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Time Series Analysis of 20 Years of Hourly Precipitation in Southwest Michigan

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ABSTRACT. *Hourly precipitation data from Oshtemo Township, Michigan, located approximately 55 km east of the lee shore of Lake Michigan, for the period of April 1980 through March 2000 were examined. Diurnal analysis of precipitation as well as time series analysis of precipitation were performed on the study period. An overall nocturnal maximum in the mean accumulation of precipitation was detected during the 2-hour periods before 2000 LST and 2200 LST. Elevated spring and fall accumulations were responsible for this evening maximum. Elevated summer and winter accumulations were responsible for a weak secondary morning maximum. An overall morning maximum in the mean precipitation hours was detected during the 2-hour period before 1000 LST. ARIMA modeling verified that both precipitation accumulations and counts, for all times of the day, were significant at the 5% level. A storm event model was developed from the time series, the resulting values of which can be used as input in mesoscale climate, hydrological, and agricultural computer models: the mean pulse duration was 2.44 hours; the mean interlude between pulses was 37.64 hours; the mean event accumulation was 4.1 mm; and the mean rate was 1.8 mm / hr. Finally, inter-annual analysis performed for the period of 1981 to 1999 showed that there was no statistically significant change in precipitation over the period.*

INDEX WORDS: *Precipitation variability, precipitation diurnal cycle, precipitation seasonality, Michigan.*

INTRODUCTION

Precipitation plays a crucial role in the hydrologic budget of southwest lower Michigan and the larger Great Lakes drainage basin. High temporal and spatial variability make surface observations of precipitation very important for complementing radar and satellite observations. Climatologically, the largest average accumulations of precipitation in Michigan occur in the southwest portion of the Lower Peninsula (Eichenlaub *et al.* 1990). This is due in part to late fall and winter "lake-effect" precipitation events that are caused by modifications of cold air masses moving over the relatively warm surface of Lake Michigan, and in part to year-round synoptic-scale weather systems that stream moisture northward from the Gulf of Mexico. Lake-effect snows occur throughout the winter months but are relatively more productive in December when there is a greater temperature contrast between the lake surface and the overrunning air (Changnon 1968). Some locations in Southwest Michigan can average in excess of 250 cm of snow per year (Eichenlaub *et al.* 1990) and individual storm totals can often exceed 25 cm. Abnormally low snowfall amounts have been known to occur during El Niño years (Kunkel *et al.* 2000). Spring and summer are characterized by warm and humid air masses that allow for the common occurrence of convectional rain and thunderstorm activity. These storms can frequently weaken because of enhanced atmospheric stability resulting from warm air masses moving over the relatively cool lake waters. In fact, mean annual precipitation accumulations over Lake Michigan have been estimated to be 6% less than that which is found over its surrounding basin (Changnon 1972). Nevertheless, southern Michigan storms should never be underestimated, as they can be quite severe both in terms of their magnitude and their impact on human lives (Foltman 1995).

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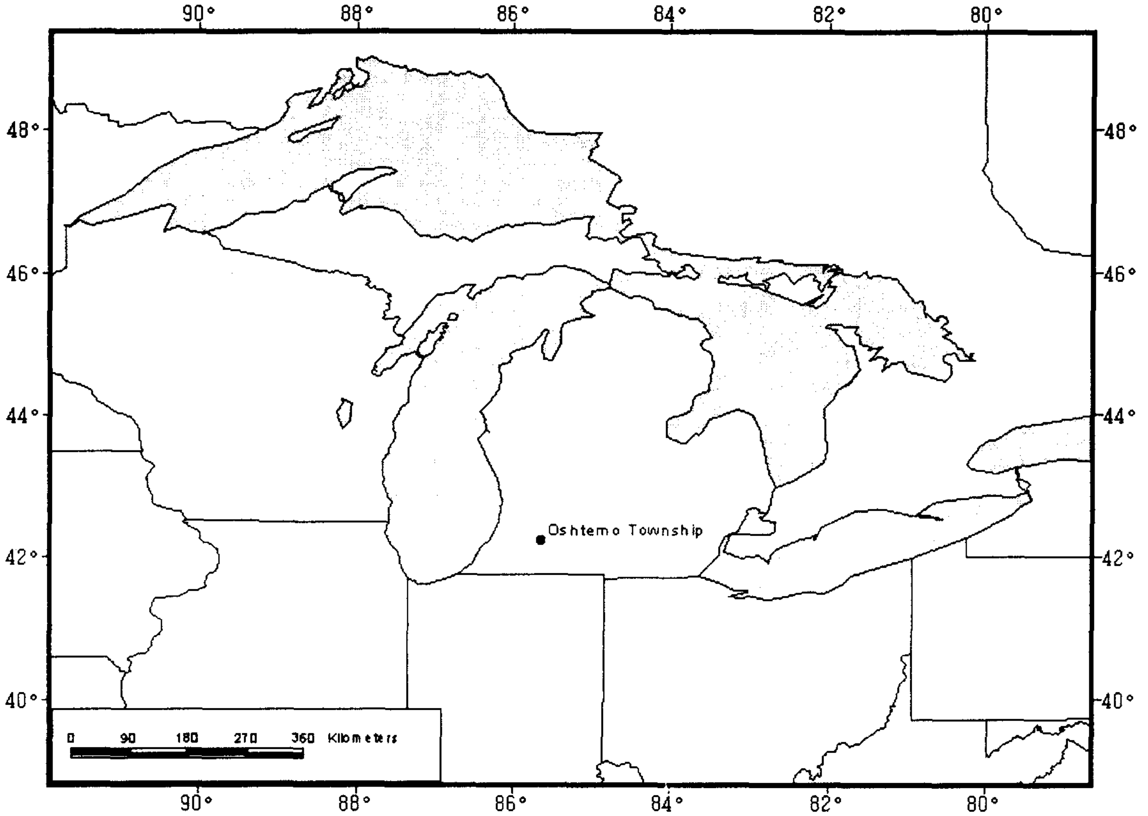

FIG. 1. Site location of Osthemo, Michigan

climatological station in Oshtemo Township, Michigan, since 1979. Precipitation records from this station were processed and analyzed to provide a better understanding of the local precipitation regime and its structure. The site is located at 42° 16′ N Latitude, 85° 44′ W Longitude (Fig. 1). This is approximately 55 km east of the western shoreline of Lake Michigan and 6.4 km west of the Kalamazoo city limit. The station is in a ridge at the southern edge of the Kalamazoo moraine. It sits at an elevation of 294 m above mean sea level.

