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Forecasting impacts of climate change on Great Lakes surface water temperatures

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ABSTRACT

Temperature influences the rates of many ecosystem processes. A number of recent studies have found evidence of systematic increases in Great Lakes surface water temperatures. Our study aims to construct empirical relationships between surface water temperatures and local air temperatures that can be used to estimate future water temperatures using future air temperatures generated by global climate models. Remotely sensed data were used to model lake-wide average surface water temperature patterns during the open-water period in Lakes Superior, Huron, Erie, and Ontario. Surface water temperatures typically exhibit linear warming through the spring, form a plateau in mid-summer and then exhibit linear cooling in fall. Lake-specific warming and cooling rates vary little from year to year while plateau values vary substantially across years. These findings were used to construct a set of lake-specific empirical models linking surface water temperatures to local air temperatures for the period 1995–2006. Hindcasted whole-lake water temperatures from these models compare favourably to independently collected offshore water temperatures for the period 1968–2002. Relationships linking offshore water temperatures to inshore water temperatures at specific sites are also described. Predictions of future climates generated by the Canadian Global Climate Model Version 2 (CGCM2) under two future greenhouse gas emission scenarios are used to scope future Great Lakes surface water temperatures: substantial increases are expected, along with increases in the duration of summer stratification.

Introduction

Climate change is expected to have numerous effects on freshwater systems, including changes to water clarity, water levels, pH, ice cover and surface water temperatures (Magnuson et al., 1997; Schindler, 2001). Increased water temperatures are expected to have important biological effects (Shuter et al., 2002) such as changing the distribution of fish species (Chu et al., 2005), facilitating the spread of warm-water species into new habitats (Sharma et al., 2007; Shuter and Post, 1990), increasing the length of the growing season, and changing the availability of different habitats within a lake (Ficke et al., 2007).

The Great Lakes Basin contains 20% of the world's surface freshwater and supports a human population of over 30 million (Magnuson et al., 1997). Thus, it is important to understand the potential effects of climate change on this system and a number of recent studies have begun to do so. Several have found trends indicating recent increases in water temperatures. For example, McCormick and Fahnenstiel (1999) found evidence of water temperature warming trends at 5 out of 7 Great Lakes nearshore sites over 25–87 years and increases in the length of summer stratification at several sites. Jones et al. (2006) found Western Lake Erie summer water temperatures increasing and winter length decreasing, as predicted by most climate change models. Dobiesz and Lester (2009) detected significant increases in summer water temperatures for Lake Huron, the central basin of Lake Erie and Lake Ontario, while Assel (2005) found a decrease in the occurrence of severe winter ice cover in 1998–2002 compared to 1977–1982. Similarly, Austin and Colman (2007) observed increasing summer water temperatures in Lake Superior over 1979–2006, coupled with a decrease in winter ice cover.

The goal of our study was to predict surface water temperatures in Lakes Superior, Huron, Erie, and Ontario for 4 time periods (1971–2000 “norms” period, 2011–2040, 2041–2070, and 2071–2100) under different CO_2 emission scenarios. We used two scenarios developed by the Intergovernmental Panel on Climate Change (IPCC A2 and B2). The A2 and B2 scenarios assume relatively high and relatively low greenhouse gas emission levels for the period 2000 to 2100, respectively (Nakicenovic et al., 2000). The changes in climate arising from these emission scenarios were forecast using the Canadian Global Climate Model Version 2 (CGCM2) (Flato et al., 2000; Flato and Boer, 2001). Our approach was to use historical data to build empirical models of the links between air and water temperature

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conditions and then to use those models to translate forecasts of future air temperatures into forecasts of future water temperatures.

Our primary focus was to analyze observed variation in annual cycles of surface water temperature, as reflected in daily, lake-wide average values derived from satellite-based thermal imagery. However, the Great Lakes exhibit significant and systematic patterns of spatial heterogeneity in surface water temperatures. Differences between inshore and offshore sites can be particularly large, are common in spring and fall and are associated with thermal bar formation, seiche activity and other physical processes that are active in large, deep lakes (eg. Csanady, 1971). To illustrate both the magnitude and seasonal variation typical of such heterogeneity, we also carried out a comparative analysis of long term, daily surface water temperature records from several inshore sites in Lake Ontario and Lake Erie.

Methods

Characterizing annual water temperature cycles: lake-wide averages

Remotely sensed whole-lake surface water temperatures (SWT) from the NOAA Great Lakes CoastWatch Program's Great Lakes Surface Environment Analysis (GLSEA) composite charts were used to model water temperature cycles in Lakes Superior, Huron, Erie, and Ontario for 1995–2006 for the open-water period. Lake surface temperatures were estimated daily using cloud-free AVHRR satellite imagery calibrated with in situ limnological buoy observations for all lake cells on a 512 × 512 grid covering the Great Lakes region (Schwab et al., 1999). Values for clouded grids were estimated using a temporal and spatial interpolation algorithm. Consistent estimates for lake-wide mean daily surface temperatures were computed and made available to the general public at the NOAA Coastwatch website (http://coastwatch.glerl.noaa.gov/statistic/statistic.html). These daily values are the raw data we used to characterize the annual water temperature cycle for each lake in each year from 1995 to 2006. Each annual cycle was characterized by 3 separately fitted parts: a spring warming trend, a mid-summer plateau temperature, and a fall cooling trend (Fig. 1).

To determine spring warming and fall cooling trends, daily whole-lake mean surface water temperature data were sorted from individual lakes and years as belonging to the spring or fall. Spring was defined as the part of a year that exhibited consistent increasing water temperature trends. Fall was defined as the part of the year where water temperatures showed consistent decreasing trends.

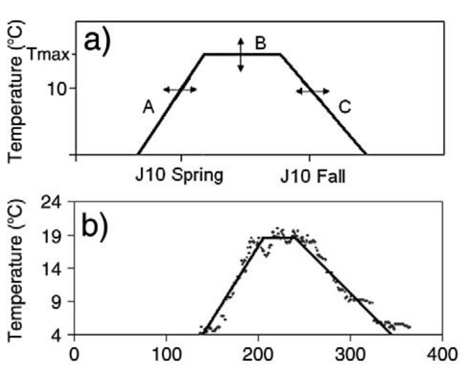

Fig. 1. (a) Conceptual diagram of the surface water temperature model for the open-water period. Spring slopes (A) and fall slopes (C) are consistent for a lake, with intercepts varying annually. The value of the summer plateau (B) varies annually. J10 values are the days of the year in the spring and fall when the temperature is 10 °C. T_{max} determines the height of the summer plateau and is estimated as the twentieth highest temperature for a year. (b) An example of an annual, full-year fitted surface water temperature model with observed daily GLSEA surface water temperatures plotted for Lake Superior in 1998.

Application of this condition led to omission of those time periods when temperatures were less than 7 °C in lakes Huron and Ontario, and those time periods when temperatures were less than 6 °C in lakes Superior and Erie.

