a circulatory pattern with a lakeward return flow at higher altitude). These onshore winds moderate surface air temperatures inland.

Lyons (1972) and others have shown that these lake breezes can penetrate about 40 km inland. However, citing Herkoff (1969), Lyons cautions that it is unwise to track lake breeze penetrations by isotherm analysis as surface air modifies rapidly and reaches near-inland values after traveling only a few kilometers. In other words, while lake breeze penetration may extend considerable distances onshore, the temperature moderating effects are often confined to a lesser distance from the shoreline. Similarly, it may be argued that prevailing synoptic winds blowing off of the lake modify surface air temperatures only a few kilometers inland. In the city of Buffalo, consideration must also be given to surface air temperature modifications associated with the urban heat island.

The official weather data for Buffalo, New York are collected by the National Weather Service (NWS) at the Buffalo Niagara International Airport (42.94°N and 78.73°W). This site is located 14 km inland from Lake Erie (Fig. 1). While the NWS site has moved a number of times[1], the various locations were only located a few blocks from one another, and always about 1.5 km from the Lake Erie waterfront (Fig. 1).

Pre-1943 NWS climate data would have recorded the influence of the station's proximity to Lake Erie. A comparison of NWS climate data for Buffalo prior to 1943 (1914 to 1942) with Lockport, New York (Fig. 1), the closest inland station with an uninterrupted record, reveal that Buffalo experienced a typical lake-effect control, cooler than Lockport during the spring and early summer and warmer than Lockport during fall and winter (Quinn et al. 1982). After the weather station's 1943 move to the inland location, the difference in temperature between Buffalo and Lockport all but disappeared. Quinn et al. (1982) concluded that the lake effect was essentially eliminated from Buffalo's climate record. Prior to the weather station's move to the airport, two years of NWS data (1941 and 1942) were simultaneously collected at both the waterfront (former) and inland (current) sites. As with the Buffalo-Lockport pre-1943 comparison, the simultaneous collections revealed that the lake effect was absent from the inland site (Quinn et al. 1982). However, with the exception of those two years, no data have previously been available for direct comparison between the inland airport site and locations closer to the waterfront.

Air temperature data from a waterfront location were recently found in the log books of the Colonel Ward Pumping Station, located at the confluence of Lake Erie and the Niagara River (Fig. 1). The Colonel Ward Pumping station air temperature data were not available to Quinn et al. (1982) in their assessment of Buffalo's "lost" lake effect. The availability of the post-1942 pumping station temperature data may serve as a proxy for the original NWS downtown location, allowing for a longer-term comparison of waterfront and inland (airport) station temperatures.

Objectives of this paper are: 1) to compare surface air temperature data from Buffalo's current inland weather station with that recorded at the waterfront Colonel Ward Pumping Station in order to determine if the lake effect climatology has been "lost" from the post-1942 temperature record; and 2) to determine if the seasonal and annual temperature means of the inland weather station have been impacted by its move inland.

METHODOLOGY

We obtained air temperature data from the log books of the Colonel Ward Pumping Station.[2] The log book data provide a single daily air temperature recorded continuously (no data gaps) over a period of 60 years (1927 to 1987). The data from 1943 to 1987 (45 years) were used in this study.[3] There is no information on the type of thermometer used, nor of its exposure. Notations in the log books clearly indicate that temperatures were recorded as daily averages. We speculate that air temperatures were taken three times a day, once each shift, and then averaged.

