington Island, Wis., and Manistique and Port Inland, Mich. Downwind stations are Charlevoix,

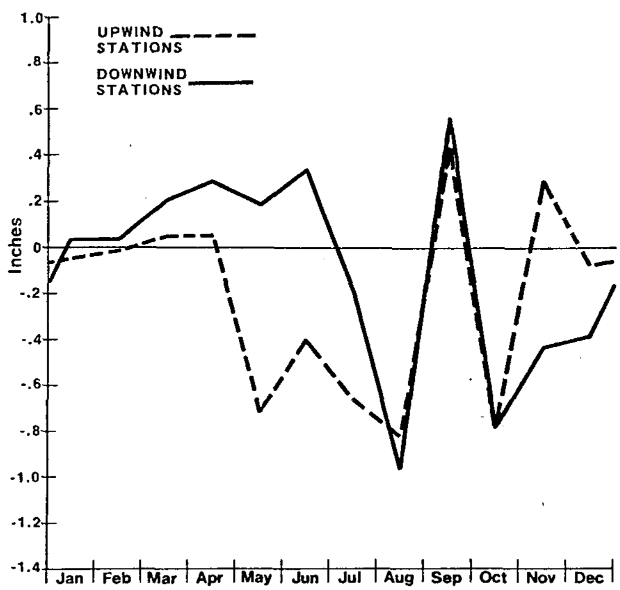

FIG. 3. Differences in average monthly precipitation, lake minus land, for upwind and downwind land stations.

Table 3. Total precipitation (inches) by warm and cold seasons, using the same time periods as Changnon, for upwind and downwind land stations and lake stations. Lake-to-land ratios are indicated for upwind and downwind cases by seasons.

		Warm season (June–Oct)	Ratio (Lake/Land)	Cold season (Nov–May)	Ratio (Lake/Land)
Upwind	Lake	13.10	1.04	16.33	0.97
	Land	12.65		16.80	
Downwind	Lake	13.10	0.93	16.33	1.00
	Land	14.15		16.41	

Petoskey, Cross Village and Mackinaw City, Mich. Fig. 3 shows differences in average monthly precipitation between lake and land stations. For the upwind comparison, the land stations show higher precipitation than the lake during the warmer months from May through August. The reverse situation is true for the remainder of the year with the exception of a large difference (0.78 inch) in October and minor differences in December (0.07 inch), January (0.05 inch) and February (0.02 inch). For the downwind comparison, the lake shows higher precipitation than the land for the first half of the year (January–June). During the last half of the year (July–December), with the exception of September, the downwind land stations show higher precipitation than the lake.

Using the same time periods (governed by storage gage readings) as Changnon, data from this study indicate the results shown in Table 3. Changnon found ratios of lake-to-land precipitation of 0.93 for upwind stations during the warm season and 1.06 during the cold season. In this study, for upwind stations, lake precipitation showed a ratio of 1.04 in the warm season and a ratio of 0.97 for the cold season. For downwind stations the ratios [0.93 (warm), 1.00 (cold)] are close to those found by Changnon [0.95 (warm), 1.02 (cold)].

A comparison of differences between lake stations and upwind and downwind land stations, as shown in Fig. 3, indicates that if differences exist in predicting lake precipitation from either upwind or downwind stations, those differences might occur on a seasonal basis. If those relationships can be more fully defined, within the limits of significance of the data as described later, then entire land precipitation networks for estimating overlake precipitation might be planned, operated and maintained on a seasonal basis.

Upchurch (1976) used lake data from most of the island stations used here to compute monthly lake-land ratios for upwind stations which were farther inland (100 mi) than those used here and clustered in a fairly small geographical area nearly directly west of the island stations. Using the same lake locations as Upchurch and the upwind land stations specified for this study, the lake-land ratios in Table 4 were obtained. The significant difference in the range of the values is probably due to the fact that Upchurch's land stations are not near the coastline and are therefore more subject to variations in precipitation confined to the local land area which is too geographically remote from the lake to influence the island stations. The general agreement between the two sets of values indicates that upwind stations tend to be unaffected by the lake environment. The distance inland for downwind stations is probably much more critical.

Blust and DeCooke (1960) compared island precipitation with downwind stations. They found that lake precipitation was 6.2% lower than the land during the summer and 4.5% higher than the land during the winter. Using the same time periods, data in this study, as shown in Table 5, indicate that lake precipitation was about the same as on the land during the summer and 6.4% lower than the land during the winter. In the same table an examination of the percent deviation, according to Blust and DeCooke, computed from data in this study on a month-to-month basis, yields values that show a wide variation from the seasonal (summer, winter) means. It would seem that future studies in addition to addressing the significance of the differences, as discussed later, should only consider data from recording gages since wide variations are masked when using storage gages.

A summary of ratios on a month-to-month basis using data from this study is given in Table 6. The

Table 4. Comparison between ratios obtained by Upchurch and Bolsenga for upwind land stations and selected northern Lake Michigan island stations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bolsenga*	1.04	1.05	1.09	1.07	0.75	0.86	0.76	0.68	1.11	0.59	1.18	1.04
Upchurch	1.39	2.26	1.05	0.89	0.83	0.49	0.70	0.64	1.10	0.96	1.62	1.32

* Current study.

