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Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes

Michael J. McCormick
NOAA, Great Lakes Environmental Research Laboratory, 2205 Commonwealth Boulevard, Ann Arbor, Michigan 48105

Gary L. Fahnenstiel
NOAA, Lake Michigan Field Station, 1431 Beach Street, Muskegon, Michigan 49441

Abstract

In the Great Lakes region, the observational evidence for climatic change has been primarily limited to changes in lake-ice conditions, with no long-term trends identified in water temperatures. Seven nearshore water intake sites (Bay City, Michigan; Green Bay, Wisconsin; Sault Ste. Marie, Michigan; St. Joseph, Michigan; Sandusky Bay, Ohio; Put-In-Bay, Ohio; and Erie, Pennsylvania) in the Great Lakes were chosen, and their data were examined for any climatic trends. Regression results on the annual mean temperatures showed varying support in favor of a warming trend at five of the seven sites. A new approach facilitated determination of the interannual variability in the timing of the 4°C temperature of maximum density. Two of the three sites with data records extending back to the early part of this century (Sault Ste. Marie and Put-In-Bay, respectively) showed a 4- and a 6-h yr^{-1} rate of increase in the maximum potential duration of summer stratification (DSS). Over the time span of these two data sets, this equates to a 14- and 18-d increase in the potential DSS, respectively. The rate of increase in the duration data was skewed, with most of the increase due to an earlier transition to springlike conditions. Finally, the data do not extend far enough back in time to know if these climatic trends are part of an unresolvable natural cycle or forced by anthropogenic activity.

General circulation models (GCM) representing physical processes from both the atmosphere and ocean have seen widespread application in attempting to forecast the long-term implications of increasing atmospheric CO_2. Observational evidence for global warming centers on long-term temperature records (Hansen and Lebedeff 1988; Wigley et al. 1989) and proxy climate variables, which infer historical global temperatures based on ice core analyses (Barnola et al. 1987), tree ring data (Feng and Epstein 1996), bore hole temperatures, and the retreat of mountain glaciers (Ott 1997). At the same time, new insights suggest that much of the observed warming may be partially explained by a reduction in the diurnal temperature range for most parts of the world (Easterling et al. 1997).

Both modeling and data approaches toward understanding global processes are hampered by uncertainty. Grotch (1988) documents a 2–3°C departure from global median temperatures with four different GCMs when they were used to simulate current conditions. Observational data also suffer from possible bias due to changes in land use patterns and inadequate spatial coverage. The limitations of GCMs on global scales grow when viewed at regional scales (Grotch 1988). However, some observational problems associated with global assessments are minimized on regional scales because of the existence of more adequate data sources.

Global climate modeling results have predicted that the greatest climate warming is projected to occur during the winter months at high northern hemisphere latitudes (IPCC 1992). Smaller scale climate modeling efforts in the Great Lakes region have identified additional potential problems resulting in increased coastal erosion due to changes in the nearshore-ice complex (Banes et al. 1993), concerns over the impact of lowered lake levels (Croley 1990; Changnon 1993), changes in the thermal structure of the lakes with stronger stratification and a longer stratified season (McCormick 1990), concerns over hypolimnion anoxia in the lower Great Lakes (Blumberg and DiToro 1990; Schertzer and Sawchuk 1990), and potential changes in fish communities (Magnuson et al. 1990; Regier et al. 1990). The major difficulty confronting modeling efforts is resolving the radiative perturbation that climate change represents in a credible manner. For example, all of the thermal structure sensitivities identified in McCormick (1990) resulted from a change as low as 6 W m^{-2} in the annual heat flux. When compared against monthly ranges of ± 250 W m^{-2} and daily ranges, over the course of a year, of $\pm 1{,}000$ W m^{-2}, the power of small signals when they persist and the valuable role of observation for testing theoretical expectations generated from climate change studies are emphasized.

Observations on climate warming effects have been noted in northwestern Ontario lakes (Schindler et al. 1996*a*), with warmer air and water temperatures and a longer ice-free season. These effects have been linked to additional problems involving acid rain and ultraviolet radiation (Schindler et al. 1996*b*). Empirical evidence suggests that regions of Lake Huron may have a warmer and shallower epilimnion today

Acknowledgments

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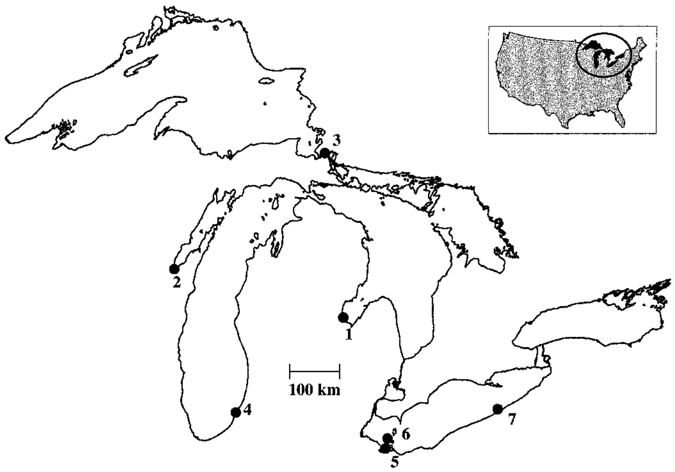

Fig. 1. Nearshore water temperature site locations: (1) Bay City, Michigan; (2) Green Bay, Wisconsin; (3) Sault Ste. Marie, Michigan; (4) St. Joseph, Michigan; (5) Sandusky Bay, Ohio; (6) Put-In-Bay, Ohio; and (7) Erie, Pennsylvania.

than it did in the mid-1950s (King et al. 1997). Recent reductions in Great Lakes winter ice coverage may increase phosphorus concentrations and accelerate eutrophication concerns (Nicholls 1998). Several studies further suggest that reduced ice coverage has occurred on both small scales (Anderson et al. 1996) and large scales throughout the Great Lakes (Hanson et al. 1992; Assel and Robertson 1995). However, no long-term trends in water temperatures of the Great Lakes have been identified.