The recording precipitation gauge, or pluviograph, registers the data with an ink trace on rectangular paper charts containing hours and dates along the x-axis and precipitation accumulations in inches along the y-axis. Seven days of data are recorded on each chart. The gauge record began on 18 July 1979 at 0400 Eastern Daylight Time (EDT) and continues to this date. The values were always recorded in local time (LT). All values reported during local daylight time (LDT) were converted to local standard time (LST) for this study. The record contains some missing data (Table 1). Overall, the dataset set contained less than 11% missing recording hours per year after 1980. Less than 5% missing hours occurred in 15 of the years. Four years had complete records. Data recorded before 1 April 1980 were excluded from this study due to their sporadic availability. There were potential sources of error as a result of the subjective aspect of chart reading and systematic instrument error, although the credibility of the precipitation record was addressed by comparing the monthly totals to those of a nearby station.

This study aims to determine:

1. the monthly, seasonal, and annual variability of the diurnal precipitation cycle in Oshtemo Township;
2. a representative "storm event" model to describe the structure of the precipitation amount, intensity, duration, and interlude; and
3. the inter-annual variability of precipitation.

The methods in this study are based on those used in a time-series analysis of hourly rainfall au-

TABLE 1. Hours of missing data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Percent
1979							411	39	21	34	0	478		
1980				82	43	39	242	0	116	0	79	410	1,011	15.3*
1981	26	0	0	90	50	223	0	21	6	6	0	95	517	5.9
1982	0	0	154	184	0	0	0	0	0	16	0	0	354	4.0
1983	451	0	0	0	0	17	0	0	0	0	0	229	697	8.0
1984	135	0	0	0	0	0	0	0	0	0	0	0	135	1.5
1985	425	11	0	0	0	0	0	0	0	0	0	447	883	10.1
1986	81	36	0	0	0	0	0	0	0	0	0	0	117	1.3
1987	0	0	54	113	0	0	0	73	0	0	65	80	385	4.4
1988	312	484	0	0	0	0	0	0	47	0	0	0	843	9.6
1989	0	0	0	0	0	0	0	0	0	0	0	101	101	1.2
1990	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1992	0	126	38	0	0	27	0	0	0	0	0	0	191	2.2
1993	0	0	0	16	0	0	0	0	34	0	0	0	50	0.6
1994	0	0	0	0	0	91	0	0	0	0	154	0	245	2.8
1995	0	0	0	161	59	18	0	0	0	0	0	0	238	2.7
1996	0	0	0	0	0	0	0	0	0	0	212	68	280	3.2
1997	0	0	0	0	0	0	0	0	0	0	33	0	33	0.4
1998	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1999	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
2000	0	0	0											

*Does not include January, February, and March

tographic rain gages in the Brazilian Amazonia that yielded information on the structure of the precipitation as well as the temporal and spatial variability (Butzo 1993, Cutrim *et al.* 2000).

Climatologists have analyzed the diurnal variability of precipitation for many regions and individual locations, especially since Wallace (1975) attempted to "provide a comprehensive and consistent documentation" of diurnal variation of precipitation and thunderstorms at different levels of intensity over the United States during the summer and winter seasons. Some notable studies include analyses of the diurnal variation of precipitation for the northeast United States during all four seasons (Landin and Bosart 1985), for the Canadian prairies during growing season (Chakravarti and Archibold 1993), for individual states such as Florida (Schwartz and Bosart 1979) and New Mexico (Tucker 1993), for very heavy summertime precipitation in the eastern and central United States (Winkler 1987), and for various categories of heavy hourly precipitation during all four seasons (Winkler *et al.* 1988).

There are various benefits to be gained from studying the diurnal patterns of the Oshtemo station. On a wider scale, general insights are gained into the influences of large lakes on the local climatology of stations located along the lee side of these lakes. Indications of these influences are investigated in the diurnal cycle. On a local scale, diurnal precipitation climatology is important for planning anthropogenic activities such as the use of ground water supply and the management of storm drainage control. Oshtemo Township, like many other locations in the Great Lakes region, is experiencing rapid population growth accompanied by intense urban development. While residential and commercial development are economically welcome, the environmental impact is of concern and should be carefully addressed. Land use and cover change affects the local water budget by changing the permeability of the surface, therefore reducing the ground water recharge and increasing evaporation. Furthermore, rates of infiltration, run-off, and evaporation vary throughout the day as the air temperature and relative humidity change. The diurnal cycle of the precipitation plays an important role in the management of the activities dependent on water resources.

This study also finds and analyzes all precipitation storms and interludes in order to develop a "storm event" model that described the structure of the precipitation amount, intensity, duration, and interlude. The definitions are based on Cutrim *et al.*

(2000). A *storm*, also referred to as a *pulse*, is at least 1 hour of precipitation bounded on either side by at least 1 hour without precipitation. An *interlude* is at least 1 hour without precipitation bounded on either side by a storm (pulse). An *event*, also referred to as a *storm event*, is a storm and the interlude that follows it. A *precipitation hour*, or *occurrence*, is any hour with precipitation. The resulting values of the storm event model can be used as input in various computer generated models which include, but are not limited to, mesoscale hydrologic models, watershed models, agricultural models, mesoscale climatic models, local-scale drainage models, and hydro-geological models.

DIURNAL ANALYSIS

Month-by-month precipitation was accumulated for each hour of the day for each month of the 20-year study period, 1 April 1980 through 31 March 2000. The number of precipitation hours, or occurrences, for each month was recorded as well. This section examines the diurnal cycle in 2-hour intervals.