Temperatures during the interval between the spring warming period and the fall cooling period could be represented reasonably well by a lake-specific constant, the summer plateau temperature, which varied from year to year. The value of this constant (T_{max}) for a particular year was estimated as the twentieth highest daily water temperature observed in that year. This particular order statistic was chosen after iterative assessment of higher and lower orders using simple indices of fit.

We found year-to-year variation in spring warming and fall cooling rates to be low (Fig. 2: standard deviations for spring and fall rates were roughly 20% and 12% of mean values respectively). This empirical finding permitted us to obtain reasonably accurate representations of the spring warming and fall cooling periods in each lake by assuming a linear spring warming (or fall cooling) trend, with a slope that was fixed across years and an elevation that varied from year to year. Analysis of covariance (ANCOVA) was used to fit such a model to the spring data for each lake and to the fall data for each lake. Year specific differences in the elevation of these trend lines were characterized by year-specific estimates of the spring day when temperatures reach 10 °C ($J10_{spring}$) and the fall day when temperatures decrease to 10 °C ($J10_{fall}$). Although the choice of a threshold temperature to characterize elevation differences is essentially arbitrary, 10 °C is a useful value because the resultant J10 values provide direct measures of shifts in the timing of spring warming and fall cooling periods and, for most years in most lakes, 10 °C marks the mid-point between the relatively unchanging temperatures of winter and summer.

Thus, we were able to represent the annual open-water temperature cycles for a particular lake for the period 1995–2006 by a three part model, consisting of a lake-specific spring warming rate with year-specific elevations, lake and year-specific summer plateau temperatures, and a lake-specific fall cooling rate with year-specific elevations (Fig. 1b). Using this scheme, we characterized the temperature cycle for each lake in each year by 2 lake-specific parameters (spring and fall slope) and 3 year-specific parameters ($J10_{spring}$, T_{max} and $J10_{fall}$).

McCormick and Fahnenstiel (1999) identified the length of the part of the year where temperatures exceed 4 °C as the maximum potential duration of summer stratification (MDSS). Because variation in the length of this period has important consequences for biological production (Ficke et al., 2007), we generated lake and year-specific estimates of MDSS using our three part model.

Comparing inshore site-specific temperatures with lake-wide averages

Daily mean surface water temperature records were obtained from monitoring programs maintained at water treatment plants with shallow, epilimnetic intakes, located at (i) Bay of Quinte, north shore Lake Ontario; (ii) Port Dover, north shore, east basin, Lake Erie; (iii) Elgin, north shore, central basin, Lake Erie; (iv) Leamington, north shore, west basin, Lake Erie (Fig. 3). The Lake Ontario site is located in a shallow, enclosed bay, largely isolated from the main lake. The Lake Erie sites are all located along the north shore, but differ in their exposure to hypolimnetic water from seiche activity: both the east and central basins stratify and there are no physical barriers separating the intake sites on those basins from the main lake; in contrast, the west basin does not stratify and the west basin intake site is over 20 km from the nearest basin (the central basin) that does stratify. For Lake Erie sites, daily mean water temperature values were available for the period 1995–2006, while Bay of Quinte data was available for 1995–2000. We examined seasonal variation in the differences observed between these daily inshore mean temperatures and the lake-wide means obtained from satellite imagery.

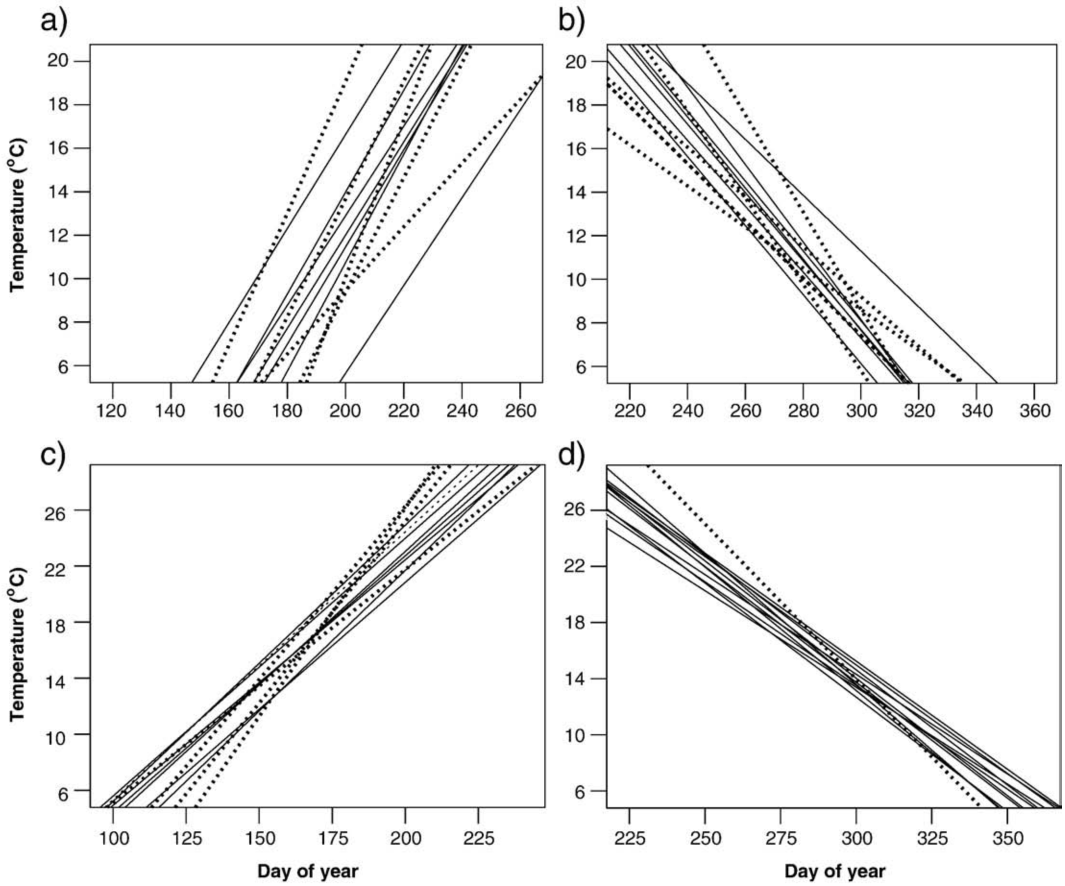

Fig. 2. Linear models of surface water temperatures vs. day of year in spring and fall for Lake Superior (a and b, respectively), and Lake Erie (c and d, respectively) 1995–2006. Solid lines indicate slopes within 0.025 °C/day of the common slope used for that lake. Dotted lines indicate slopes outside of that range.