Knowledge of the climatological distribution of temperature is fundamental to determining physical dynamics and to evaluating biological health and productivity of the ecosystem. It serves as a basis for gauging the impact of potential climatic change, and if the climatological data are extensive enough, then historical analogs may be identified that may mimic conditions suggested by simulations based on future climate scenarios. Despite the known importance of temperature, relatively little information exists for determining the offshore climatology of the Great Lakes (i.e., Church 1945; Ayers 1965; McCormick 1990; Lesht and Brandner 1992; McCormick and Pazdalski 1993), yet considerable nearshore water intake temperature data exist from many locales in the region. This paper focuses on water temperature data taken from seven sites in the Great Lakes. An annual climatological cycle is calculated for each site, and additional analyses are performed based on the annual mean temperatures. More importantly, a new approach is employed to make explicit use of natural markers: time and the 4°C temperature of maximum density. This allows clear access to the underlying climate structure and thus, with the application of this approach, provides additional insights into the nature of climatic trends in the nearshore water temperatures of the Great Lakes.

Data description

Figure 1 shows the locations of the seven sites used in these analyses. The sites were chosen to represent the diversity of nearshore environments in the Great Lakes. The sites analyzed represent oligotrophic to eutrophic conditions, are subject to annual ice coverage, and represent the different physical regimes as found in open coastlines and in embayments. Although numerous sites exist in the Great Lakes region that regularly record water intake temperatures, relatively few have intact data records that exist past 30 yr. Still other sites may have raw data for much longer periods, but access to the data was limited to onsite examination, and the associated cost of data compilation was prohibitive. One limitation common to all of these data sets is ignorance over the measurement errors inherent to these data. No one at the individual sites was able to quantify data accuracy, and therefore, no attempt was made here to assess data accuracy, other than by careful editing to remove obvious errors and by assuming that any remaining errors were randomly distributed.

The complete data sets used here can be found in McCormick (1996*a–g*). A brief description of each set follows.

1. Bay City, Michigan—Water temperature data from the water intake crib at Bay City, Michigan, were obtained from the plant from 1946 through November 1993. However, no data were available from 1956 to 1966 and 1968. Prior to 1951, the crib was located in Saginaw Bay, Lake Huron, approximately 2 km offshore, with a water intake 1.5 m below the surface and a total water depth of 2.5 m. After 1951, a new intake crib (43.718°N, 83.901°W) became operational approximately 6 km northwest of the old site, extending nearly 3 km offshore, with the water intake at 3.3 m below the surface and a total water depth of 4.3 m. Water temperatures are recorded in the plant once every 8 h and then averaged into a daily value. This portion of Saginaw Bay is shallow, and intrusions of Lake Huron water are limited and episodic in nature (Danek and Saylor 1977). The limited mixing with Lake Huron contributes to maintaining eutrophic conditions in Saginaw Bay, with some of the highest recorded standing stocks of phytoplankton and productivity (Vollenweider et al. 1974) seen in the Great Lakes.

2. Green Bay, Wisconsin—Water temperature data were recorded by Wisconsin Public Service Corporation's Pulliam Power Plant in Green Bay, Wisconsin. The plant is located at the mouth of the Fox River, and data were obtained from 1947 through 1990.

The plant's water intake is located at 44.539°N and 88.006°W in water that is <2 m in depth. The plant's water supply is derived from a combination of the Fox River and Green Bay, both of which are eutrophic environments (Chen et al. 1983). This location is subject to large temperature swings during the spring and fall because of the proximity of these two dynamically different environments.

Data were only available onsite in a hand-written format. The water temperature records were recorded at hourly intervals, transcribed into a computer-compatible format, and then averaged into one daily value. Some data were lost or destroyed, resulting in large data gaps extending up to weeks in some years.

3. Sault Ste. Marie, Michigan—Water temperature data from two sites near the eastern end of Lake Superior were obtained from 1906 through 1992. Both data sets record water temperatures from the Saint Mary's River in Sault Ste. Marie, Michigan. The first data set is from the Edison Sault Hydroelectric Plant and covers the period from 1906 to 1963. Temperatures were recorded once daily from April through December at the plant (46.497°N, 84.332°W). The sensor is located near the bottom of the 6-m-deep open channel (Edison Sault Electric Co. Canal) that diverts water from the river to the plant. The canal is 3.5 km long, 61 m wide, and 6 m deep and runs through the center of Sault Ste. Marie. The transit time for the canal water is 20–30 min from the river to the hydroelectric plant. The archived data were provided by the Sault Ste. Marie office of the National Weather Service.

More recent data from 1964 through 1992 were obtained from the U.S. Army Corps of Engineers (COE) hydroelectric plant located in the St. Mary's River adjacent to the shipping locks. Partial data sets from December though February were also obtained for 1957 through 1963 and were used to supplement missing Edison data during that time. Measurement details at the COE plant are similar to the other data set, with readings taken once daily, near the 6-m-deep bottom, at the hydroelectric plant's gate slot (46.506°N, 84.349°W). The relatively rapid transit times for waters draining from Lake Superior through this river and the low observed turbidity found there suggest that these data are representative of the oligotrophic conditions that exist in the lake.

The two hydroelectric plants are only 1.7 km apart. From 1967 through 1983, the COE plant recorded monthly averaged temperatures from the two plants. The monthly averaged data appeared to show no bias between the data sets, with temperatures in close agreement during the winter months, and yet occasionally, they differed by up to 1.5°C during summer and fall. Whether these differences are a result of instrument/operator error, sampling errors, or some other explanation cannot be discerned. However, some of the analyses used here are not as sensitive to potential temperature and sampling errors that occur during summer and early fall.

4. St. Joseph, Michigan—Water intake temperature data were recorded at the water intake plant in St. Joseph, Michigan. Data were available from 1936, 1937, 1940–1945, and 1960–1992. According to the plant manager, all data from 1946 to 1959, 1938, and 1939 were lost.

Prior to 1956, the water intake was located in Lake Michigan approximately 450 m from shore at 4 m below the surface with a total water depth of 5 m. After 1956, the intake was shortened to 350 m with comparable water depths and was located at 42.097°N, 86.505°W. All temperature data were recorded in the plant once daily and compiled into an ASCII format by plant personnel.