The overall analysis was obtained by adding the individual 2-hourly totals of all months in the study period and dividing by the total number of years in the study period. The seasonal analysis of the diurnal cycle of precipitation was obtained by adding the 2-hourly totals of the 3 months for each season and dividing by the number of years in the study period. The seasonal accumulation was calculated using the following equation:

$$\overline{X}_{\text{winter,spring,summer,fall}} = \left(\sum_{i=1}^{20} \sum_{j=1}^{3} \sum_{k=1}^{n_j} x_{i,j,k} \right) / \, N \qquad (1)$$

where $\overline{X}$ is the mean hourly precipitation for a given 2-hour period of the day, for a season, over the 20-year period; x is the amount of precipitation accumulated for a given 2-hour period of the day; i represents each year of the study period; j represents each month of a season; k represents each day of the month; n_j represents the number of days in month j; and N = total number of years in the study period, 20 years. Similarly, the seasonal occurrence, or precipitation hours, was obtained from:

$$\overline{Y}_{\text{winter,spring,summer,fall}} = \left(\sum_{i=1}^{20} \sum_{j=1}^{3} \sum_{k=1}^{n_j} y_{i,j,k} \right) / \, N \qquad (2)$$

where $\overline{Y}$ is the mean number of precipitation occurrences for a given 2-hour period of the day, for a season, over the 20-year period; y is the number of times precipitation occurred at a given 2-hour period of the day; and all other variables are as described in Equation 1.

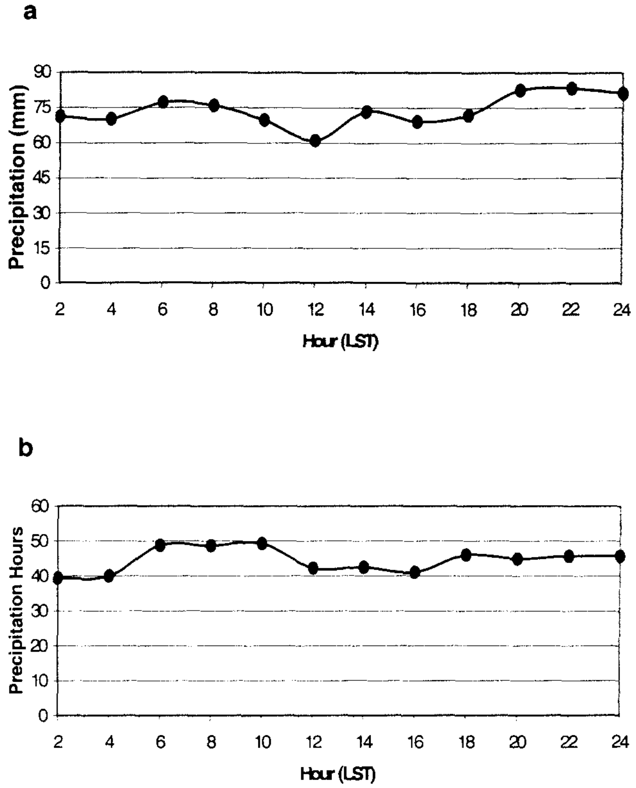

FIG. 2. Diurnal cycle of (a) the mean annual precipitation accumulation (mm), and (b) the mean annual number of precipitation hours for the period April 1980–March 2000.

Overall, precipitation in Oshtemo Township occurred at all hours of the day and night, and, for the most part, was evenly distributed (Fig. 2). For the study period, a nocturnal maximum of 83 mm was detected in the mean precipitation accumulation (2000 LST and 2200 LST) and a morning maximum of 49.3 hours was detected in the mean precipitation occurrences (1000 LST). A slight secondary maximum occurred during the morning hours. The minimum mean accumulation occurred during the middle of the day at a value of 61 mm (1200 LST). A secondary evening maximum period in the mean precipitation occurrences was detected with a peak value of 46.0 hours. These results show that for the study period there were more hours with precipitation during the late morning, but the actual precipitation amounts were heavier in the evening.

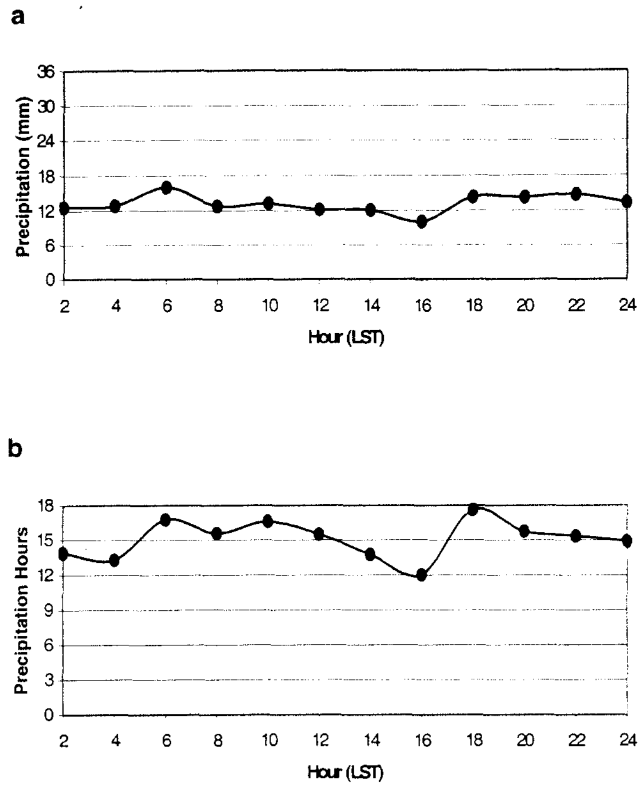

FIG. 3. Diurnal cycle of (a) the mean annual precipitation accumulation (mm), and (b) the mean annual number of precipitation hours for the winter months (Dec, Jan, Feb).