Linking historical variation in annual water temperature cycles to historical variation in climate

Climate data were downloaded from the Environment Canada website (http://www.climate.weatheroffice.ec.gc.ca) for three climate stations for lakes Superior, Huron, Erie and Ontario for the years 1968–2006. Reported daily values for air temperature were used to calculate monthly, seasonal, and annual means for each of the three sites on each lake. Inter-site correlations among these means were also determined. Within lakes, between site correlations for mean

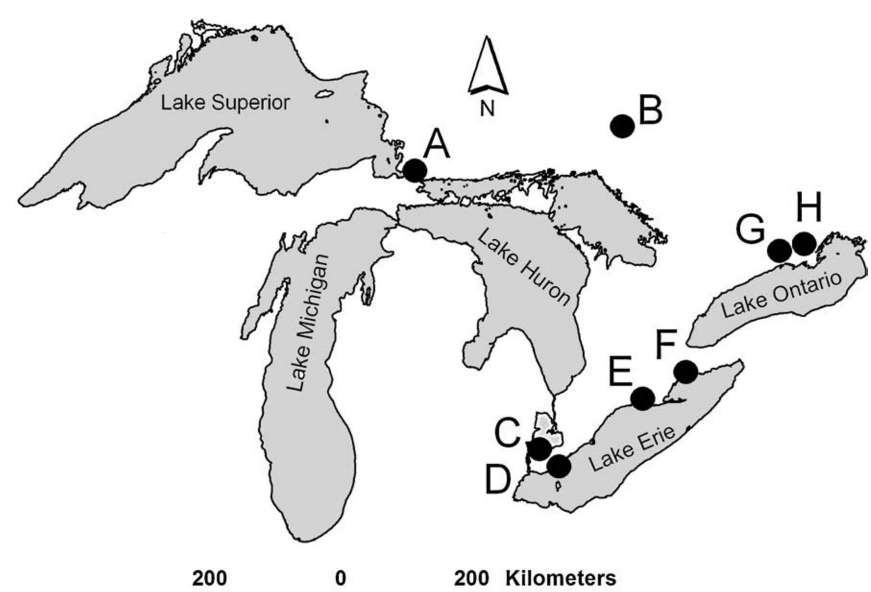

Fig. 3. Map of the Great Lakes with locations of Environment Canada weather stations and inshore water temperature observation sites marked: Sault Ste. Marie (A), Sudbury (B), Windsor (C), Leamington (D), Elgin (E), Port Dover (F), Trenton (G), and the Bay of Quinte at Belleville (H).

annual temperature were high: values ranged from 0.86 to 0.98. This finding, coupled with the general observation (Koenig, 2002) that air temperatures exhibit significant correlations among stations that are separated by distances of up to 2500 km, suggests that data from a single local climate station can serve as a reasonable index of interannual variation in climate for a whole lake. The stations used for subsequent analysis were Sault Ste. Marie, Sudbury, Windsor, and Trenton for lakes Superior, Huron, Erie, and Ontario, respectively (Fig. 3).

With T_{max}, $J10_{spring}$, and $J10_{fall}$ as dependent variables and monthly, 6 month and 12 month air temperature means as independent variables, best subsets regression and AIC criteria (Analytical Software, 2008) were used to identify the 'best' relationships linking water temperature variables to air temperature variables.

Model validation

We used an independent set of average weekly surface water temperature estimates to assess the accuracy of our models. Dobiesz and Lester (2009) compiled an extensive environmental data set for Lakes Huron, Erie and Ontario from point-in-time, point-in-space survey and monitoring data collected by various U.S. and Canadian government agencies over the period 1968–2002. The surface water temperatures recorded in this data base were collected within the top 2 m of the water column. The date and time of each measurement was recorded, as well as the depth of the water column where the measurement was made. For each lake, surface water temperature values collected offshore (water column depth >10 m), from deep basins (mean basin depth >10 m) were grouped by year and week to arrive at a weekly offshore average value. We then compared each of these observed values with a predicted value derived from our 'best' empirical model for the lake, using the Environment Canada climate data appropriate for the year and week in question (see the Regression analysis of water temperature and air temperature data and forecasts of water temperatures section in Results below). Comparisons were restricted to data from deep, offshore basins (central, south, north basins of Huron; east and central basins of Erie; west and central basins of Ontario) because these basins cover the majority of the lake surface, and thus are most likely to reflect the whole-lake GLSEA temperatures. Data from nearshore, shallow basins were excluded because they often exhibit temperature patterns that differ from that of the whole lake and thus are unlikely to be well predicted by a whole-lake model (Csanady, 1971).

Forecasting future surface water temperatures

Regression models were used to predict future Great Lakes' water temperatures from forecasts of future climates. IPCC A2 and B2 CO_2 emission scenarios (Nakicenovic et al., 2000), applied to the Canadian Global Climate Model Version 2 (CGCM2: Flato et al., 2000; Flato and Boer, 2001), were used as sources for predicted future mean monthly air temperatures for the periods 2011–2040, 2041–2070, and 2071–2100. Scenario A2 assumes world human population levels continue to increase rapidly, reaching 15 billion by 2100. Annual global CO_2 emissions increase in parallel, reaching a level in 2100 that is about 3.5 times the level in 2000. Scenario B2 assumes a slower increase in population size (10.4 billion in 2100) and significant reductions in per capita rates of CO_2 production. This leads to projected annual CO_2 emissions levels in 2100 that are about 1.5 times the level in 2000. These particular scenarios are useful in impact assessment studies because they effectively bound the expected range of emission scenarios developed by the IPCC for the period 2000–2100.

The Canadian Forest Service (McKenney et al., 2006) has translated these future climate projections into a series of maps that provide monthly air temperature predictions for Ontario on a 10 km spatial grid. Thin plate spline methods (ANUSPLIN; Hutchinson, 1995) were used to interpolate this fine scale grid from the coarse resolution (~400 km) grid generated by the CGCM2. Future air temperature forecasts for each month at each of our 4 weather station were generated as follows: (i) for the fine scale grid square containing the weather station, the difference in temperature between the mean CGCM2 value for the month in the 1971–2000 norm period and the mean CGCM2 value for the month in the 2011–2040 period was determined; (ii) this difference was then added to the mean temperature observed for the month at the weather station for the period 1971–2000; (iii) this procedure was then repeated to generate forecasts for the 2041–2070 period and the 2071–2100 period. Forecasts were done in this way to allow for the small discrepancies (typically <1 °C) that exist between the observed norm values at each of the weather stations and the CGCM2 norm values for grid squares containing the weather stations. Predicted $J10_{spring}$ and $J10_{fall}$ values were then used to estimate the number of days in each year with a temperature >4 °C (MDSS).

Results

Historical variation in lake-wide water temperature cycles

Some time trends were apparent in our 12 years of annual water temperature statistics. T_{max} appeared to increase slightly over the study period in all lakes except Erie, though the changes are not significant (ANCOVA, $p = 0.3651$; Fig. 4). However, MDSS values increased significantly across all lakes (ANCOVA, $p = 0.0268$; Fig. 4).