St. Joseph is located on an open coastline, and the water intake pipe is in a location subject to coastal upwellings. Our climate trend analyses for this site will focus on data from 1960 to 1992. And, based on inferences from Lake Michigan core data on microfossil abundance and composition (Stoermer et al. 1990), the temperature data from this period can be considered as being from a eutrophic environment.

5. Sandusky Bay, Ohio—The data used here were provided by the Ohio Department of Natural Resources, Lake Erie Fisheries Unit, Sandusky Bay. The data were measured at the U.S. Gypsum Co. water intake located in Sandusky Bay at 41.487°N, 82.872°W. Water depth at the intake is approximately 1.5 m, and the Sandusky Bay location is nearly 15 km from where the bay enters Lake Erie. The bay is shallow and eutrophic (Bolsenga and Herdendorf 1993).

All data were recorded from 1961 through 1993 using an analog temperature-recording unit (Taylor Instruments). The temperature signal is traced automatically by a pen onto an 11-in. paper disk that holds up to 7 d of data. The raw data were converted into a digital format by using a CalComp digitizer and appropriate software. The digitizer was used to measure the radial distance of the raw temperature trace, which is directly proportional to temperature. The digitizer was set to continuously measure the radii every 0.25 mm of arc length for each day and then calculate an average daily temperature in degrees Celsius. Throughout the data set, there were numerous occasions when the paper disk was not changed on a weekly interval, resulting in some significant data gaps. The data gaps were extensive enough that the following years were excluded from all of the analyses: 1978, 1984, 1985, and 1988–1992.

6. Put-In-Bay, Ohio—Water temperature data were measured at the Put-In-Bay fish hatchery located on South Bass Island in the Western Basin of Lake Erie. The entire western basin of Lake Erie including the region surrounding South Bass Island is classified as eutrophic (Bolsenga and Herdendorf 1993). The water collection site was located at 41.659°N, 82.825°W. Temperature data were measured in the hatchery from waters drawn near the hatchery site, where waters are shallow, with depths ranging from 1 to 2 m. The data were collected by the Ohio Department of Natural Resources, Lake Erie Fisheries Unit, Sandusky Bay, from 1918 through 1992. The data from 1918 through 1961 were taken directly from Ohio Department of Natural Resources (1961). All remaining data were recorded on an analog temperature-recording unit identical to that used to record the Sandusky Bay data set. The Put-In-Bay data were also processed in the same manner as described above.

Some significant data gaps occur in this data set, which suffered from the same kinds of problems seen in Sandusky Bay. In particular, no data were available for 1937 and 1938.

7. Erie, Pennsylvania—Water temperature data were from the Erie, Pennsylvania, Chestnut Street Water Treatment Plant located on the Eastern Basin of Lake Erie. The water intake pipe is 1.5 m in diameter and extends approximately 2 km offshore to 42.157°N, 80.153°W, where the total water depth at the intake is 8.5 m. Data were obtained from 1916 through 1992; however, no data were available for 1956. Water temperatures were recorded once daily between 0800 and 0900 h in the plant. Throughout most of the data years, temperatures were not recorded on Sundays, except for 1959–1963 and again in 1979–1981, when Sunday temper-

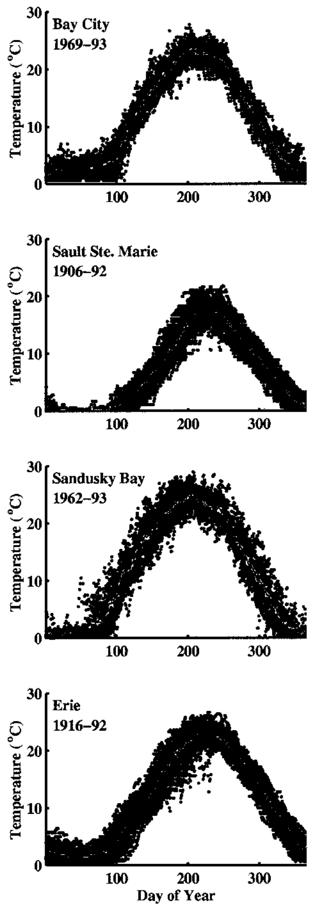

Fig. 2. Scatter plots of all available water temperature data at each site. The mean annual temperature cycle is depicted, and all data within 0.25°C of the mean have been removed for added clarity.

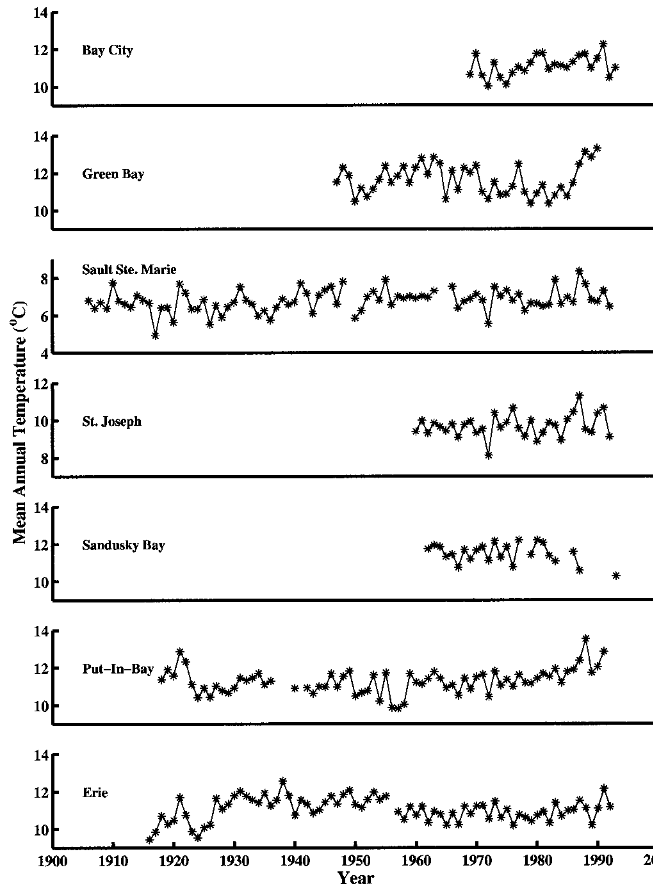

Fig. 3. Annual mean temperatures for each site.

atures were recorded for most of the year. Since its original installation in 1908, the water intake location has remained unchanged throughout the duration of this data set. All of the water intake temperature data were recently transcribed into a computer-compatible format by plant personnel.