TABLE 5. Total precipitation for data from this study, using the same periods as Blust and DeCooke (1960) and percent deviation {[(water minus perimeter)/perimeter]×100} as by Blust and DeCooke (1960). Also, percent deviation on a monthly basis.

	Total precipitation (inches) Perimeter	Water	Deviation (%)
Summer (May–Oct)	14.11	14.03	−0.6
Winter (Oct–May)	16.45	15.40	−6.4

Deviation (%)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
−2.3	2.8	11.8	10.0	7.0	15.9	−8.6	−28.1	14.9	−30.4	−11.0	−17.4

values include lake data from all stations, combined ratios include all land station data, and upwind and downwind ratios include data from all stations specified earlier. The range of the three sets of values is about equal. The yearly averages of ratios are upwind 0.92, downwind 0.98, combined 0.94. On a yearly basis, downwind land stations closely approximate the over-lake precipitation but the values might be biased since the lake stations are closer to the downwind than the upwind shore.

4. Significance of the results

Numerous studies have been completed on the subject of gage catch errors. Literature reviews are available which comprehensively cover the subject but only a few individual studies most pertinent to this study are mentioned.

Larson and Peck (1974) have determined that a 45% catch deficiency at 10 mph is probable for solid precipitation with a 70% deficiency probable at 20 mph. A 10% deficiency at 10 mph is probable for liquid precipitation. Shields reduce errors for solid precipitation significantly but have small beneficial effects for liquid precipitation. Winds were not recorded at either the island stations or the National Weather Service stations. However, it is probably safe to say that wind speeds occurring during at least portions of many of the precipitation events were of sufficient velocity to cause significant errors in the measured precipitation. Differences in wind effects between the lake and land stations would also have occurred. In most cases the differences found here between lake and land precipitation on both a monthly and seasonal basis are not greater than the limits of error cited by Larson and Peck.

Peck *et al.* (1974) found that gage exposure was a dominant factor in precipitation measurement errors in the Lake Ontario basin. Properly exposed gages averaged a 16% greater catch during the winter than existing climate gages. Kresge *et al.* (1963) examined the data from storage gages on Lake Michigan and concluded that exposure had a significant relation to gage catch, especially during the winter.

The island gage sites were selected to provide the greatest amount of protection possible under the existing conditions. The degree of protection is not uniform, however, and varies from well protected for most of the sites to nearly unprotected at Ile aux Galets where little natural protection was available. Fig. 4 shows a comparison between monthly Beaver Island (GLERL) precipitation and monthly precipitation at the other islands in the network. It is immediately apparent that the precipitation at the Beaver Island gage is larger than the precipitation at all of the smaller islands during a significant portion of the period of measurement. Most of the cases where precipitation on the smaller islands exceeded Beaver occurred in the fall and winter. These higher readings are probably due to

TABLE 6. Ratios of lake precipitation to upwind, downwind and combined (all stations) land precipitation data. Also, paired t statistic for various degrees of freedom (df) for combined, upwind and downwind land station data vs lake station data. Value of 2.78 required for 5% significance at 4 df and 3.18 at 3 df. Months showing statistical significance are italicized.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upwind	0.97	0.99	1.03	1.02	0.79	0.86	0.75	0.75	1.11	0.70	1.09	0.96
Downwind	1.02	1.03	1.12	1.10	1.07	1.16	0.91	0.72	1.15	0.70	0.89	0.83
Combined	1.00	1.01	1.06	1.05	0.89	0.98	0.82	0.74	1.13	0.70	0.99	0.89
t upwind	0.16	0.06	0.19	0.78	2.72	2.16	*2.91*	2.63	1.84	1.89	0.96	0.90
t downwind	0.13	0.18	0.63	*3.38*	0.78	2.01	0.50	2.63	1.51	*3.61*	2.10	1.63
t combined	0.01	0.03	0.46	2.72	1.46	0.38	1.67	*23.87*	2.03	2.47	0.21	1.81
df	4	4	4	4	4	4	4	4	4	3	4	4

exposure effects of the larger versus the smaller islands as noted by Kresge *et al.* (1963).

Differences exist between the two Beaver Island gages, St. James at the north end and Beaver Island at the south end. Monthly precipitation values of the St. James (National Weather Service) and Beaver Island (Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration) gages, using the same data periods for both stations, November 1963 through June 1968, except for months of missing data for either station as given by Table 1, are shown in Fig. 5. In the cooler portion of the year the St. James gage reads lower than the Beaver Island gage, but the reverse is true during the remainder of the year. The fact that the St. James gage was unshielded and of a different type than the Beaver Island gage provides a major portion of the explanation. However, other factors must also be considered such as exposure and geographical location coupled with a possible northerly flow in winter producing a higher catch at the southern gage which would be sheltered by the island.