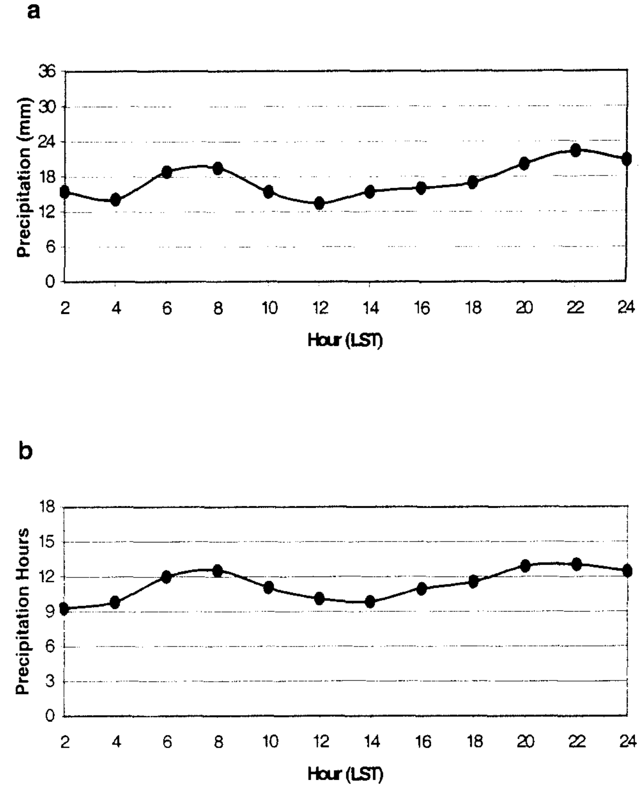

FIG. 4. Diurnal cycle of (a) the mean annual precipitation accumulation (mm), and (b) the mean annual number of precipitation hours for the spring months (Mar, Apr, May).

Seasonal Analysis

a) Winter Season (December, January, February): The mean accumulation during this season peaked shortly before sunrise (0600 LST) at a value of 16 mm (Fig. 3). A slightly smaller peak was detected during the evening at a value of 15 mm. The minimum in winter occurred during the afternoon at a value of 10 mm. The maximum mean number of precipitation occurrences occurred during the last 2 hours of the afternoon at a value of 17.6 hours, while slightly smaller values were observed during the morning hours. These results show that during the winter season, the heaviest accumulation of precipitation occurred during the morning hours, while the greatest number of precipitation occurrences occurred during the last 2 hours of the afternoon.

b) Spring Season (March, April, May): Both the mean accumulation of precipitation and the mean number of precipitation occurrences peaked in the evening during this season (2200 LST) at values of 22 mm and 13.1 hours, respectively (Fig. 4). A secondary peak of 20 mm in the precipitation accumulation was detected during the morning. The minimum precipitation accumulation occurred during the middle of the day at a value of 13 mm. Slightly smaller peaks in the mean number of precipitation occurrences occurred around 0600 LST, 0800 LST, 2000 LST, and 2400 LST at values of 12.0 hours, 12.6 hours, 12.9 hours, and 12.5 hours, respectively. A nocturnal maximum is therefore dominant during the spring season in both the mean precipitation accumulation and the mean precipitation occurrences.

c) Summer Season (June, July, August): The mean accumulation of precipitation during this season peaked during the morning in similar fashion to the winter season (0600 LST) at a value of 27 mm (Fig. 5). Slightly smaller values were observed around 0400 LST, 0800 LST, and 2400 LST at values of 25 mm, 24 mm, and 24 mm, respectively. The minimum occurred during the last 2 hours of the afternoon at a value of 17 mm. The maximum

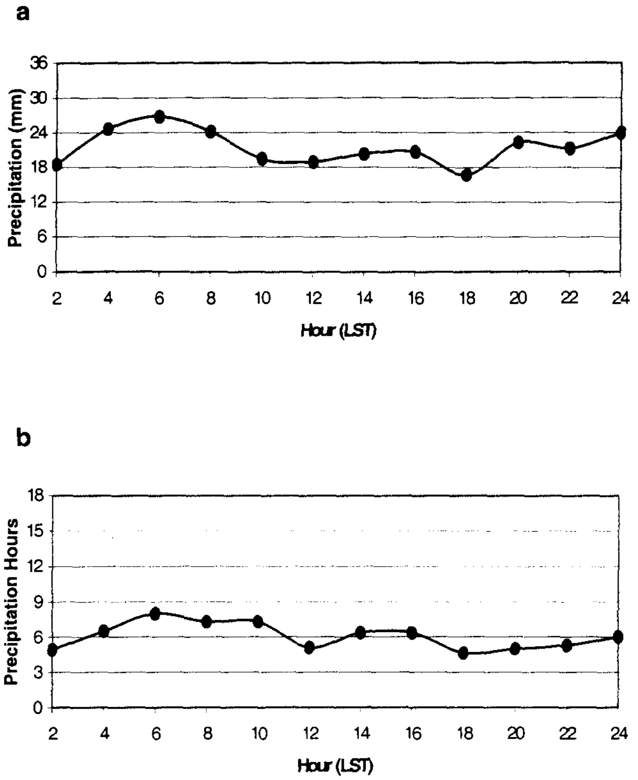

FIG. 5. Diurnal cycle of (a) the mean annual precipitation accumulation (mm), and (b) the mean annual number of precipitation hours for the summer months (Jun, Jul, Aug).

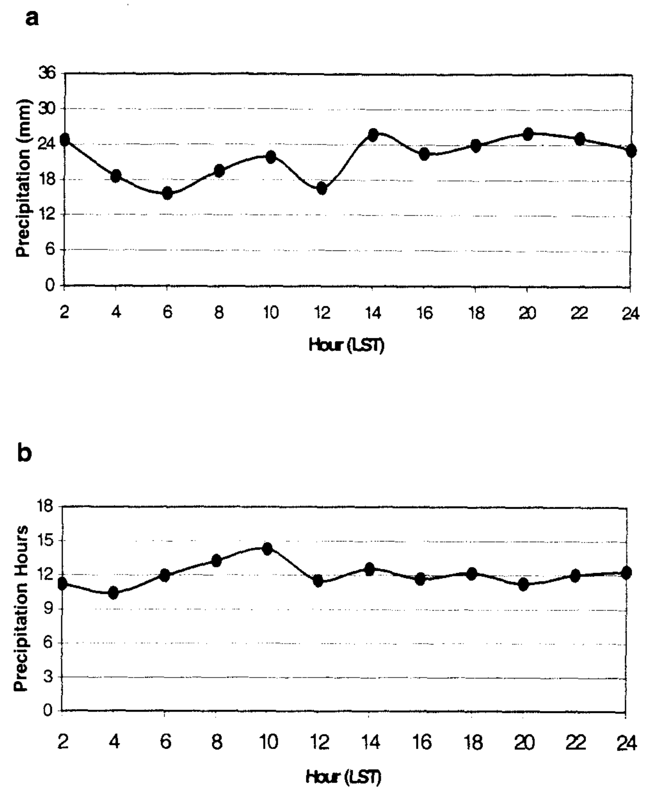

FIG. 6. Diurnal cycle of (a) the mean annual precipitation accumulation (mm), and (b) the mean annual number of precipitation hours for the autumn months (Sep, Oct, Nov).