Results

Marked differences were found in the temperature data for the seven sites (Fig. 2), reflecting the diversity of nearshore environments. Each site shows the mean annual signal, with Sault Ste. Marie having the smallest amplitude and consistently the lowest wintertime temperatures. The St. Joseph data show the largest variability about the mean during the summer months of any of the data sets. This variability is attributed to the large volume of cold bottom water in Lake Michigan ventilated along the eastern shore when strong northerly winds cause coastal upwelling, exposing large regions to rapid temperature changes.

The annual mean temperatures were calculated for each site and are illustrated in Fig. 3. All available data were used, except for Put-In-Bay, where, in addition to the missing data previously described, the years 1939 and 1941 were also not included in the calculations because only 94 and 139 d of data were recorded, respectively. Simple linear regressions were performed on each of the data sets, and the results are shown in Table 1. Sault Ste. Marie and Put-In-Bay had the most statistically significant trends, showing positive warming trends of nearly 0.01°C yr^{-1}. The results from the Erie and Green Bay data sets strongly suggest that no trend in mean temperatures exists. Bay City and St. Joseph data also show some support for a long-term warming trend, while the Sandusky Bay results suggest that a cooling trend may be present. However, Sandusky Bay has the shortest time duration of data, spanning only 24 yr, and any trends in the data may be due more to the limited time span of the data rather than indicative of a true long-term trend.

Temperature data from each site represent a single point measurement that is difficult to interpret during the summer months, when lake waters are stratified, because of the uncertainty in knowing the correspondence between the recorded temperature and the volume of water these data represent. At some coastal locations, the water intakes may be in shallow, well-mixed waters, where this is not a concern; however, without detailed knowledge of the circulation and residence time of these waters, additional data uncertainty is introduced, uncertainty that stems from ignorance over whether the temperature data are more representative of surface waters, bottom waters, or the entire water column. An-

Table 1. Regression results of the annual mean temperature vs. year.

	Bay City	Green Bay	Sault Ste. Marie	St. Joseph	Sand. Bay	Put-In-Bay	Erie
Slope (°C y^{-1})	0.029	0.001	0.006	0.014	−0.021	0.009	0.0004
Intercept	10.7	11.6	6.5	9.5	11.7	11.0	11.0
R^2	0.15	0	0.07	0.05	0.08	0.08	0
F-statistic	4.0	0.01	6.4	1.7	1.9	5.7	0.02
P-value	0.06	0.94	0.01	0.21	0.18	0.02	0.90
Overall mean temperature	11.11	11.65	6.71	9.78	11.56	11.25	11.05

nual mean temperatures calculated from data that are subject to these concerns are potentially limited in value because of their sensitivity to summer conditions and sensor location. The combination of limited data, sensor location, and potential summer bias may complicate the identification of any climatic trends in the annual mean. To examine the data for the presence of additional climatic signals, which may be of greater limnological significance, the following approach was used.

First, data from each site were organized into a two-dimensional matrix, T(yr,d), where T is the vertical axis and represents temperature, and the two horizontal axes correspond to yr, for year, and, d, for day of the year, respectively.

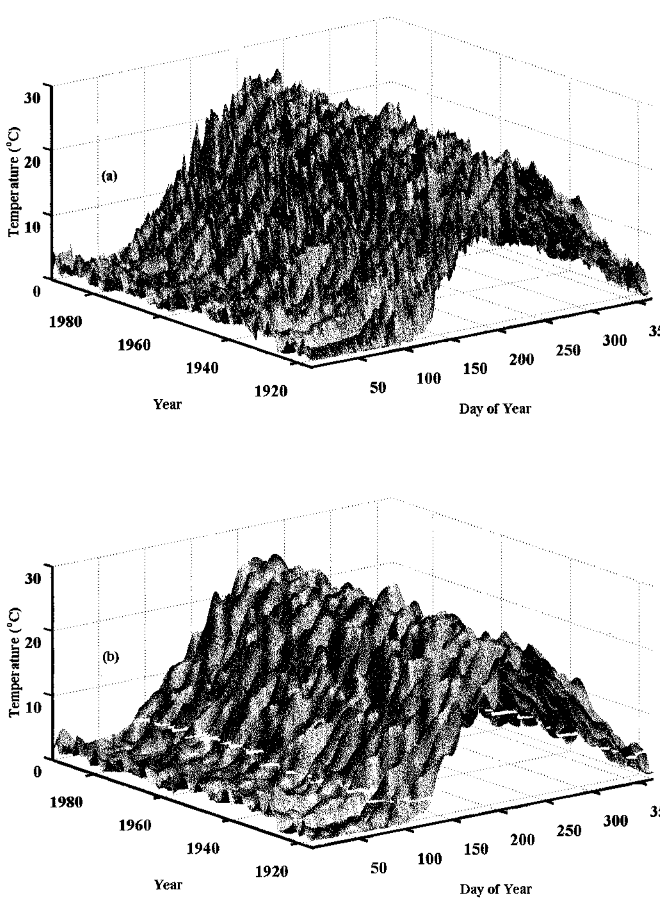

Fig. 4. Three-dimensional plot of the Erie, Pennsylvania, data set, (a) raw data, (b) low-pass–filtered data. The white 4°C contour line depicts the spring and fall transition dates.

Second, the data gaps in both yr and d were filled by linearly interpolating between data in both directions. To properly account for leap years, the year was divided into 366 d. During nonleap years, the 366th d was replaced with data from 1 January from the following year. An example of what the data look like in this context is presented for Erie, Pennsylvania, in the top panel of Fig. 4. The raw data generate a rugged topography, making it difficult to detect any underlying structure other than the annual signal unless some minimal filtering is done to remove the high frequencies that mask that structure.