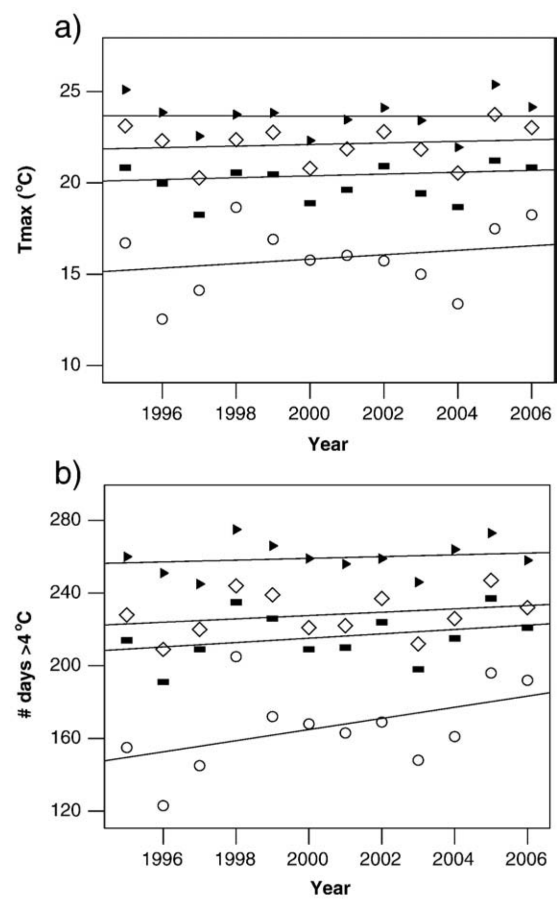

Fig. 4. Observed changes in (a) T_{max} and (b) MDSS (the number of days with SWT >4 °C) for 1995–2006 for lakes Superior (○), Huron (■), Erie (▶), Ontario (◊). Positive trends in T_{max} were non-significant (ANCOVA, $p < 0.3651$), while the positive trends in MDSS values were significant (ANCOVA, $p = 0.0268$).

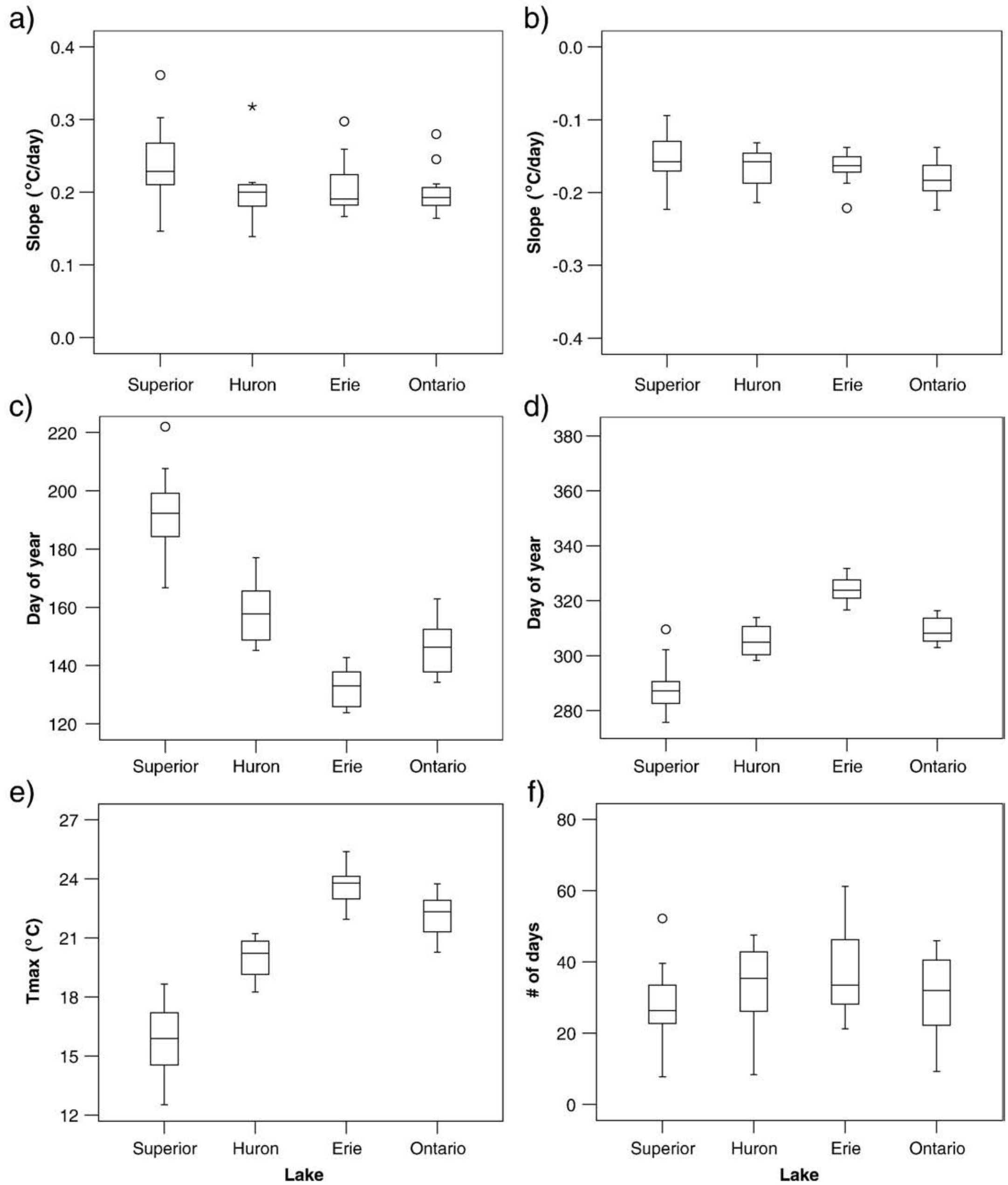

Fig. 5. Boxplots showing variation in (a) spring and (b) fall surface water temperature slopes, variation in (c) spring and (d) fall J10 values, variation in (e) T_{max} values, and (f) variation in plateau lengths; based on 1995–2006 GLSEA data for Lakes Superior, Huron, Erie and Ontario.

Given the relatively low year-to-year variation in spring warming and cooling rates (Figs. 5a, b), it is not surprising that the spring and fall data from each lake were well described by simple linear models with warming and cooling rates fixed across years (Table 1). These warming and cooling rates were similar for lakes Ontario, Erie and Huron. The Lake Superior warming rate was somewhat higher than the warming rate common to the other lakes while the Lake Superior cooling rate was somewhat lower. The resulting J10 values showed greater variation in the spring than in the fall (Figs. 5c, d) while T_{max} values and summer plateau lengths varied widely both within and between lakes (Figs. 5e, f). Our T_{max} values provided a good representation of temperatures typical of the summer 'plateau' period in the annual water temperature cycle. For Lake Superior, 75.9% of the daily observations from the 12 plateau periods fell within 1.5 °C of their respective T_{max} values while 94.6% of observations fell within 3 °C. For lakes Huron, Erie, and Ontario, 86.1%, 89.6%, and 83.9% of daily plateau temperatures fell within 1.5 °C of their respective T_{max}, values, while 100% of observations fell within 3 °C.

