climate change
RESEARCH INFORMATION NOTE
Note Number 7 2008

Potential Changes in Future Surface Water Temperatures in the Ontario Great Lakes as a Result of Climate Change

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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). The increased water temperatures that are expected to result from climate change will have important biological effects, 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), increasing the length of the growing season, and changing the availability and distribution of different habitat types within a lake (Ficke et al. 2007).

The Great Lakes Basin contains 20% of the world's freshwater and supports a human population of more than 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 that indicate recent increases in water temperature. For example, McCormick and Fahnenstiel (1999) found evidence of increasing water temperature at five out of seven near-shore sites in the Great Lakes over the past 25 to 87 years, and increases in the length of the period of summer temperature stratification at several sites. Jones et al. (2006) found increasing summer water temperatures and decreasing winter length in western Lake Erie, as has been predicted by most climate change models. Dobiesz and Lester (in prep.) detected significant increases in summer water temperatures for Lake Huron, Lake Ontario, and the central basin of Lake Erie, whereas Assel (2005) found a decrease in the occurrence of severe winter ice cover between 1998 and 2002 compared with coverage between 1977 and 1982. Similarly, Austin and Colman (2007) observed increasing summer water temperatures in Lake Superior between 1979 and 2006, coupled with a decrease in winter ice cover.

The goal of the present study was to predict surface water temperatures in Lake Superior, Lake Huron, Lake Erie, and Lake Ontario during three time periods (2011 to 2040, 2041 to 2070, and 2071 to 2100, with 1971 to 2000 used as the base period) under two different warming scenarios (IPCC A2 and B2 CO_2-equivalent scenarios; Nakicenovik et al. 2000). To do so, we used historical data to develop empirical models of the links between climate and water temperature conditions, and then used those models to translate forecasts of future climate into forecasts of future water temperatures.

Methods

Characterizing Annual Water Temperature Cycles

We used remotely sensed whole-lake surface water temperatures (SWT) from the NOAA Great Lakes Surface Environment Analysis (GLSEA) program (http://coastwatch.glerl.noaa.gov/overview/cw-overview.html) to model water temperatures in Lake Superior, Lake Huron, Lake Erie, and Lake Ontario from 1995 to 2006. We fitted a simple model (Figure 1) consisting of three parts: a spring warming period, a period of maximum mid-summer temperature, and a fall cooling period.

To determine the spring warming and fall cooling rates, we classified data from individual lakes into spring, summer, and fall periods as follows. Care was taken to focus on those periods in each year that exhibited strong and consistent increasing (spring) or decreasing (fall) trends in temperature. Figure 2 shows data for Lake Superior, which are representative of the patterns for the other lakes. Thus, any temperatures less than 7°C were not used from Lake Huron and Lake Ontario, and temperatures less than 6°C were not used from Lake Superior and Lake Erie.

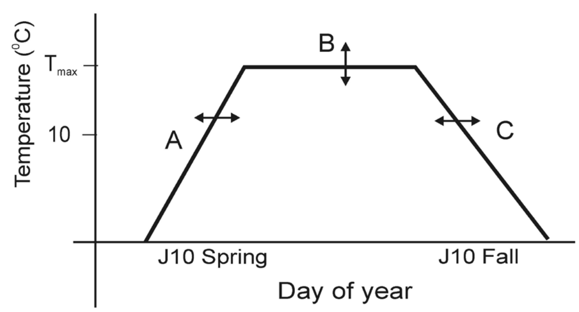

Figure 1. Conceptual diagram of the surface water temperature model. Spring slopes (A) and fall slopes (C) are consistent for a lake, but the *x*-intercepts vary annually. The value of the summer plateau (B) varies annually. J10 values are the days of the year in the spring and fall when the temperature is 10°C. T_{max} determines the temperature of the summer plateau and is estimated as the median of the ten highest temperatures observed during the year.