Finally, each data set was low-pass filtered. A digital elliptical filter was used in MATLAB to low-pass filter the data. The filter was applied in both forward and reverse directions to avoid any phase distortions. The filter was applied within each year, and a cutoff period was chosen to remove that portion of the signal with <20-d periods. This cutoff period eliminates nearshore signals due to coastal upwellings/downwellings and Kelvin wave propagation that complicate data interpretation, yet it is short enough in duration to allow excellent resolution of the annual temperature cycle. The bottom of Fig. 4 shows an example of the low-passed data structure.

There is little loss of information in using the low-pass–filtered data, and what little loss there is occurs primarily during the summer months, when the potential for additional data uncertainty due to the previously described sampling concerns is highest. Figure 5 shows the interannual variance in the annual temperature cycle for the raw and low-pass–filtered temperature data for all sites. The variance distributions of both Green Bay and Sandusky Bay differ from the other sites by showing their greatest variability during spring and fall, while peak variability at the other sites occurs during the summer months. The temperature variance at Green Bay and Sandusky Bay is more suggestive of an environment with little thermal inertia rather than that of a large lake with its large heat storage capacity and correspondingly high thermal inertia.

Using the low-passed data better reveals the low-frequency variability within the data sets than using the raw data alone. By using these data in conjunction with the temperature of maximum density (~4°C), changes in the annual distribution of temperature can be detected by contouring the data sets and determining whether or not the 4°C contours diverge, converge, or are approximately parallel in time. For the purposes of these analyses, the last occurrence of a 4°C temperature in spring and the first occurrence of a 4°C temperature in fall can be considered as marking the maximum

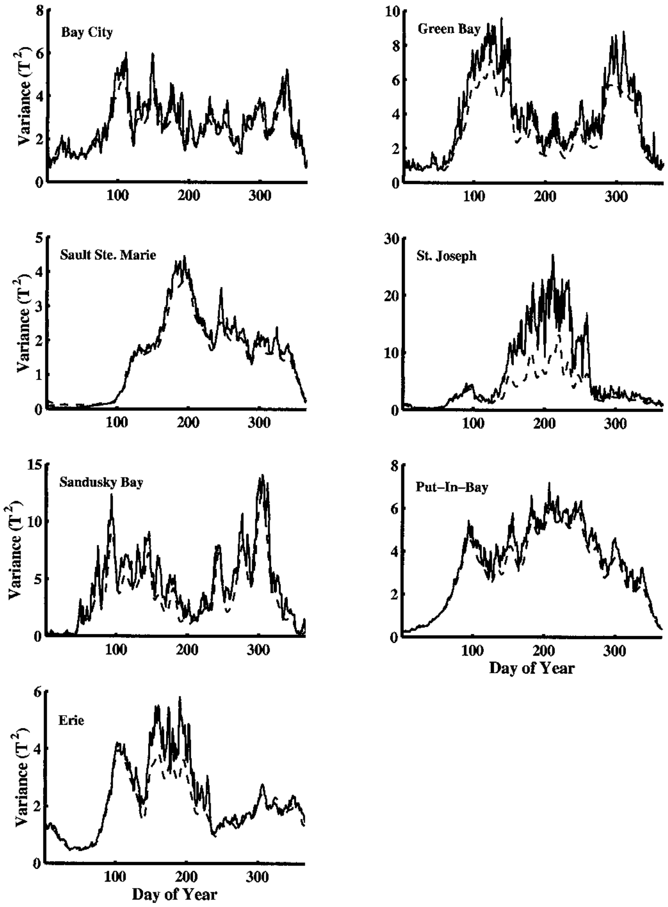

Fig. 5. Temperature variance about the mean annual cycle of raw (solid line) and low-pass–filtered (dashed line) data for all sites.

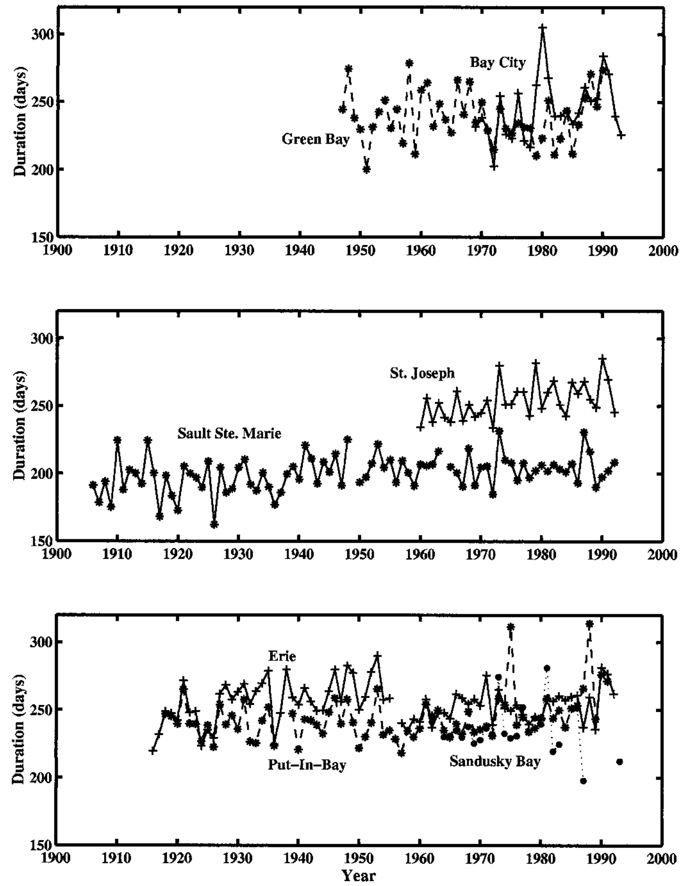

Fig. 6. The maximum potential DSS data vs. year for each site.

potential duration of summer thermal stratification—or equivalently, the maximum potential DSS. The 4°C contour in Fig. 4 marks the transition points in the annual thermal cycle between the period of summer stratification and winter conditions, where the water column is generally near isothermal and well mixed. The water column at these sites may be well mixed and isothermal at temperatures other than 4°C, but our purpose was not to identify the time of overturn but rather to select an indicator of limnological importance that would provide a basis for examining interannual and lower frequency variability.