Table 1
Fitted slopes for fall and spring surface water temperature data.

Lake	Season	Slope (°C/day)	Adj-R^2
Superior	Spring	0.22448	0.8442
	Fall	−0.13947	0.9098
Huron	Spring	0.19197	0.8281
	Fall	−0.16170	0.9478
Erie	Spring	0.19409	0.9022
	Fall	−0.16211	0.9530
Ontario	Spring	0.19268	0.8050
	Fall	−0.17516	0.9300

All fitted models significant at $p<0.0001$.

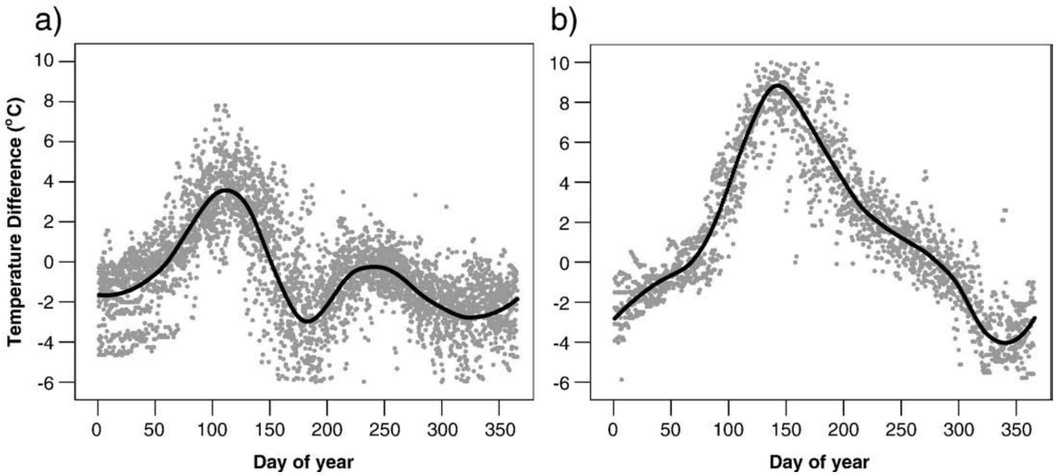

Fig. 6. Observed and smoothed daily temperature differences (C°) between lake-wide mean values and inshore site-specific values. (a) Bay of Quinte observations cover the period 1995–2000; (b) Port Dover observations cover the period 1995–2006. Temperature differences beyond −6 °C ($n = 22$ for Quinte, $n = 102$ from Dover) were not included in the plot; maximum observed differences for these two sites were −12 °C and −14 °C, respectively.

Seasonal variation in the difference between inshore site-specific temperatures and lake-wide averages

In each of the sites we examined, the same seasonal pattern of temperature differences (Fig. 6) was evident. In late winter–early spring (days 60–90), the inshore temperature rises above the lake-wide temperature, reaching a peak in mid to late spring (days 100 to 150). In late summer–early autumn (days 240–270), inshore temperatures fall below the lake-wide mean and stay there. Sites isolated from seiche effects (Quinte, Leamington) were consistently warmer than the lake-wide average throughout the summer and early fall. This positive difference peaked in late spring and declined steadily thereafter, disappearing by mid-fall. Sites that were exposed to seiche effects (Port Dover, Elgin) exhibited a more rapid decline in this temperature difference, with negative values becoming common by early summer (day 180). The magnitude of the peaks and troughs in this general pattern differed widely among sites. At Port Dover and Elgin, extreme negative differences were sporadically observed in late spring–early summer. These extreme values (i.e. values up to 14° lower than whole-lake surface values) occurred when large temperature differences between hypolimnetic and epilimnetic waters are common. This suggests that they reflect inshore intrusions of cold, metalimnetic and hypolimnetic water driven by upwellings. The occurrence of these events is frequent enough to drag the smooth curve for Port Dover down into negative values by early July (Fig. 6b). Later in the summer, the frequency of occurrence of these events drops off and the smooth curve moves up somewhat before beginning a second descent into negative territory in early fall. In contrast, the temperature difference plot for Quinte (a site isolated from upwelling events) did not exhibit the sporadic occurrence of very negative values in summer and consequently its smooth curve descended steadily from a high on day 150 to a low on day 340.

Regression analysis of water temperature and air temperature data and forecasts of water temperatures

The regression analyses of SWT statistics on climate variables yielded high adjusted-R^2 values, ranging from 0.73 to 0.91 for T_{max}, 0.79 to 0.90 for $J10_{spring}$, and 0.53 to 0.84 for $J10_{fall}$ (Table 2). All models were significant at the $p < 0.05$ level with the exception of the Huron $J10_{fall}$ model which was marginally non-significant ($p = 0.0507$).

Validation results (Fig. 7) showed our models predicted offshore temperatures quite well both before and after 1995. For each 6 °C interval of predicted temperature, the median absolute deviation of predicted from observed values was less than 1 °C 80% of the time and was never more than 1.2 °C. This pattern and magnitude of deviations did not change significantly across years ($p = 0.64$: ANCOVA of deviation on year, with lake as categorical variable).

Future surface water temperatures are expected to be considerably warmer than currently observed across spring, summer, and fall periods. For example, by the 2071–2100 period, summer plateau surface temperatures are expected to rise by 3.3 to 6.7 °C under the A2 scenario and by 2.4 to 4.6 °C under the B2 scenario, depending on the lake (as illustrated in Fig. 8). Spring J10 values will occur 35 to 47 days earlier under A2 and 24 to 31 days earlier under B2, while fall J10 values will occur 26 to 51 days later under A2 and 18 to 36 days later under B2. These changes translate into an increase in MDSS of 42 (in Lake Erie under B2) to 90 days (in Lake Superior under A2) over the interval from 1971–2000 to 2071–2100. There are reciprocal decreases (Fig. 9) in the period over which temperatures are <4, an index of winter duration (Jones et al., 2006). Overall estimated changes from

Table 2
Air temperature–surface water temperature parameter regression results.