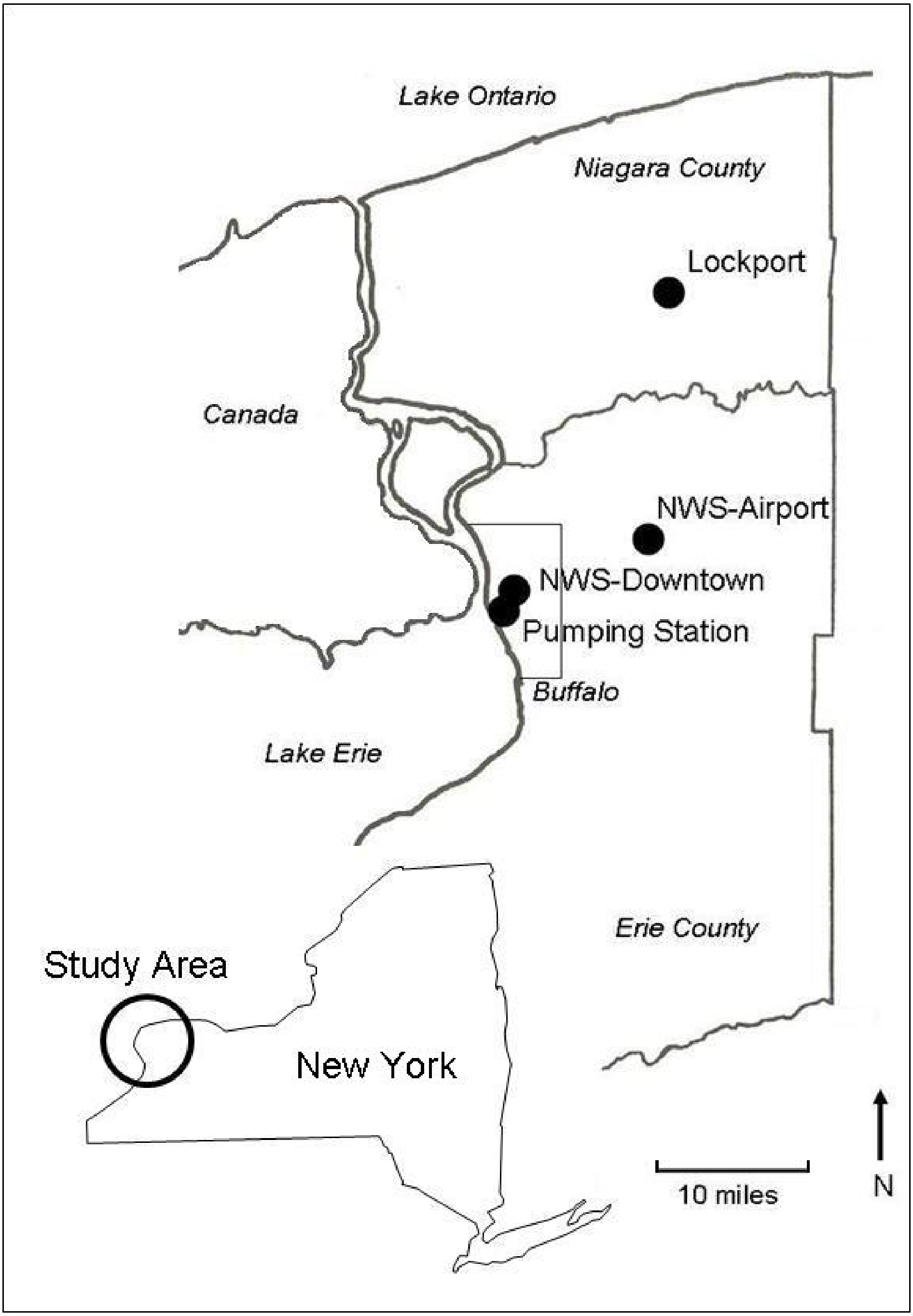

Figure 1. Map of Western New York showing the location of three sources of weather data used in this paper, as well as the pre-1943 NWS downtown site.

Comparisons with NWS temperatures show that the values recorded in the log books are not the same, but are reasonably similar (e.g. within a few degrees), indicating that the data were not simply copied from the NWS record and that the thermometer used was given a proper exposure (i.e. protected from exposure to the sun). Daily averages from the log books were used to calculate annual averages and an average monthly time series. We also obtained monthly air temperatures (1943 to 1987) from the NWS site located inland at the Buffalo Niagara International Airport. Monthly temperature values were taken from Buffalo's NWS web site.[4]

The monthly temperature values calculated for the pumping station and obtained from the NWS were calculated from daily averages. However, the daily average temperatures were calculated differently for the two sites. The pumping station daily average temperature is likely based on three single measurements, whereas the NWS daily average is based on hourly averages.

Temperature differences were calculated for each month by subtracting the monthly average temperature as recorded at the airport inland station from those values at the waterfront pumping station (Difference °F = Waterfront °F – Inland °F). The difference in temperatures between the two locations is defined here as the "lost lake effect." A negative difference indicates that the waterfront is cooler than the inland (NWS-airport) site. A positive difference indicates that the waterfront is warmer than the inland site.