Interannual changes in the maximum potential DSS as determined from the 4°C contours are shown in Fig. 6 for each site. Each site shows varying degrees of cyclic behavior in the duration data vs. year. Examining the three longest data sets (Sault Ste. Marie, Put-In-Bay, and Erie), it is apparent that ''extreme'' events have occurred repeatedly throughout these data sets. The annual mean temperatures (Fig. 3) show a similar pattern as well. Data patterns like those illustrated here suggest that care must be exercised when selecting the time interval over which to look for data trends. For example, if regressions were performed on the 1960–1990 data, significant trends might be identified; however, if that window were shifted to 1950–1980, completely different conclusions might be drawn. To minimize this concern, all regressions were performed on the entire data sets only. However, the shortness of the Bay City (25 yr) and Sandusky Bay (only 24 yr of data) data sets suggests caution in comparing the results of the data analyses of the shorter data sets with those generated from the longer ones.

Simple linear regressions were performed on all of the site data to see if any long-term trends were present in the DSS data and, if so, then to examine whether or not these trends were due to changes in the spring and/or fall transition dates. The regression analyses were divided into two parts. The first part focused on all of the data sets, while the second part examined the spring and fall transition dates. Also, any data gaps that may have existed in the data sets and that were subsequently filled by linear interpolation to aid filter application and contouring were ignored in all of the following regressions.

Regressions were performed on all of the calculated duration data, and the results are shown in Table 2. The five most statistically significant sites (Sault Ste. Marie, Put-In-Bay, St. Joseph, Bay City, and Erie) all showed positive trends in the maximum potential DSS. Sandusky Bay showed a negative trend, and the Green Bay results were not statistically significant. Of the five former sites, Erie had a very low R^2 and a P value $= 0.35$, offering only marginal support for the presence of a long-term trend. The results of the regressions for these five sites are plotted in Fig. 7.

Two of the three longest data sets (Sault Ste. Marie and

Table 2. Regression results of DSS vs. year.

	Bay City	Green Bay	Sault Ste. Marie	St. Joseph	Sand. Bay	Put-In-Bay	Erie
Slope (day yr^{-1})	1.09	−0.06	0.17	0.65	−0.37	0.25	0.07
Intercept	156.4	242.7	191.8	204.3	263.7	230.1	250.9
R^2	0.13	0.001	0.12	0.22	0.03	0.10	0.01
F-statistic	3.3	0.06	10.8	8.8	0.70	8.1	0.9
P-value	0.08	0.81	0.001	0.006	0.41	0.006	0.35
Correlation with mean annual temperatures	0.72	0.71	0.75	0.70	0.20	0.65	0.74

Put-In-Bay) showed highly significant trends corresponding to an annual increase in the duration data of 4 and 6 h yr^{-1}, respectively. Over the time span of these data sets, this represents a change of 14 d in DSS for Sault Ste. Marie and 18 d for Put-In-Bay. The median rate of increase in DSS for all sites excluding Green Bay was 5 h yr^{-1}.

The correlation coefficients between the DSS and annual mean temperature data were also calculated (Table 2). The correlation was high for all sites, except Sandusky Bay, suggesting that >40% of the variability in the DSS data could be explained by changes in the annual mean temperatures alone. The positive correlation between the DSS data and the mean annual temperatures further suggests that increases in DSS result in a possible increase in the mean annual temperature as well.

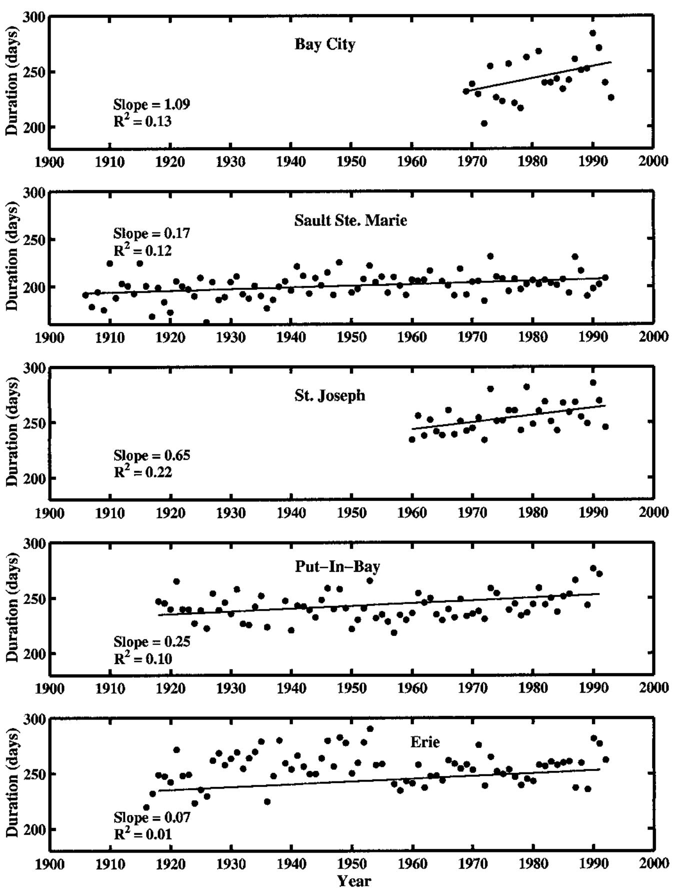

Fig. 7. Plot of maximum potential DSS data from sites showing significant trends over their entire data set (Table 2).

Additional regressions were performed to examine how the lengthening in the maximum potential DSS depends on changes in the spring and fall transition dates, i.e., 4°C temperature markers used to define the maximum potential DSS. Tables 3, 4 show the regression results of the spring and fall dates of transition. In Table 3, all sites showed a negative trend, indicating an earlier arrival of springlike conditions. The Sandusky Bay results were not significant, while the Green Bay results were weakly supportive of a negative trend. The remaining sites suggest an earlier spring transition date ranging from a low of 1.4 h yr^{-1} for Sault Ste. Marie to a high of 16.6 h yr^{-1} for Bay City. The overall median rate of change for all sites (excluding Sandusky Bay) was a negative 3.8 h yr^{-1}.