T_{max}

Lake	Constant	$July_{mean}$	$August_{mean}$	$Jan–June_{mean}$	Adj-R^2
Superior**	1.94	0.38	0.35	0.73	0.9089
Huron*	4.26	0.52	0.32	0.11	0.7331
Erie**	4.96	0.33	0.55	−0.15	0.8377
Ontario*	1.21	0.57	0.43	0.10	0.7727

$J10_{spring}$

Lake	Constant	$April_{mean}$	May_{mean}	$June_{mean}$	$Oct_{year-1}–Mar_{mean}$	Adj-R^2
Superior*	198.52	−3.91	−0.89	0.14	−4.31	0.8283
Huron**	196.19	−2.14	−0.29	−2.65	−3.67	0.8956
Erie*	218.63	−1.48	−1.48	−2.33	−1.06	0.8502
Ontario*	244.78	−2.34	−0.61	−4.19	−3.03	0.7941

$J10_{fall}$

Lake	Constant	$Sept_{mean}$	Oct_{mean}	$Mar–Aug_{mean}$	$Sept_{year-1}–Aug_{mean}$	Adj-R^2
Superior*	178.35	2.00	3.44	2.73	2.96	0.8042
Huron	273.15	2.03	2.49	−3.22	5.24	0.5294
Erie*	245.12	2.26	2.94	0.37	−0.18	0.8440
Ontario*	242.54	2.89	4.44	−4.78	5.69	0.7833

T_{max} is the twentieth highest temperature for a lake for a year. $J10_{spring}$ is the day of the year in the spring when the water temperature is predicted to reach 10 °C. $J10_{fall}$ is the day of the year in the fall when the water temperature is predicted to reach 10 °C. Huron $J10_{fall}$ regression yielded a p-value of 0.0507.
* $p < 0.01$.
** $p < 0.001$.

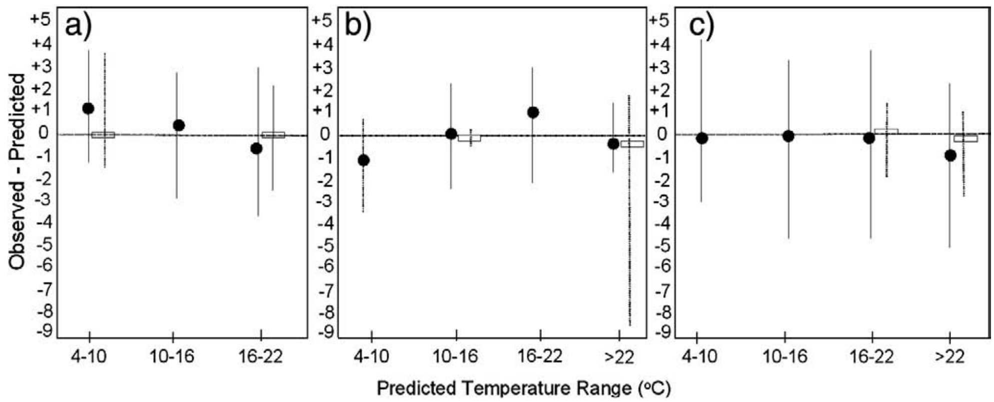

Fig. 7. Validation results for lakes (a) Huron, (b) Erie, and (c) Ontario comparing model predicted temperatures with an independent dataset of weekly surface temperatures. Dots indicate the median of the deviations for observations from 1968 to 1994 and rectangles mark the medians from 1995 to 2002. Solid whiskers include the range of 90% of the deviations. Dotted whiskers mark the range of all observations for temperature ranges with 15 or fewer observations. No predicted temperatures exceed 22 °C for Lake Huron.

1971–2000 to 2071–2100 in the surface water temperature cycle for the A2 scenario for each lake are illustrated in Fig. 10. Table 3 provides full predictions for each variable and time period.

Discussion

Model reliability

Our set of lake-specific air temperature/water temperature regression models is derived from 48 independent sets of observations of air and water temperatures: 12 years of observations for each of 4 lakes. Although the degrees of freedom for each regression relationship associated with each lake is low, and the predictor variables used in each regression are not strictly independent, the R^2 values are generally high (typically >0.78, Table 2) and these high R^2 values are achieved with the same set of independent variables for each of our 4 lakes. The fact that structurally similar relationships provide good descriptions of the detectable links between air and water temperatures in 4 independent data sets (1 set for each lake) supports the assumption that these relationships are capturing important aspects of the quantitative associations that link air temperatures to water temperatures in this set of neighboring large lakes, and are not simply reflecting ephemeral associations that are often found in small data sets. This assumption is reinforced by the fact that our models are quite effective (Fig. 7) at hind casting independently determined, weekly, site-specific offshore surface temperatures over a much longer time frame (35 years: 1968–2002).

Our approach to forecasting assumes that surface temperatures will respond linearly to changes in local air temperatures. Importantly, Austin and Colman (2007) found trends suggesting summer surface water temperatures in Lakes Superior, Huron, and Michigan have increased at a faster rate than regional air temperatures. This pattern is attributed to reduced winter ice cover causing an earlier onset of stratification which results in a longer surface water temperature warming period (Austin and Colman, 2007). The longer warming period results in higher water temperatures than would be expected by increased summer air temperatures alone. Winter ice cover duration is significantly correlated with mean September to May air temperatures (Jensen et al., 2007). Because our regression models linking air to water temperature include winter air temperatures in the 6 and 12 month air temperature means, our models likely capture some of the positive feedback effects that reduced winter ice cover and earlier stratification have on summer water temperatures.

The results obtained in the model development and validation phases of our study strongly support the assumption that our empirical models are capable of predicting how surface water temperatures are affected by the variability in air temperatures observed over the period 1968–2006. However, these models are subject to the weakness inherent in any empirical approach: their reliability is questionable as soon as they are used to forecast the consequences of climatic conditions that are outside the bounds

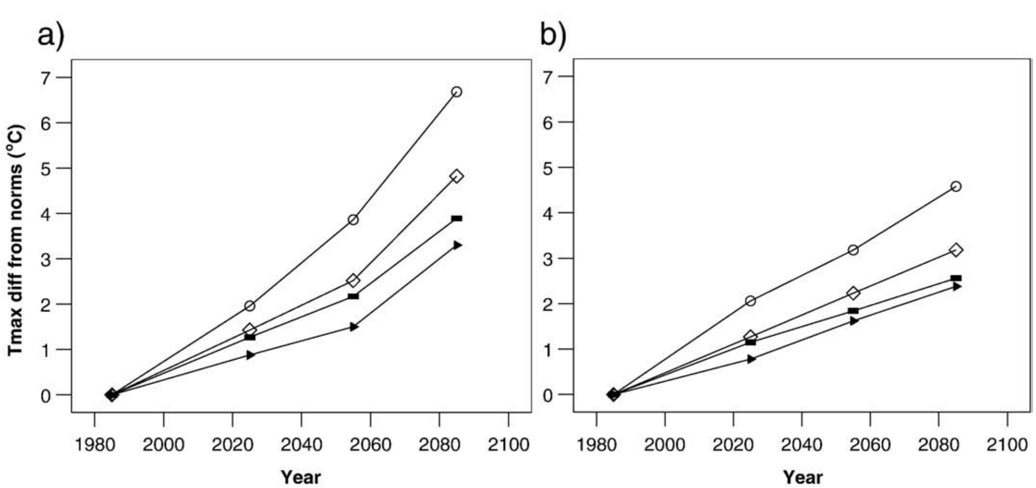

Fig. 8. Difference in T_{max} values from 1971 to 2000 norms for 2011–2040, 2041–2070, and 2071–2100 for (a) IPCC A2 and (b) B2 scenarios for lakes Superior (○), Huron (■), Erie (▶), Ontario (◊). T_{max} is estimated as the twentieth highest temperature observed in a lake for a year.