We created monthly lake-effect graphs for the 45-year study period. Seasonality is discussed in terms of four meteorological seasons: Winter (December – February), Spring (March – May), Summer (June – August), and Autumn (September – November). The significance of the lake effect was determined by a two-tailed paired T-test at a 90% confidence level.

MONTHLY TIME SERIES

An examination of the 1943 to 1987 monthly time series, comparing monthly temperature data between the waterfront and inland sites, shows a level of yearly variability approaching, and sometimes exceeding, 4.0°F. While year-to-year monthly variability in the lake effect is to be expected, the overall direction (positive or negative), with few exceptions, is consistent over the years (Figs. 2-5). Waterfront temperatures during winter months (December, January, and February) are warmer (Fig. 2). By March, temperature differences fluctuate above and below zero, preceding cooler waterfront temperatures in April, May, and June (Figs. 3-4). By July (Fig. 4), temperature differences again fluctuate around zero, preceding warmer waterfront temperatures for August, September, October, and November (Figs. 4-5). These patterns are typical of a lake effect, and their presence in these calculations strongly supports the weakening or absence of a lake effect at the current Buffalo weather station.

A major exception to this pattern occurs from 1943 to 1950 when the spring cooling persists through fall months, ending in November and December. An examination of Lake Erie water temperature (sampled at the water intake of the Colonel Ward pumping station) and Buffalo's air temperature (both sites) trends reveal no obvious clues that help explain this uncharacteristic lake effect behavior.

AVERAGE MONTHLY TIME SERIES

A comparison of average monthly temperatures between the waterfront and inland sites clearly shows a classic lake breeze along Buffalo's waterfront (Fig. 6). Two data sets are presented: 1943 to 1987 (45 years), and 1951 to 1987 (36 years). The latter data set does not include the uncharacteristically cool period of the 1940's.

During the winter months (December, January, and February) the Lake Erie waterfront air temperatures averaged 0.80°F (45 year record) and 0.93°F warmer (36 year record), respectively, than the current inland site. March is a transition month for both data sets, showing no statistically significant