mean number of precipitation occurrences (8.0 hours) occurred around 0600 LST, which coincided with the time of the peak mean accumulation. Slightly smaller peaks in the mean number of precipitation occurrences were observed around 0800 LST and 1000 LST. A morning maximum was dominant during the summer season in both the mean number of precipitation occurrences and the mean accumulation.

d) Autumn Season (September, October, November): The mean precipitation accumulation peaked at a value of 26 mm twice during this season (Fig. 6). The first peak occurred during the afternoon (1400 LST) while the second was nocturnal (2000 LST). Slightly smaller peaks occurred around 0200 LST, 1800 LST, and 2200 LST at values of 25 mm, 24 mm, and 25 mm, respectively. It is also worth noting that values over 22 mm were observed during all afternoon and evening hours. The minimum mean accumulation occurred during the morning at a value of 16 mm. The maximum mean number of precipitation events occurred around 1000 LST at a value of 14.3 hours, which did not coincide with the times of either of the peak mean accumulations. These results show that the heaviest accumulation of precipitation during the autumn season occurred throughout the afternoon and evening hours while the greatest number of precipitation hours occurred during the morning.

Time Series Analysis

Autoregressive Integrated Moving Average (ARIMA) modeling (Box *et al.* 1994) was applied for the two-hourly precipitation time series. This method was used to determine whether statistically significant differences existed from season to season, for each 2-hour period of the day, for the entire 20-year period. Here we define the winter, spring, summer, and fall seasons as in the seasonal analysis section.

Following the Box-Jenkins methodology, a sample autocorrelation function (ACF) plot and a partial autocorrelation function (PACF) plot were employed for each of the 12 periods of the day, for both precipitation accumulations and counts. A plot of ACF values at different lags was used to find a working series of stationary time points for the precipitation parameters, *accumulation* and *counts.* For both precipitation parameters, the ACF plots clearly indicated the time series to be non-stationary, thus needing further manipulation by differencing. The ACF plot for the first differences produced a series with a stationary non-seasonal component, but the same plot showed the need for further differencing of the seasonal component of the series, which occurs every four time periods. The periods of differencing, therefore, are 1 for the non-seasonal component, and 1 for the seasonal component of order 4. This differencing scheme produced a stationary time series, which is a prerequisite in ARIMA Modeling.

The ACF and PACF plots of the differenced series were then used to determine the autoregressive (AR) component and a moving average (MA) component of the series. Except for precipitation count at 6 a.m. the ARIMA model for each of the differenced precipitation time series, y_t, were identified as:

$$\text{ARIMA}(0,1,1)\times(0,1,1)_4 \qquad (3)$$

The non-seasonal, θ, and seasonal, Θ, parameters of the model equation were tested for significance by using conditional least square estimation of θ and Θ for each differenced time series. Both precipitation accumulations and counts, for all times of the day, were significant at the 5% level.

PULSATILE ANALYSIS

All precipitation storms and interludes found during the study period were analyzed in order to develop a "storm event" model that describes the structure of the precipitation amount, intensity, duration, and interlude over time. Table 2 presents the statistical summary of all pulses during the 20-year period using various pulse parameters that were defined by Butzow (1993) and Cutrim *et al.* (2000). *Pulse* is the duration of the precipitation pulse, or the hour of the last non-zero entry of a pulse minus one less than the hour of first non-zero entry of a pulse. *Interlude* is the duration of the dry period between precipitation pulses, or the hour of the first entry of a given precipitation pulse minus one less than the hour of the last non-zero entry of the previous precipitation pulse. *Start to peak (h)* is the duration between the start of a precipitation pulse and the peak of the precipitation pulse. *Peak to end (h)* is the duration between the peak of a given precipitation pulse and the end of that same precipitation pulse. The hour of the peak accumulation is included in both the start to peak (h) and peak to end (h) periods. These are therefore overlapping periods and their sum will add up to one more than the pulse length. *Peak accumulation* is the greatest amount of precipitation that fell in any 1 hour for a given precipitation pulse. *Pulse accumulation* is the total precipitation accumulation for a given precipitation pulse. *Start to peak (mm)* is the total precipitation before and including the peak time of a given precipitation pulse. *Peak to end (mm)* is the total precipitation after but not including the peak time of a given precipitation pulse.

There was an average of 886.3 mm of precipitation per year, which is consistent with other stations in southwest lower Michigan (Eichenlaub *et al.* 1990). The mean pulse accumulation was 4.1 mm. From the total of 4,372 pulses, 2,750 pulses (63%) yielded less than 2.5 mm with 822 (19%) of these

TABLE 2. Pulsatile analysis table for the period April 1980–March 2000.

	Pulse (h)	Interlude (h)	Start to Peak (h)	Peak to End (h)	Peak Accum. (mm)	Pulse Accum. (mm)	Start to Peak (mm)	Peak to End (mm)
Mean	2.44	37.64	1.51	1.93	2.3	4.1	3.0	1.0
Median	1.00	6.00	1.00	1.00	1.0	1.3	1.3	0.0
Mode	1.00	1.00	1.00	1.00	0.3	0.3	013	0.0
Maximum	28.00	817.00	22.00	27.00	45.7	104.4	66.5	46.7
SD	2.43	70.41	1.28	1.76	3.6	7.0	5.1	3.0
Variance	5.93	4,956.98	1.63	3.09	0.5	1.9	1.0	0.4
Skewness	3.40	3.28	5.03	3.95	101.8	105.1	100.3	158.8
Kurtosis	18.81	14.57	43.42	27.18	602.8	672.9	566.1	1,384.5
Sum	10,679.00	164,561.00	6,620.00	8,427.00	10,163.3	17,725.1	13,234.7	4,490.5
Sum/yr	533.95	8,228.05	331.00	421.35	508.2	886.3	661.7	224.5