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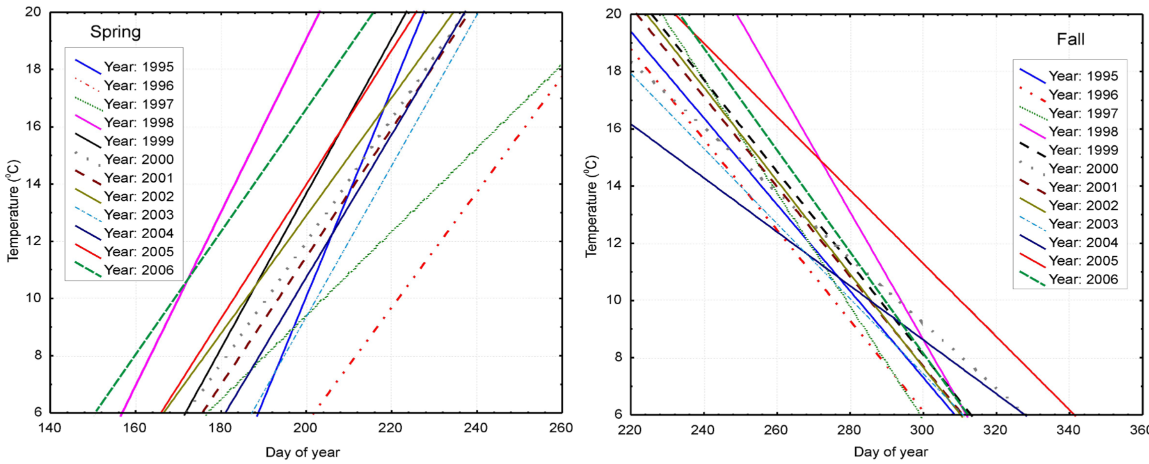

Figure 2. Linear models of surface water temperatures vs. day of year in the spring (left) and fall (right) for Lake Superior from 1995 to 2006.

Since the observed year-to-year variation in the rates of spring and fall temperature changes was quite low for each lake (Figure 3), the spring warming and fall cooling periods could be represented reasonably well by assuming a linear spring warming and fall cooling trend, with a slope that was fixed across years and *x*-intercept values that varied from year to year. We used analysis of covariance (ANCOVA) to fit this model to the spring and fall data for each lake. This allowed us to estimate the day of the year (DOY) in spring when temperatures had increased to 10°C ($J10_{spring}$) and the day of the year in fall when temperatures had fallen to 10°C ($J10_{fall}$). Temperatures during the interval between the spring warming period and the fall cooling period could be represented reasonably well by a lake-specific constant that varied from year to year. The value of this constant (T_{max}) for a particular year was estimated as the median of the ten highest daily water temperatures observed in that year.

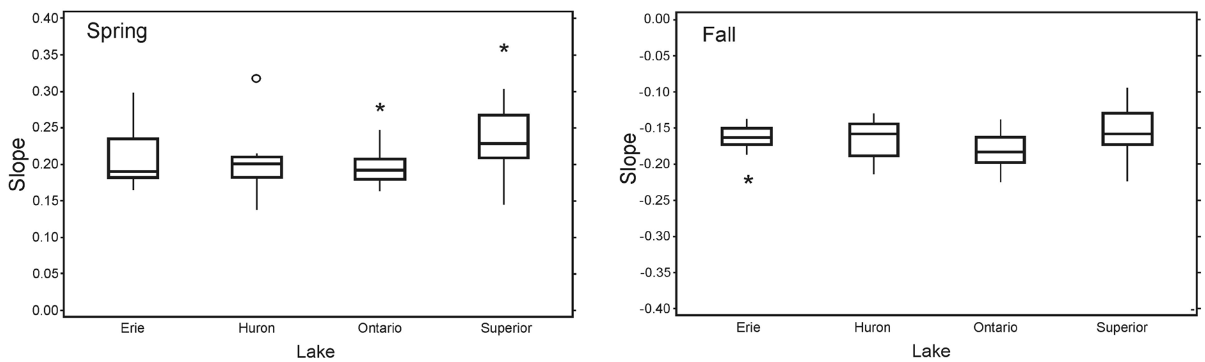

Figure 3. Boxplots showing the variation in the rates of spring and fall surface water temperature changes (slopes) from 1995 to 2006 for the Great Lakes in Ontario.