Results of the fall transition date regressions (Table 4) were highly significant for most of the sites, with the exceptions of Erie, which showed no discernible trends, and Bay City, which was only moderately supportive of a positive trend. A positive trend indicates a later arrival of the fall transition date, and four of the sites (Bay City, Sault Ste. Marie, St. Joseph, and Put-In-Bay) showed positive trends ranging from a low of 1.7 h yr^{-1} for Put-In-Bay to a high of 9.6 h yr^{-1} for Bay City. The Green Bay and Sandusky Bay results showed significant negative trends, indicating an earlier occurrence of the fall transition, with a yearly rate of decrease of 4.6 h yr^{-1} for Green Bay and 10.1 h yr^{-1} for Sandusky Bay. The overall median rate of change for all sites, excluding Erie, was a positive 2.2 h yr^{-1}.

Comparison of the spring and fall transition date analyses shows the median rate of change in the spring transition date to be 70% greater than the rate of increase in the fall transition date. Thus, the lengthening in the maximum potential DSS is asymmetrical in time, with most of the change due to an earlier arrival of the spring transition date compared to changes that occur during the fall.

The presence of long-term trends in the annual mean temperatures and in the maximum potential DSS data suggests that changes in interannual variability may be occurring as well. Two measures were employed to estimate interannual variability, and both led to similar conclusions. The first indicator was based on the annual average of the mean absolute difference between the daily temperature and the long-term daily average temperature. The site-specific long-term daily average temperature is highlighted in Fig. 2. The absolute values of daily temperature departures from the long-

Table 3. Regression results of date of spring transition vs. year.

	Bay City	Green Bay	Sault Ste. Marie	St. Joseph	Sand. Bay	Put-In-Bay	Erie
Slope (day yr^{-1})	−0.69	−0.14	−0.06	−0.43	−0.05	−0.18	−0.08
Intercept	149.3	97.5	136.2	122.4	90.7	101.2	103.4
R^2	0.14	0.02	0.03	0.17	0.001	0.09	0.03
F-statistic	3.6	0.9	2.3	6.4	0.02	6.7	2.0
P-value	0.07	0.35	0.13	0.02	0.89	0.01	0.16

term average were calculated, then a single yearly average was formed. The yearly average mean absolute difference in temperature was then regressed against time, and the results are shown in Table 5. The Erie and Green Bay results were not significant, while changes in interannual variability were weakly supported at Put-In-Bay. Highly significant changes were suggested for Sault Ste. Marie, followed by Bay City, St. Joseph, and Sandusky Bay in decreasing order of statistical significance. Of the later sites just mentioned, only Sault Ste. Marie showed a long-term trend toward a positive increase in interannual variability, while the other three locales suggested that an actual reduction in interannual variability might be occurring.

The same conclusions were reached when the annual temperature variance (Table 6) was examined. The temperature variance for each year's data at each site was calculated and regressed against time. Again, Sault Ste. Marie showed a highly significant increase in interannual variability, while the other sites suggested either no change in variance or a small tendency toward a decrease in interannual variability.

Discussion and conclusions

The duration data analyses provided new understanding of the annual temperature cycle at our study sites, and they were critical for identifying changes in the regional climatology of nearshore water temperatures. Although nearshore water temperatures may be useful for site-specific ecological studies, their value is potentially compromised when the data represent only a single point measurement, as these data do. Interpretation of single point measurements becomes complicated when waters stratify, and uncertainty exists over the volume of water that the data represent. This only adds to the difficulty in detecting meaningful trends in the annual mean water temperatures and their associated confidence intervals. These obstacles are not easily overcome without requiring the use of additional assumptions that may only be testable through modeling exercises (Jones et al. 1997; Zheng et al. 1997) or by applying new approaches such as we did here.

The most difficult of the sampling concerns with the raw data, i.e., interpreting data from the stratified season, were avoided, and new insights were gained from the explicit use of natural markers: time and the 4°C temperature of maximum density. These two markers define the maximum potential DSS. The duration data generated by this approach are important limnological events in the annual temperature cycle, as represented by the spring and fall 4°C transition dates. The duration data encompass the more active growing season, when phytoplankton growth rates are greatest (Fahnenstiel and Scavia 1987), and, if the active growing season definition is extended to include the 4°C transition dates, then the regression analyses on the duration data suggest an increased growing season for the majority of the study sites. Indeed, the strong correlation between the duration data and the annual mean temperatures lends additional support for this interpretation as well. Furthermore, the rate of increase in the duration data was asymmetrical in time, with most of the increase occurring in the spring relative to the fall.

In spite of these trends, the cycliclike behavior of the data sets suggests it is possible to identify a long-term climatic trend where none may exist. For example, if a 30-yr window is used for regression analyses, then casual examination of these data sets suggests that the results are dependent on the specific location of that window. If the behavior of the longer data sets (Sault Ste. Marie, Put-In-Bay, and Erie) is representative of the long-term behavior of other locales in the Great Lakes, then a 30-yr data record may be inadequate for detecting any long-term trends. Thirty-year trends may provide highly valued information, but any extrapolation or forecasting beyond that time window requires additional insight gained from other sources or explicit assumptions designed to clarify the uncertainty surrounding any estimated trends. The Sandusky Bay, Bay City, and St. Joseph data sets are relatively short (24, 25, and 33 yr of data, respectively) and are subject to these same concerns—i.e., would

Table 4. Regression results of date of fall transition vs. year.

	Bay City	Green Bay	Sault Ste. Marie	St. Joseph	Sand. Bay	Put-In-Bay	Erie
Slope (day yr^{-1})	0.40	−0.19	0.11	0.23	−0.42	0.07	−0.01
Intercept	305.8	340.2	328.0	326.8	354.2	331.3	354.3
R^2	0.05	0.07	0.12	0.07	0.15	0.04	0.001
F-statistic	1.2	3.1	11.4	2.2	3.7	2.9	0.06
P-value	0.28	0.09	0.001	0.14	0.07	0.09	0.81

Table 5. Regression results of the annual average of the mean absolute difference between the daily temperature and the daily long-term average temperature vs. year.