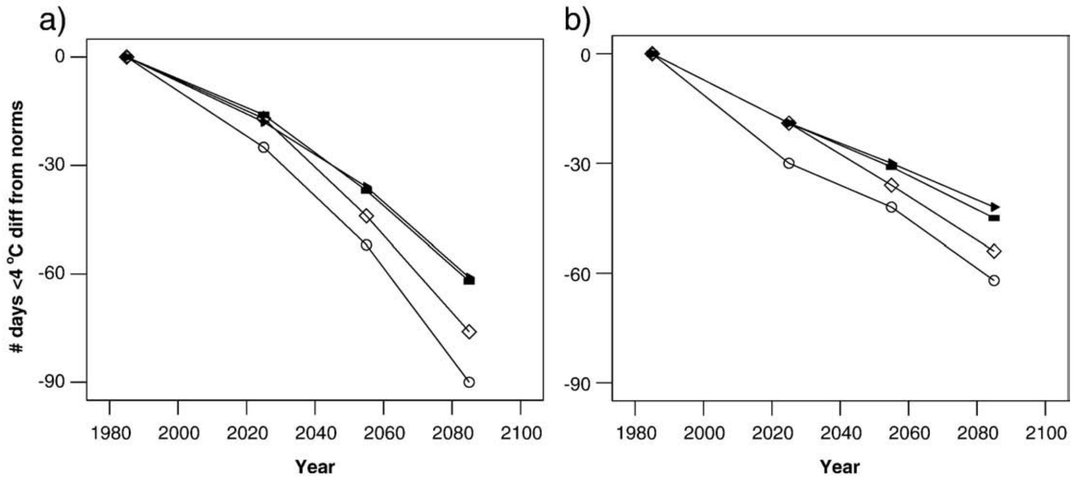

Fig. 9. Difference in number of days with surface water temperatures <4 °C from 1971 to 2000 norms for 2011–2040, 2041–2070, and 2071–2100 for (a) IPCC A2 and (b) B2 scenarios for lakes Superior (○), Huron (■), Erie (▶), Ontario (◊).

defined by the conditions that occurred over the historical period for which they were developed and tested. We compared the forecasts of future monthly air temperatures with the historical record of observed temperatures for the period 1968–2006 to determine when future climates escape the bounds of historical variability. By 2070, predicted climates have fully escaped the historical range for all lakes. Therefore the time course of predicted water temperature conditions (Figs. 8, 9) should be seen as increasingly speculative as one approaches the end of the century.

Summary and conclusions

In summary, our results suggest that our empirical models (Table 2) can provide reasonably accurate (Fig. 7) forecasts of surface water temperatures under the range of current IPCC emission scenarios for the period 2011–2070. Forecasts for the period 2071–2100 should be deemed more speculative since they involve extrapolation outside of the range of climatic conditions for which the models were calibrated. Significant improvements in both the accuracy of these models, and their forecasting range, could be achieved by iterative re-calibration to more recent GLSEA data as it becomes available.

The accuracy of our predictions of future water temperatures is also limited by the accuracy of both the future emission scenarios and the climate model used to predict future air temperatures. The emission scenarios that underlie our water temperature forecasts effectively bound likely future emission time series, as defined by the IPCC. These scenarios and the resultant climate projections are revised regularly, with each new IPCC report. Our models can easily be used to generate revised future water temperature forecasts as new air temperature forecasts become available.

Implications of findings

The finding that warming and cooling water temperature patterns in all four lakes follow relatively stationary slopes across the 12 years for which whole-lake data is available (Fig. 5) is surprising given the

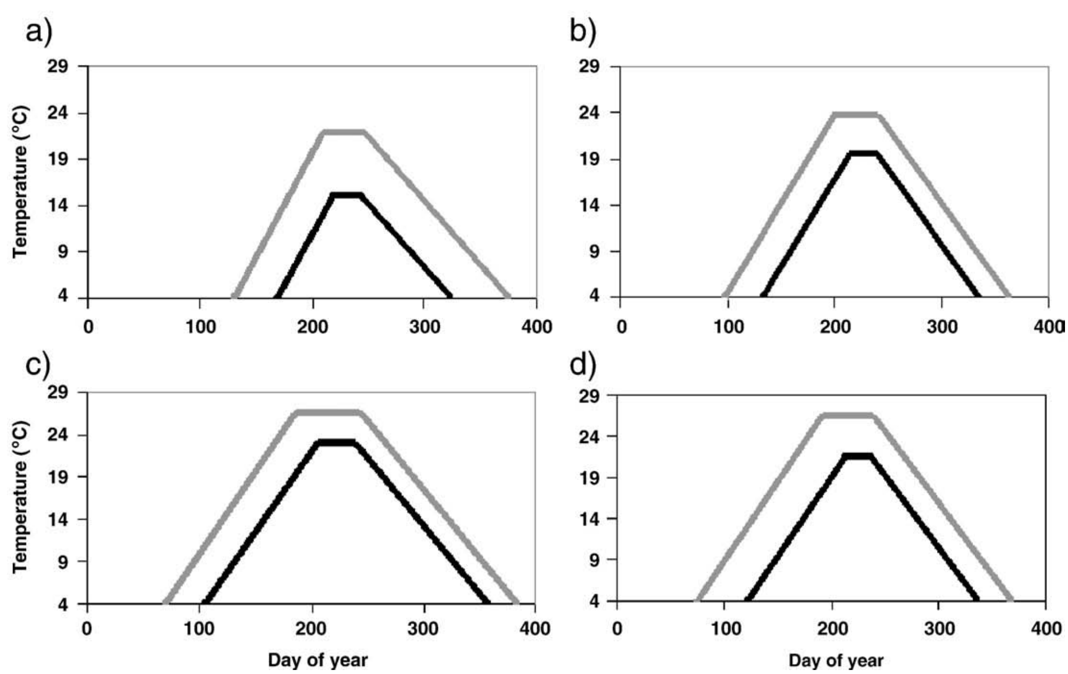

Fig. 10. Estimated average temperature cycles for the open-water period for lakes (a) Superior, (b) Huron, (c) Erie, and (d) Ontario for 1971–2000 (black lines) and 2071–2100 under the IPCC A2 scenario (grey lines).

Table 3
Predicted values of T_{max}, $J10_{spring}$, and $J10_{fall}$ under the IPCC A2 and B2 scenarios for lakes Superior, Huron, Erie, and Ontario.