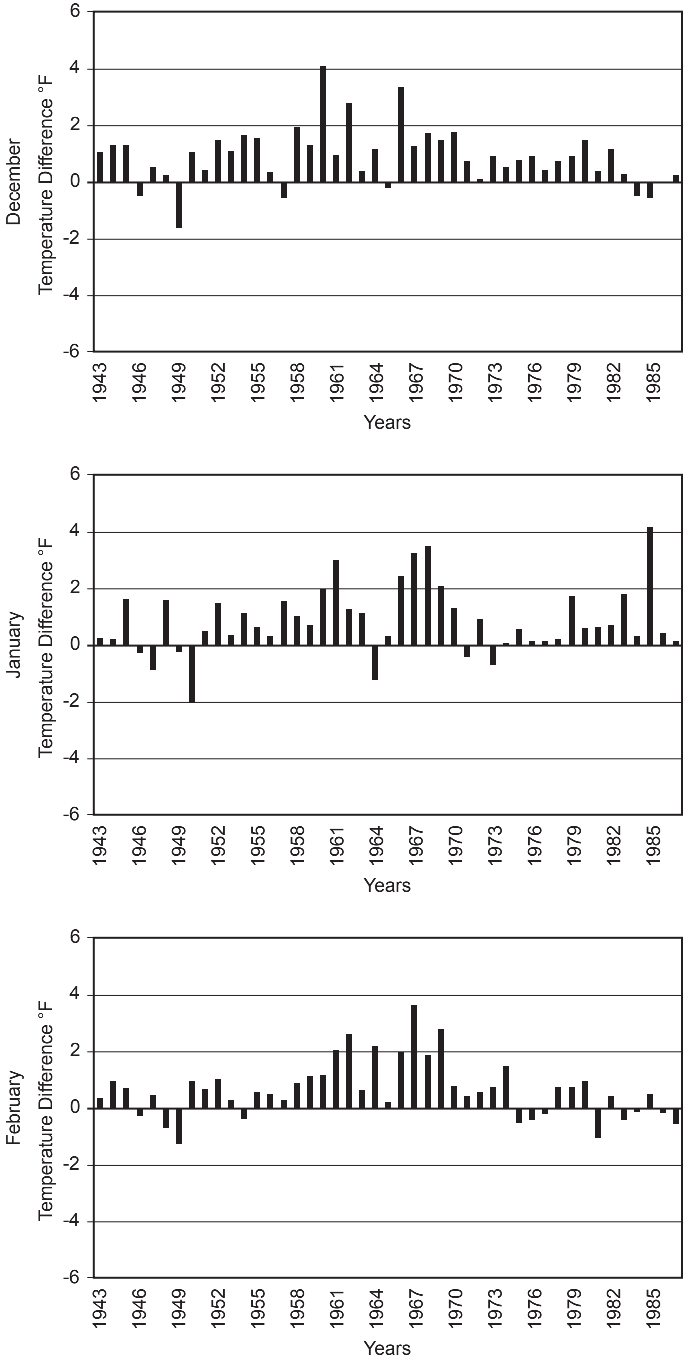

Figure 2. Winter lake effect (December-February). Positive differences indicate a warmer waterfront site, while negative differences indicate a cooler waterfront site.

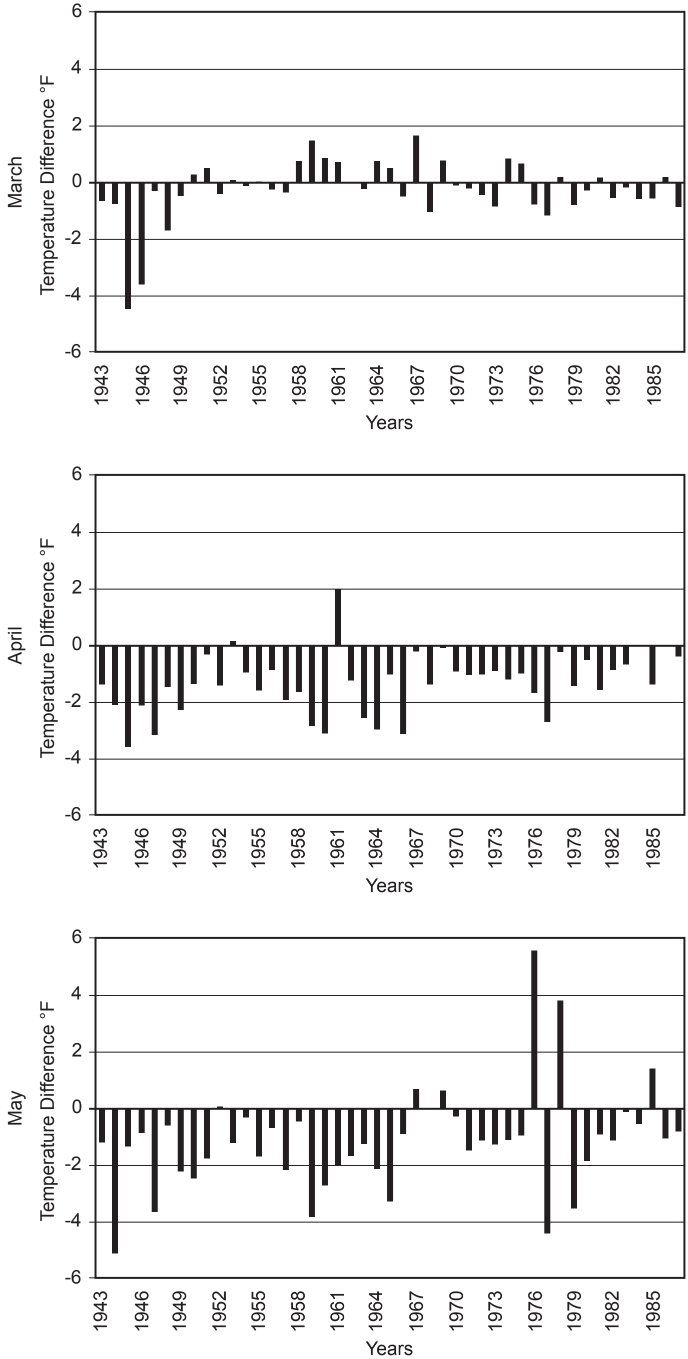

Figure 3. Spring lake effect (March-May). Positive differences indicate a warmer waterfront site, while negative differences indicate a cooler waterfront site.