	Bay City	Green Bay	Sault Ste. Marie	St. Joseph	Sand. Bay	Put-In-Bay	Erie
Slope (°C yr⁻¹)	−0.03	0.001	0.006	−0.016	−0.017	−0.004	−0.0004
Intercept	9.8	8.1	5.2	7.3	9.6	8.2	7.0
R^2	0.19	0.001	0.14	0.11	0.13	0.02	0.001
F-statistic	5.4	0.04	13.8	3.8	3.3	1.2	0.04
P-value	0.03	0.85	0.0004	0.06	0.08	0.28	0.84
Overall mean temperature difference	7.2	8.1	5.5	6.1	8.3	8.0	7.0

additional data alter their results? However, in the case of highly significant, relatively strong trends, with relatively high R^2, such as the duration data results for St. Joseph, then higher confidence is warranted in the results. The St. Joseph DSS results appear to be part of a long-term trend, while the absence of relatively strong statistical indicators in the Sandusky Bay and Bay City results suggests that more caution should be applied in generalizing from their results. Therefore, the shorter the time duration that a data set spans, relative to longer data sets, the more significant the regression results must be in order to compensate for the limited time window of investigation.

The Green Bay and Sandusky Bay results showed more similarity with one another than to the other sites. Figure 5 shows that these two sites have a similar variance distribution that appears to be more characteristic of an environment with low thermal inertia, as suggested by the high variability seen in the spring and fall data. In particular, all of the Green Bay temperature data were taken at the mouth of the Fox River. The Fox River contributes the largest percentage of the total phosphorus load of any river that empties into Lake Michigan (Robertson 1997). This river also has the largest total drainage area of all Lake Michigan tributaries (Robertson 1997). Consequently, climatic trends in the Green Bay data may be hidden because of the high data variability resulting from the interaction of the Fox River and Green Bay. If the sensor were located in either Green Bay proper or further upstream in the Fox River, then, perhaps, any climatic trends present in the region's water temperatures would have been easier to detect.

Of the three longest data sets, the Erie, Pennsylvania, analyses suggest that historical analogs for present-day trends may exist at some sites in the Great Lakes region. Recall that the Erie duration data failed to show any trend in the annual mean temperatures and only weak support for a trend in the maximum potential duration data over the entire data set. Examination of the Erie data in Fig. 6 shows that the longest duration data occurred in well-defined episodes from the 1930s through the early 1950s. The Erie, Pennsylvania, data appear to represent a water temperature climatology different from the two western basin study locations in Put-In-Bay and Sandusky Bay. This difference in behavior is supported by ice climatology work (Assel 1990), which suggests that a different water temperature climatology applies to the eastern and western basins. More importantly, the behavior of the Erie data set shows the presence of a historical analog to recent trends. The existence of such an analog should serve as a cautionary example against extrapolating to larger scales or generalizing on any single site-specific results.

Consistent with recent IPCC (1992) assessments, no widespread pattern emerged from attempts to assess changes in interannual variability. However, the annual mean temperature and duration data analyses suggest that significant changes have occurred. The majority of the duration data regression analyses suggest a lengthening of the maximum potential DSS with an earlier transition to springlike conditions. Hanson et al. (1992) present data rooted in the works of Karl et al. (1988) and Boden et al. (1990), showing a springtime warming trend in atmospheric temperatures throughout the Great Lakes region. This trend was based on observations from 1954 to 1984, and it suggests that a regional warming of nearly 0.8°C for the March–May period has occurred. Similarly, Bolsenga and Norton (1993) found that annual land-based temperatures increased throughout the Great Lakes region from 1901 to 1987, with increases in springtime temperatures occurring as well. Lake-ice records further suggest warmer springtime temperatures based on observations and modeling of ice-departure dates (Hanson et al. 1992; Assel and Robertson 1995; Anderson et al. 1996). In addition, studies focused on changes in the active

Table 6. Regression results of annual temperature variance vs. year.

	Bay City	Green Bay	Sault Ste. Marie	St. Joseph	Sand. Bay	Put-In-Bay	Erie
Slope (°C² yr⁻¹)	−0.54	0	0.10	−0.20	−0.28	−0.06	0.01
Intercept	107.9	75.7	33.8	65.9	105.0	82.5	61.8
R^2	0.19	0.02	0.19	0.08	0.17	0.01	0.001
F-statistic	5.4	0.7	20.1	2.7	4.5	1.0	0.1
P-value	0.03	0.41	0.0001	0.11	0.05	0.32	0.76
Overall mean variance	64.5	79.8	38.9	50.8	84.0	78.9	62.3

growing season on land (Keeling et al. 1996; Myneni et al. 1997) suggest that recent increases in the length of the growing season have occurred and that these changes were brought about by an earlier onset to springlike conditions.

The climatic trends identified here represent maximum or near-maximum conditions in the potential DSS. If these conditions persist long enough, then new limnological environments in the nearshore regions will be defined, resulting in potentially significant alterations of community composition and dynamics from the lower food web on up to fish. How the scale and nature of the casual mechanism driving these changes are related to phenomena of global importance cannot be identified here. In fact, there is no clear way to discern whether the climatic trends seen in these data are anthropogenic in cause or merely the consequence of a naturally occurring yet unresolvable low-frequency climate signal.

In conclusion: (1) The annual mean temperatures from five of the seven sites in the coastal regions of the Great Lakes suggest the presence of a long-term warming trend. (2) The explicit use of time and the 4°C temperature of maximum density are natural markers that can be used to gain additional insights into the annual temperature cycle and its interannual variability and to resolve climatic trends that cannot be obtained from examining the annual mean temperatures alone. (3) Two of the three sites with data records extending back to the early part of this century (Sault Ste. Marie and Put-In-Bay, respectively) showed a 4- and 6-h yr^{-1} rate of increase in the maximum potential DSS. Over the time span of these data sets, this equates to a 14- and 18-d increase in the potential duration of the stratified season for Sault Ste. Marie and Put-In-Bay, respectively. (4) The rate of increase in the duration data was skewed, with most of the increase due to an earlier transition to springlike conditions. This result is consistent with regional studies on lake-ice and atmospheric temperature trends, suggesting a recent moderation in winter severity. (5) Finally, the data do not extend far enough back in time to know if these climatic trends are part of an unresolvable natural cycle or forced by anthropogenic activity.

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