Lake	Time period	Scenario	T_{max} (°C)	Δ T_{max} from norms (°C)	$J10_{spring}$ (DOY)	Δ $J10_{spring}$ from norms	$J10_{fall}$ (DOY)	Δ $J10_{fall}$ from norms
Superior	1971–2000	Norm	15.1		195.8		280.4	
	2011–2040	A2	17.0	+2.0	185.8	−10.0	295.5	+15.0
	2011–2040	B2	17.1	+2.1	183.4	−12.4	297.1	+16.6
	2041–2070	A2	18.9	+3.9	174.0	−21.8	310.1	+29.6
	2041–2070	B2	18.2	+3.2	178.2	−17.6	305.0	+24.5
	2071–2100	A2	21.8	+6.7	157.5	−38.3	331.7	+51.2
	2071–2100	B2	19.7	+4.6	169.8	−26.0	316.6	+36.1
Huron	1971–2000	Norm	19.7		164.6		298.8	
	2011–2040	A2	21.0	+1.3	156.5	−8.1	306.9	+8.1
	2011–2040	B2	20.9	+1.2	154.8	−9.8	307.8	+9.1
	2041–2070	A2	21.9	+2.2	144.8	−19.8	315.6	+16.8
	2041–2070	B2	21.6	+1.8	148.2	−16.5	312.4	+13.7
	2071–2100	A2	23.6	+3.9	129.4	−35.2	325.7	+26.9
	2071–2100	B2	22.3	+2.6	140.5	−24.1	319.5	+20.7
Erie	1971–2000	Norm	23.3		136.2		320.6	
	2011–2040	A2	24.1	+0.9	125.2	−11.0	327.1	+6.5
	2011–2040	B2	24.0	+0.8	124.5	−11.6	327.2	+6.6
	2041–2070	A2	24.7	+1.5	115.3	−20.8	335.5	+14.8
	2041–2070	B2	24.9	+1.6	118.8	−17.4	333.0	+12.4
	2071–2100	A2	26.6	+3.3	101.4	−34.8	346.9	+26.2
	2071–2100	B2	25.6	+2.4	112.4	−23.8	338.3	+17.7
Ontario	1971–2000	Norm	21.6		152.7		302.0	
	2011–2040	A2	23.0	+1.4	142.7	−10.0	308.9	+6.9
	2011–2040	B2	22.9	+1.3	140.4	−12.2	309.0	+7.0
	2041–2070	A2	24.1	+2.5	127.1	−25.6	320.2	+18.2
	2041–2070	B2	23.8	+2.2	131.4	−21.3	316.8	+14.8
	2071–2100	A2	26.4	+4.8	106.2	−46.5	332.7	+30.7
	2071–2100	B2	24.8	+3.2	122.0	−30.7	325.7	+23.7

T_{max} is the twentieth highest temperature observed in a lake for a year. $J10_{spring}$ and $J10_{fall}$ are the expected days of year when the surface water temperature will reach 10 °C in the spring and fall, respectively.

expected complexity of warming and cooling processes in the Great Lakes. While there is certainly some variation in the slopes across the 12 years (Fig. 5), our success in hindcasting temperatures from an independent dataset, covering a longer (35 years) time period, indicates that warming and cooling patterns are well represented by the use of a stationary slope for each lake. This pattern of narrow variation in warming and cooling rates across years for all 4 lakes seems a fruitful topic for further research, at both the empirical and mechanistic levels.

Our 3-part model (Fig. 1) is clearly a simplified representation of 'real' annual water temperature cycles. We have not attempted to model explicitly the daily variation around our smooth curves. This could be done by assuming normal error distributions estimated from the regression analyses used to generate our curves; or by generating error distributions with simulated random numbers drawn from the observed distribution of residuals around our smooth curves. Our primary results can be used to scope other aspects of the variation that is hidden by our simplified representation of the annual water temperature cycle. Some examples are: (i) offshore daily summer water temperatures: since the maximum observed daily water temperature never exceeded any of our estimated T_{max} values by more than 3 °C, it seems reasonable to suggest that adding 3 °C to a forecasted T_{max} value will provide a reliable upper bound on the daily water temperatures expected for that T_{max} value; (ii) inshore daily water temperatures: inshore daily temperatures are typically greater than offshore temperatures in spring (by as much as 8 °C) and less than offshore temperatures in fall (by as much as 6 °C); upwellings in summer can produce rapid, short term drops in inshore temperatures to levels as much as 14 °C less than offshore temperatures (Fig. 6).

Our analysis of site-specific variation in surface water temperatures illustrates the magnitude of the spatial heterogeneity that is masked by our analysis of lake-wide average values. Forecasts of future water temperatures for specific sites along the shores of the Great Lakes will be of particular value for the wide variety of stakeholders that depend on the littoral waters of the Great Lakes for such essential services as electricity generation and drinking water. Our results demonstrate the need for a new effort directed at developing simple and reliable tools for making such forecasts.

The detection of a significant increase in the MDSS from 1995 to 2006 suggests that alterations of annual water temperature patterns, consistent with expected changes in climate, are occurring in the Great Lakes over relatively short time spans. This suggestion is reinforced by the presence of similar trends in longer, independent data sets from the Great Lakes: (i) Austin and Colman (2007) found a consistent trend toward earlier initiation of summer stratification in Lakes Superior, Huron and Michigan using 25 years of temperature buoy data; (ii) Jones et al. (2006) found that their winter duration index for Lake Erie (length of annual period with surface water temperatures <4 °C) showed a significant decrease over the period 1965–2000; (iii) McCormick and Fahnenstiel (1999) found significant increases in MDSS at 5 of their 7 Great Lakes study sites, using time series data that spanned periods ranging in length from 25 to 87 years. In addition, our prediction that spring J10 values for all lakes are more sensitive to expected changes in climate than fall J10 values is consistent with McCormick and Fahnenstiel's (1999) observation that recent increases in Great Lakes' MDSS values are dependent largely on an earlier transition to spring conditions rather than on a later onset of fall conditions.

By 2071–2100, all our forecasts suggest that annual water temperature cycles will have changed the most in Lake Superior and the least in Lake Erie (Fig. 10). Typical summer surface water temperatures will have increased by as much as 6° and MDSS values will have increased by as much as 90 days. These changes will have significant affects on all of the stakeholders who live near and/or use the waters of the Great Lakes. For example: winter ice-free times will increase substantially, leading to shifts in patterns of evaporation and lake effect snow; stratification periods will lengthen, leading to increased risks of significant hypolimnetic oxygen deficits in late summer; increases in surface water temperature will increase the amount of habitat for warm-water species currently residing in the Great Lakes, as well increase the number of warm-water species capable of invading the Great Lakes (Shuter and Post, 1990; Schindler, 2001); and increases in overall growing season length will likely have extensive effects on overall ecosystem productivity. As such, our study emphasizes the need for continued work on predicting water temperatures as climate models are improved, and reinforces the importance of developing appropriate strategies to deal with these changes.

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