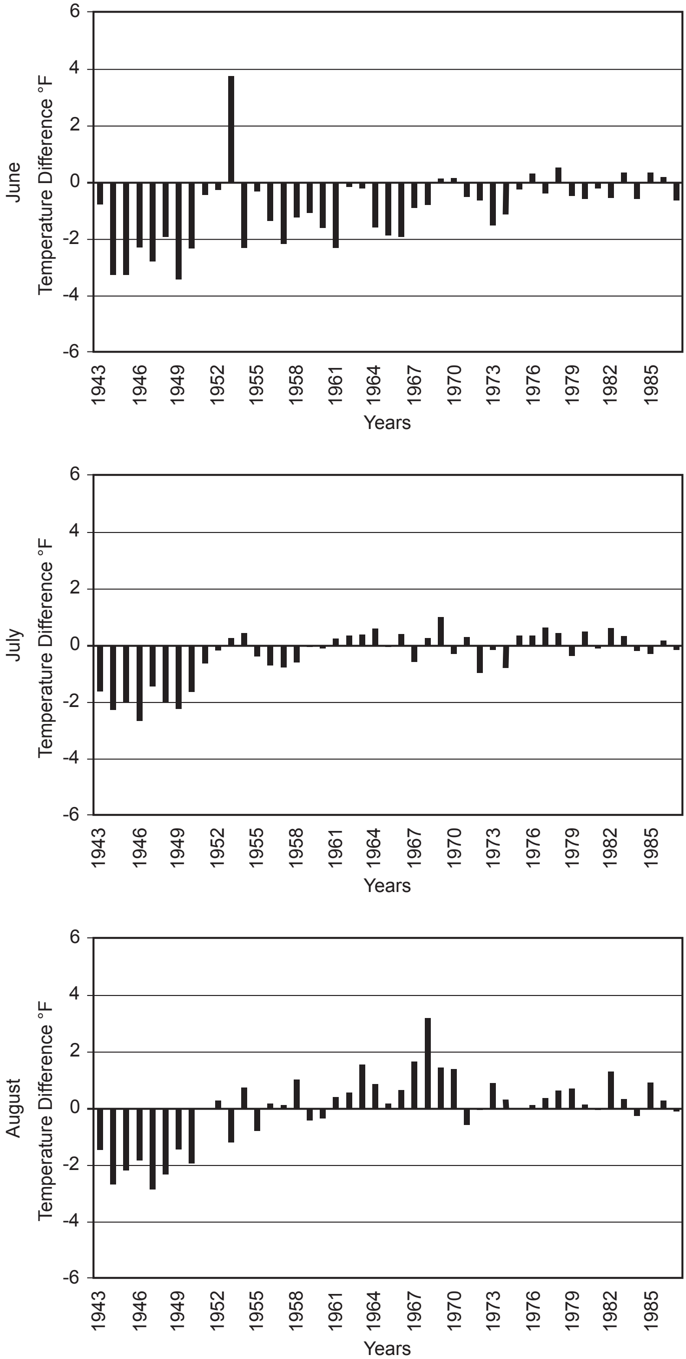

Figure 4. Summer lake effect (June-August). Positive differences indicate a warmer waterfront site, while negative differences indicate a cooler waterfront site.