The statistical significance of the lake-land differences were examined by subjecting the upwind, downwind, and combined land station data versus lake station data to a paired Student's t test at 5% significance (Table 6). The months showing statistical significance were as follows: upwind, July; downwind, April, October; combined, August. Using the t statistic for two means, no months showed statistical significance at the 5% level. Therefore, a major portion of the differences are not statistically significant and where significant differences occur no distinct pattern, such as a seasonal dependence, is detectable.

Thus, while the results of this study indicate that differences occur between lake and land precipitation, the differences are small enough to be statistically insignificant, in most cases; where larger differences occur, possible gage catch errors throw serious doubts on their significance. It is thus concluded that precipitation measurements using standard gages on most natural islands in the Great Lakes or on towers in the lake are susceptible to errors significant enough to render those readings only marginally useful for determining differences in lake-to-land precipitation. Empirical adjustments might be applied where wind speed is recorded if future studies refine the currently available information.

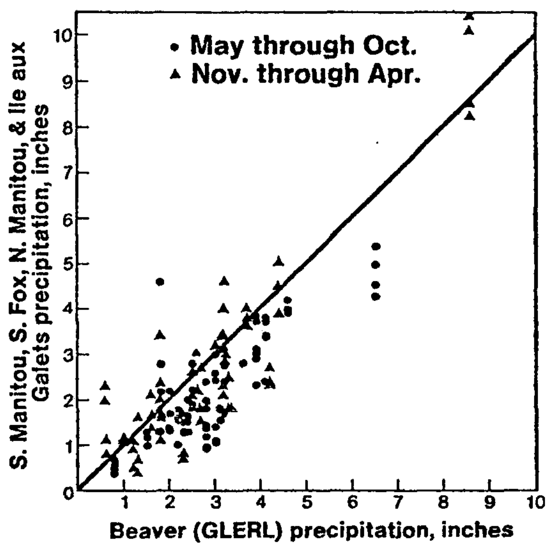

FIG. 4. Average monthly precipitation at the largest island station in the network (Beaver, GLERL) compared to monthly precipitation at the other smaller islands in the network.

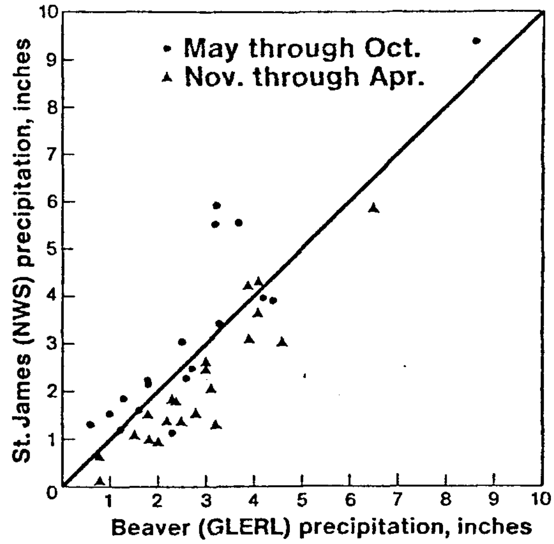

FIG. 5. Average monthly precipitation at the St. James and Beaver Island gages, both located on Beaver Island, northern Lake Michigan.

5. Summary

Information on lake versus land precipitation is provided from a network of recording precipitation gages in northern Lake Michigan. The recording gages permitted analysis on a month-to-month rather than on a seasonal basis, as when storage gages are used.

Land precipitation showed an apparent increase over lake precipitation during the warmer months with the reverse situation prevailing over the remainder of the year. Numerically, the most significant differences occurred in the summer. Several comparisons of upwind and downwind land to lake station data were made. Results compared favorably to those obtained in previous investigations. The data have provided an apparent insight into the monthly precipitation patterns of the island stations as opposed to the previously defined seasonal patterns, but it is stressed that the significance of the differences appears doubtful. Using currently available raingage instrumentation, serious gage catch deficiencies can occur which obscure the comparatively small lake to land differences. Careful site selection is a major step toward eliminating these errors, but the

number of islands in the Great Lakes are few and the number of appropriate sites on those islands even fewer. Topographic, geographic and exposure effects all seem to influence the catch on the island gages as well as the real precipitation patterns.

Tests show that the majority of the lake-land differences are not statistically significant. Only the larger lake-land differences show significance, and doubt can be cast on those results when gage catch errors are considered.

The results of this study indicate that additional work with extremely precise gage data is needed to understand the lake-land precipitation relationship. A longer time base for conventional studies such as the one described here is clearly desirable. Wind speeds should be recorded at each site with reasonable corrections applied to the precipitation data. However, the cost of such a program would be high.

The application of remote sensing methods, such as improved radar techniques, to the problem seems to show some promise (Wilson, 1976). Careful site selection for the calibration network continues to be a major consideration, but appropriate sites are usually available on the land near the radar. A simple technique, described by Bolsenga and Hagman (1975), using a Thiessen polygon network developed from carefully selected shoreline stations provided monthly values for a short period which compared favorably to radar values for overlake precipitation. Perhaps additional work in improving remotely sensed precipitation measurements coupled with development of techniques to establish relationships between standard shoreline gages and remotely sensed data would provide both the required additional accuracy and ultimate economy of operation.

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