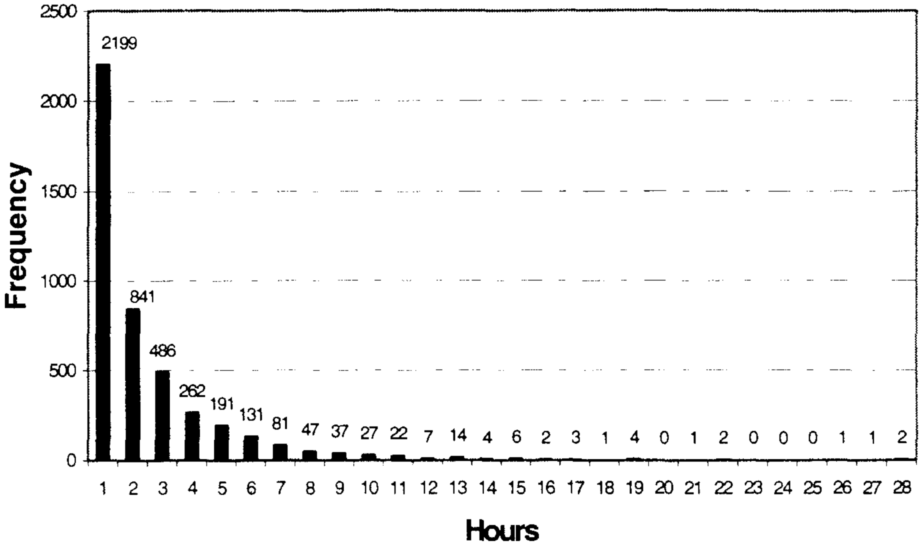

FIG. 7. Frequency distribution for duration of precipitation pulses.

being 0.3 mm. A total of 4,267 of the pulses (98%) yielded less than 25.4 mm. Only 11 pulses yielded 50.8 mm or more of precipitation. The greatest accumulation that fell in any pulse was 104 mm during an 8-hour period in the summer of 1982, and the greatest maximum precipitation for any 1 hour was 46 mm, which occurred in the summer of 1980.

The sum of all peak accumulation values was 10,163.3 mm, which was 57% of the total pulse accumulation of 17,725.1 mm. The sum of all start to peak accumulation values was 13,234.7 mm, which was 75% of the total precipitation accumulation. This meant that only 18% of the precipitation fell before the peak hour. The mean peak accumulation was 2.3 mm and the mean start to peak accumulation was 3.0 mm. The mean peak to end accumulation was 1.0 mm. A "0" (such as is found in the median and mode of the peak to end accumulation) indicated that the peak occurred during the last hour of pulse. The sum of all peak to end values was 4,490.5 mm, which was 25% of the total precipitation.

The mean pulse duration was 2.44 hours. There were 10,679 hours with precipitation during the 20-year period, which was an average of 533.95 hours per year. The mean interlude between pulses was 37.64 hours. There was an average of 8,228.05 hours per year without precipitation. The mean time between the start of successive precipitation pulses was 40.08 hours.

Frequency histograms of the pulse duration and the interlude between pulses are shown on Figures 7 and 8, respectively. Approximately half of the pulses were only 1 hour long, and over two-thirds of the pulses were of a duration of 1 to 2 hours. Slightly over 91% of the pulses lasted 5 hours or less. The longest pulse duration was 28 hours, which occurred on two separate occasions. A total of 32 mm of precipitation fell during a continuous 28-hour period in February 1990, and a total of 60 mm of precipitation fell during a continuous 28-hour period in November 1990. There was also a continuous 27-hour period during February 1985 when 46 mm fell, and a continuous 26-hour period during November 1988 when 22 mm fell. A total of 3,048 interludes, or 70% of the total number, were from 1 to 25 hours long. Of these interludes, 892 (20%) were only 1 hour long, and 1,373 (31%) were from 1 to 2 hours long. The longest interlude was 817 hours that started on 3 February 1988 and ended on 8 March 1988. However, this cannot be legitimately taken as the longest because there were extensive missing data during this period. The second highest interlude was 618 hours that started on 25 May 1990 and ended on 20 June 1990. There were no missing values during this period; this is therefore taken as the highest legitimate interlude during the 20-year period. There were seven interludes of over 500 hours, but three of them were discarded because of extensive missing values. The four highest legitimate interludes were 618 hours, 570 hours, 538 hours, and 502 hours. A total of 58% of the interludes lasted 10 hours or less.

Table 3 shows that the mean precipitation dura-

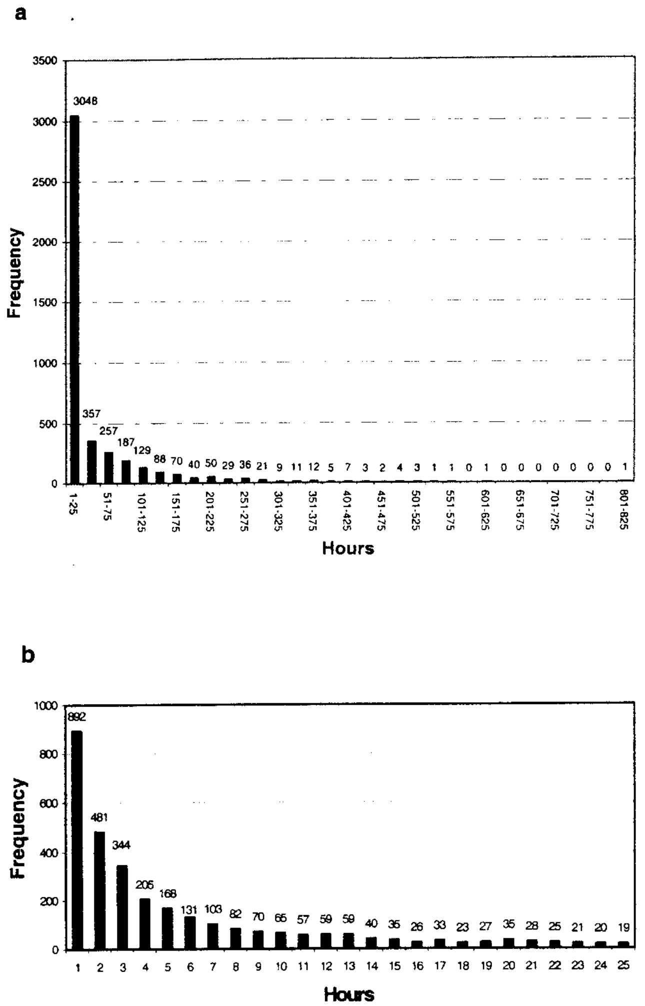

FIG. 8. Frequency distribution for (a) interludes between pulses and (b) interludes between pulses of 25 hours and less.