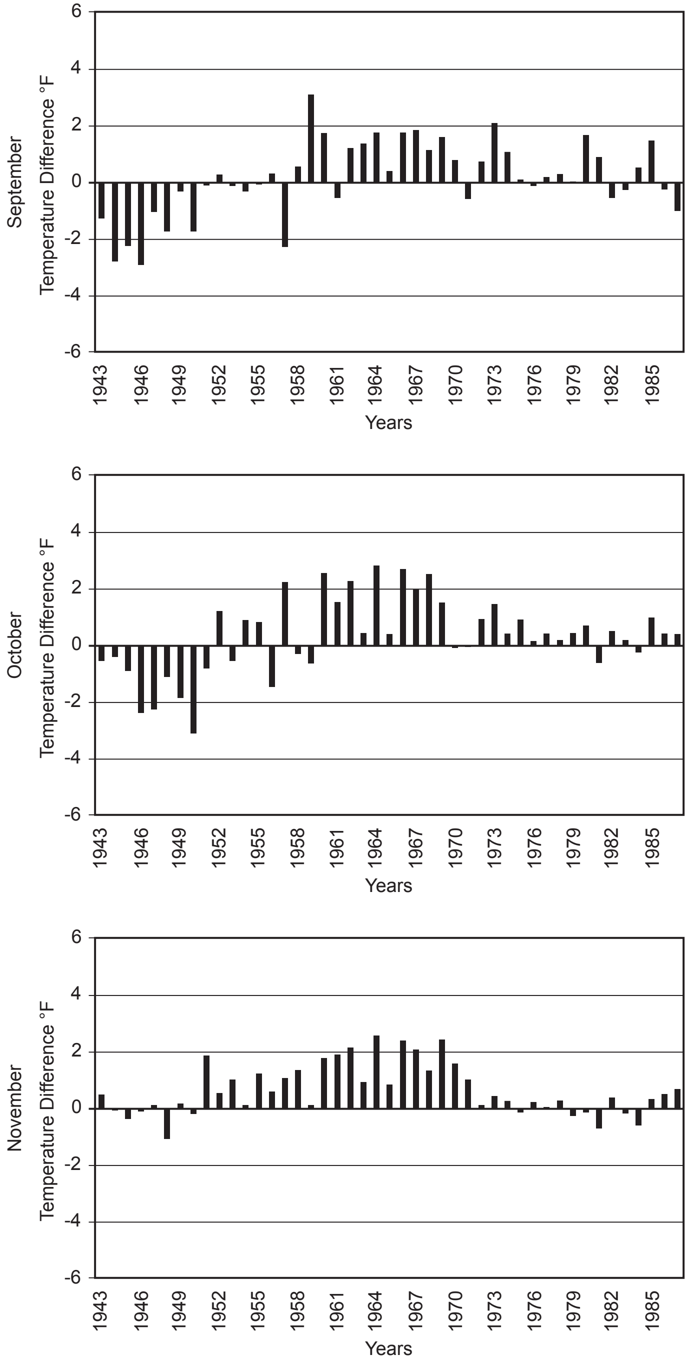

Figure 5. Fall lake effect (September-November). Positive differences indicate a warmer waterfront site, while negative differences indicate a cooler waterfront site.

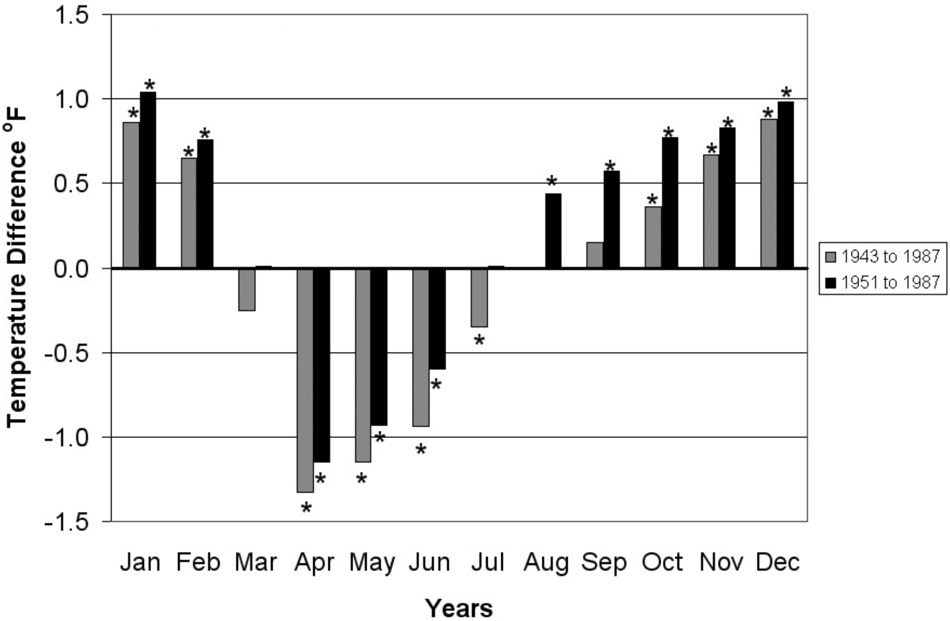

Figure 6. Average Monthly Lake Effect between 1943-1987 and 1951-1987. Positive differences indicate a warmer waterfront site while negative differences indicate a cooler waterfront site. Asterisked months (*) show significant temperature differences (paired T-test, 90% confidence level).

difference in temperatures between sites (i.e. no lake effect). The months of April, May, and June (spring and early summer) illustrate a reversal in temperatures, where waterfront temperatures are an average -0.75°F and -0.89°F cooler, respectively, than the current inland site. For both data sets, the month of April experiences the most dramatic cooling (-1.33°F and -1.15°F, respectively), with temperature differences steadily decreasing through July (-0.35°F and 0.01°F, respectively). July is a transition month for the 1943-1987 calculation, while August and September are transition months for the 1951-1987 calculations. The autumn months (October and November) illustrate warmer temperature differences along the shoreline (averaging 0.52°F and 0.77°F, respectively), and differences peak in December at 0.88°F and 0.98°F, respectively. The lake effect was statistically significant at the 90% confidence level for the months of January, February, April, May, June, October, November, and December for both datasets. July showed a significant effect in the 1943-1987 calculations, while August and September did in the 1951-1987 period.

The presence of the lake effect in the average monthly time series comparison suggests that it has been lost in the airport's post-1942 temperature record. The inland weather station is cooler by 0.80 to 0.93°F during late autumn and winter and warmer by 0.75 to 0.89°F in late spring and early summer than if it had remained at the water front. The inland station is 1.15 to 1.33°F warmer during the month of April, and 0.88 to 0.98°F cooler during the month of December, than if it had remained at the waterfront. The months of March and July (transition months) exhibit no difference - thus the air temperature record at the inland site is consistent with what would have been recorded at the waterfront site.

While the monthly temperature record (with the exception of March and July) appears to have been impacted by the weather station's move inland, the annual difference is negligible for the 1943-1987 study period (0.04°F warmer at the inland site), and slightly cooler at the inland site for the 1951-1987 study period (-0.23°F). This net cooling reflects the removal of data from the 1940s and includes the strong waterfront warming associated with the 1960s lake effect. The magnitude of the lost lake effect as determined in this study is in reasonable agreement with earlier studies (Table 1). However, the loss of the Lake Effect has led to a slightly cooler inland air temperature (warmer at the waterfront) that is contrary to the findings of Quinn et al. (1982) who report a slightly warmer Buffalo climate record in its absence (Table 1).

DECADAL SERIES

While lake effect may be seen as a zero-sum phenomenon at the annual scale, with cooler summers canceling out warmer winters, this is not always the case, and there are decadal trends apparent in the data. The 1940s exhibit the coolest net lake effect of -1.27°F (most distinct in July to October when compared with other decades), while the 1960s appear to exhibit the warmest and most pronounced net lake effect of 0.69°F (Fig. 7). Implications for the inland weather station is that the 1940s air temperature record is warmer than if the station had remained at the waterfront, and the 1960s air temperature record is cooler than if it had remained at the waterfront. The 1950s, 1970s, and 1980s appear to exhibit a net lake effect hovering around zero (Fig. 7). In other words, the lost

Table 1. Lake Effect on Buffalo's Air Temperatures (°F) as indicated by differences in waterfront and inland (airport) locations (waterfront minus airport).

Month	**This Study 1943-1987**	**This Study 1951-1987**	1941 & 1942 Simultaneous Measurements*	Lockport 1914-1942 Comparison with Buffalo#
January	**0.86**	**1.04**	0.22	0.11
February	**0.65**	**0.76**	0.79	0.00
March	**-0.25**	**0.01**	-0.50	-0.59
April	**-1.33**	**-1.15**	-1.49	-1.60
May	**-1.15**	**-0.93**	-1.98	-1.80
June	**-0.94**	**-0.60**	-1.10	-1.01
July	**-0.35**	**0.01**	-0.90	-0.50
August	**-0.01**	**0.44**	0.31	0.20
September	**0.15**	**0.57**	0.50	0.20
October	**0.36**	**0.77**	0.50	0.79
November	**0.67**	**0.83**	0.40	0.20
December	**0.88**	**0.98**	0.20	0.31
Annual	**-0.04**	**0.23**	-0.24	-0.31

* 1941 and 1942 simultaneous measurements (Quinn et al., 1982)

1914 to 1942 comparison between Buffalo, NY and Lockport, NY (Quinn et al., 1982)