TABLE 3. Model storm event.

	Duration (h)	Acumulation (mm)	Rate (mm/h)	Interlude (h)
Early	0.51	0.8	1.3	*
Peak	1.00	2.3	2.3	*
Late	0.93	1.0	1.0	*
Total	2.44	4.1	1.8	37.64

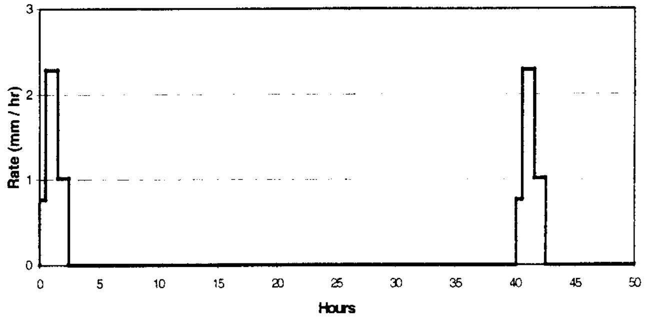

FIG. 9. Storm event model for Oshtemo Township.

tion after the peak was an average of 0.42 hours longer than the precipitation duration before the peak. It was also observed that the mean accumulation after the peak hour was 0.2 mm greater than the mean accumulation before the peak hour. This meant that the mean precipitation rate was greater before the peak hour than it was after the peak hour.

A storm event model was developed using the numbers in Tables 3. The values in Table 3 were based on the following two assumptions (Butzow 1993):

1. Peak precipitation is recorded over a period of 1 hour.
2. The sum of the early, peak, and late precipitation periods will equal the total accumulation.

The storm event model is shown in Figure 9.

INTER-ANNUAL ANALYSIS

In order to work with complete years, only the 19 years from 1981 through 1999 were used in the inter-annual analysis. A high variability was found in the yearly variation from the mean accumulation (Fig. 10a). Positive values from 129 to 206 mm above the mean were evident during 5 separate years, and negative values from 122 to 206 mm below the mean were evident during 5 separate years. The highest positive value was 206 mm above the mean in 1993, and the lowest negative value was 206 mm below the mean in 1981. There was a slight increase in precipitation over the period of record; however, the p-value (0.89) indicates that it was not statistically significant at the 5% level. For the purpose of comparison, inter-annual analyses of precipitation accumulation were performed on three nearby stations in close proximity to Lake Michigan (Fig. 11):

1. Muskegon, Michigan (43° 10′ N Latitude, 86° 15′ W Longitude)
2. Grand Rapids, Michigan (42° 53′ N Latitude, 85° 31′ W Longitude)

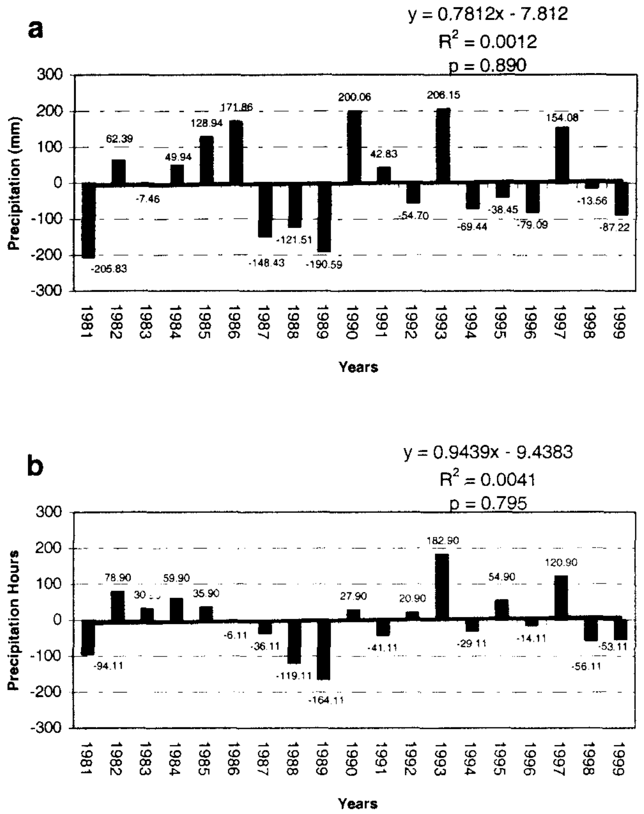

FIG. 10. Inter-annual analysis (1981-1999). (a) Deviation from the 19-year mean precipitation accumulation. (b) Deviation from the 19-year mean number of precipitation hours.

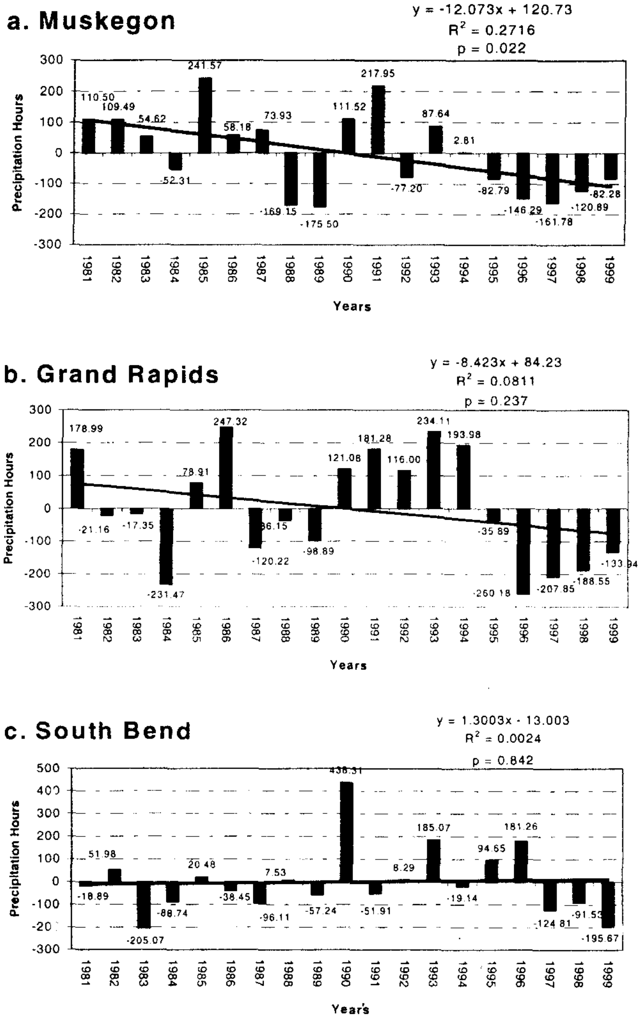

FIG. 11. Station inter-comparison (1981-1999). Deviation from the 19-year mean precipitation accumulation for (a) Muskegon, MI; (b) Grand Rapids, MI; and (c) South Bend, IN.