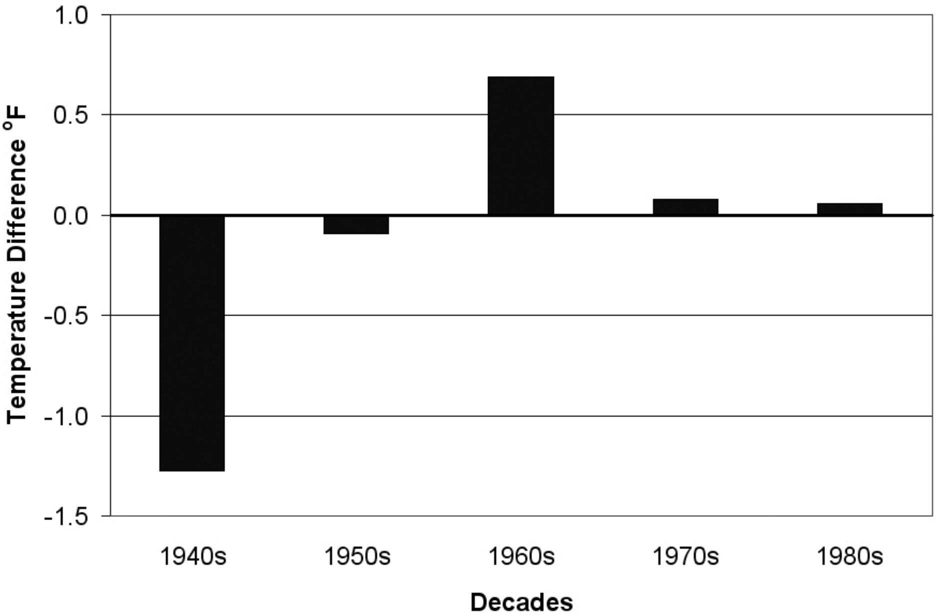

Figure 7. Decadal Lake Effect. Positive differences indicate a warmer waterfront site, while negative differences indicate a cooler waterfront site.

lake effect had a minimal impact on the annual mean temperature record during these three decades.

CONCLUSION

Differences in average monthly temperatures between the waterfront Colonel Ward Pumping Station and the inland NWS location at the Buffalo Niagara International Airport support the earlier claim by Quinn et al. (1982) that the move of the NWS to the current airport location has resulted in the loss of the lake effect in Buffalo's post-1942 climate record.

The character and magnitude of the lost lake effect can be described as one with winter months that would have averaged 0.80°F to 0.93°F warmer than the current Buffalo record. Spring and early summer temperatures would have averaged - 0.75°F to -0.89°F cooler than the current Buffalo record, with the month of April experiencing the greatest cooling (-1.15°F to -1.33°F). The autumn months would have averaged 0.52°F to 0.77°F warmer than the current Buffalo record, peaking in the early winter month of December (0.88°F and 0.98°F). March and July (and August and September to a lesser degree) appear as transition months having the least impact on the post-1942 climate record.

Within the 1943 to 1987 study period, the impact of the lost lake effect on the annual mean temperature record appears minimal (-0.04°F) as temperature gains in one season are lost in another, although this difference is dependent on the decades studied. The 1950s, 1970s, and 1980s show minimal annual temperature difference (<0.20°F) between the waterfront and inland sites, and thus the move of the NWS inland would have had a minimal impact on the annual climate record during that period. However, the 1940s lake effect would have resulted in an average annual cooling of -1.27°F, while the 1960s lake effect would have resulted in an average annual warming of 0.69°F.

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ENDNOTE

1. Prior to 1943, the NWS was located at five different locations in downtown Buffalo: Main and Seneca Streets from 1870 to 1871; Main and Swan Streets from 1871 to 1883; Seneca and Pearl Streets from 1883 to 1896; Church and Pearl Streets from 1896 to 1913; and Church and Franklin Street from 1913 to 1943 (NOAA 1980).
2. While temperature data is traditionally reported in degrees Celsius (°C), the temperature values are reported here in degrees Fahrenheit (°F), since the historic record used in this study reported temperature in °F and a conversion to °C would introduce an unnecessary degree of rounding and imprecision.
3. The validity of using the pumping station data as a suitable proxy for the NWS downtown site could be strengthened by comparing the two temperature data sets from 1927 to 1942. However, the thermometer at the NWS downtown site was located about 75 meters above the ground (rooftop) during this period (NOAA 1980), negating the value of any comparison.
4. Monthly average temperatures were obtained from [http://www.erh.noaa.gov/er/buf], with sequential links to *Local Climate*, *Local Data Records*, and *Buffalo Monthly Temperature*.

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