3. South Bend, Indiana (41° 42′ N Latitude, 86° 19′ W Longitude)

A decrease in precipitation was observed at the stations to the north of Oshtemo (Muskegon and Grand Rapids), although this decrease was not statistically significant at the 5% level for Grand Rapids. The precipitation trend for the station to the south of the Oshtemo station (South Bend) was similar to the Oshtemo station in that that there was a slight increase in precipitation that was not statistically significant at the 5% level.

A high variability was also found in the yearly variation from the mean number of precipitation hours (Fig. 10b). Two years had positive values more than 100 hours above the mean, and 2 years had negative values more than 100 hours below the mean. The highest positive value was 183 hours above the mean in 1993, and the lowest negative value was 164 hours below the mean in 1989. There was a slight increase in the number of precipitation hours over the period of record; however, the p-value (0.795) indicated that it was not statistically significant at the 5% level.

DISCUSSION AND CONCLUSIONS

This 20-year study of ground-based precipitation observations generated a unique data set for Oshtemo Township in southwest lower Michigan for the period of 1 April 1980 through 31 March 2000. Overall, the diurnal analysis revealed that precipitation was distributed throughout all hours of the day. An evening precipitation maximum period was detected in the mean accumulation and a slight secondary maximum period was detected in the mean accumulation. The seasonal analysis of the diurnal cycle indicated that elevated spring and fall accumulations were responsible for the evening maximum, and elevated winter and summer accumulations were responsible for the slight morning secondary maximum. ARIMA modeling verified that both precipitation accumulations and counts, for all times of the day, were significant at the 5% level.

The maximum mean accumulation during the winter season occurred before sunrise (0600 LST) when there is likely a large lake/air temperature contrast between the surface of Lake Michigan and the overrunning air. This 0600 LST maximum occurred primarily as a result of the precipitation patterns during January, the month which experiences the coldest "normal" low temperature. While the maximum mean precipitation hours occurred in the late afternoon before 1800 LST, the analysis of the mean accumulation indicates that these events actually produced less precipitation than the events that occurred before 0600 LST. As expected, these findings suggest that early to mid-winter snowfall in the Great Lakes region is enhanced by the lake effect.

The diurnal analysis of the spring season revealed nocturnal maxima in both the mean accumulation and the mean precipitation occurrences. These results are consistent with the current understanding of what is expected given the interaction of synoptic and local, or mesoscale circulations, activities acting over the southern Great Lakes region. Solar forcing inducted convective clouds and precipitation later in the day and the air temperature and moisture contrast of the cP and mT air masses play the most significant roles. Convective clouds increase throughout the day and precipitation is enhanced during the late afternoon and early evening hours.

The diurnal analysis of the summer season revealed morning maxima in both the mean accumulation and the mean number of precipitation hours. These results may be explained by a small difference that often exists during the morning hours between warm air temperatures and high dew point readings. Both are high during summer due to the frequent presence of the mP air mass. Atmospheric lift during the morning, when air temperatures and dew point readings are in close proximity to each other, will likely result in heavier and more frequent precipitation.

Finally, the autumn season is the most unique because it was the only season with two maxima in the mean accumulation cycle and it was the only season that manifested an afternoon maximum in the mean accumulation. It is also interesting to note that all hours from 1400 LST through 0200 LST are similar and combine to form a maximum period of 14 hours. Modifications of the cP air masses by the relatively warmer surface of Lake Michigan may play significant role in this diurnal pattern.

Most of these findings are consistent with a study by Winkler *et al.* (1988) that examined the diurnal cycle for various categories of heavy hourly precipitation across the United States during all four seasons. The time frame of seasonal maxima for precipitation accumulation at the Oshtemo station were usually consistent with what was observed by Winkler in southwest Michigan. Both studies found morning mean peak accumulations during the winter, and nocturnal autumn and spring peaks.

A storm event model for the region was developed with the mean parameters obtained from the pulsatile analysis. The values from the pulsatile analysis and the storm event model can be used as input in computer-generated local and meso-scale models. This will help scientists and engineers to better plan environmental and ground water management issues in Oshtemo Township and in surrounding locations in the Great Lakes region that have a similar climate and hydrological record.

Inter-annual analysis for the period 1981 to 1999 revealed a high variability from year to year in both the mean accumulation and the mean number of precipitation hours. Trend lines showed no statistically significant change in either the accumulation of precipitation or the number of precipitation hours. This was similar to what was observed at a nearby station in South Bend, Indiana (to the south of Oshtemo). However, a decrease in precipitation was observed at both Muskegon and Grand Rapids, though statistically significant only at Muskegon. Nevertheless, the similarity between Oshtemo and South Bend suggests that the inter-annual analysis reliably portrayed the precipitation trend in Oshtemo Township.

Overall, the findings of this study create a better understanding of the precipitation climatology of the region and will benefit both the general and scientific community in several ways. First, the research performed here serves as a baseline for future research on the local climate change. This is the first in-depth time series analysis of such magnitude performed for a location in southwest lower Michigan. Second, results may be compared with neighboring areas not under the influence of the Great Lakes. Similarities and differences between regions may be analyzed to gain a better understanding of the "lake-effect" phenomena. Third, results may provide benefits to Oshtemo Township and to other Great Lakes communities which are experiencing rapid urban development. Issues such as storm drainage management and ground water supply increase in importance as communities continue to grow. Accurate precipitation data are essential for developing adequate procedures to meet these needs.

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