Thus, we were able to represent the annual surface water temperature cycles for each lake from 1995 to 2006 using a simple three-part model that consisted of a lake-specific spring slope with year-specific *x*-intercepts, a lake- and year-specific summer plateau temperature, and a lake-specific fall slope with year-specific *x*-intercepts. This scheme allowed us to specify the annual temperature cycle for a particular lake in a particular year using only two lake-specific parameters (the spring and fall slopes) and three year-specific parameters ($J10_{spring}$, T_{max}, and $J10_{fall}$).

Using the GLSEA data, we calculated the length of the winter and ice-free periods in each year. We defined the length of the winter as the predicted number of days with temperatures less than 4°C and the length of the ice-free period as the predicted number of days with temperatures above 4°C. Winter length was calculated as a continuous season between days with these two temperatures from the fall of one year to the spring of the following year.

Linking Historical Variation in Water Temperature Cycles to Historical Variation in Climate

Climate data was obtained from three Environment Canada climate stations for each of the four Great Lakes. Monthly, seasonal, and annual means were calculated and correlations between stations and climate means were calculated. Overall, correlations among stations were high for a given lake, with Pearson correlations ranging from 0.86 to 0.98. This result, combined with the reported significant correlation of mean air temperatures over distances of up to 2,500 km (Koenig 2002), suggests that it would be feasible to use data from a single climate station per lake in our subsequent analyses. The stations we used were those in Sault Ste. Marie, Sudbury, Windsor, and Trenton for Lake Superior, Lake Huron, Lake Erie, and Lake Ontario, respectively.

Using monthly and 6- and 12-month mean air temperatures as independent variables and T_{max}, $J10_{spring}$, and $J10_{fall}$ as dependent variables, we performed a best-subsets regression for each lake. For each water temperature parameter, we chose a set of three or four climate variables as the set of best predictors. These regression models were then used to predict future water temperatures from forecasts of future climates. In this analysis, we used the IPCC A2 and B2 CO_2-equivalent scenarios as sources for predicted future mean monthly air temperatures for the periods 2011 to 2040, 2041 to 2070, and 2071 to 2100 for each climate station. The A2 scenario is characterized by high population growth and energy use, whereas the B2 scenario reflects moderate population growth and energy use (Nakicenovic et al. 2000). Any discrepancies between the Environment Canada and calculated air temperature values for the 1971 to 2000 base period were accounted for in generating our predictions of the future climate. Predicted $J10_{spring}$ and $J10_{fall}$ values were used to estimate the annual number of days in each year with a temperature <4°C.

Results and Discussion

During the base period, T_{max} appeared to increase slightly in all lakes, but the changes were not significant (ANCOVA, $p = 0.3816$; Figure 4). However, changes in the lengths of the winter and ice-free periods were significant (Figure 5). For all four lakes, winter length decreased significantly (ANCOVA, $p = 0.0036$) and the length of the ice-free period increased significantly (ANCOVA, $p = 0.0268$). Although it is possible that these trends reflect large-scale patterns associated with climate change, the timespan of the data set is too short for this hypothesis to be conclusive. As noted by McCormick and Fahnenstiel (1999), the specific interval of data being examined in climate change studies can significantly affect results.

Regression values from the surface water temperature model revealed interesting patterns. Lake-specific warming and cooling rates were not significantly different for Lake Ontario, Lake Erie, and Lake Huron, but warming was faster and cooling slower for Lake Superior (Table 1). Fitting common slopes to the multi-year data for each lake worked well, with adjusted R^2 values ranging from 0.8050 to 0.9530. Year-specific *x*-intercept values for spring and fall varied widely, both within and between lakes. The resulting J10 values showed greater variation in the spring than in the fall (Figure 6). T_{max} also varied widely both within and between lakes (Figure 7).

The regressions of T_{max}, $J10_{spring}$, and $J10_{fall}$ against SWT yielded high adjusted R^2 values, ranging from 0.74 to 0.91 for T_{max}, 0.79 to 0.90 for $J10_{spring}$, and 0.53 to 0.84 for $J10_{fall}$ (Tables 2-4). All models were significant at $p < 0.05$ except for the Lake Huron $J10_{fall}$ model, which was marginally significant ($p = 0.0507$). Future SWT values predicted using these models are presented in Tables 5 through 12 and illustrated in Figure 8. By

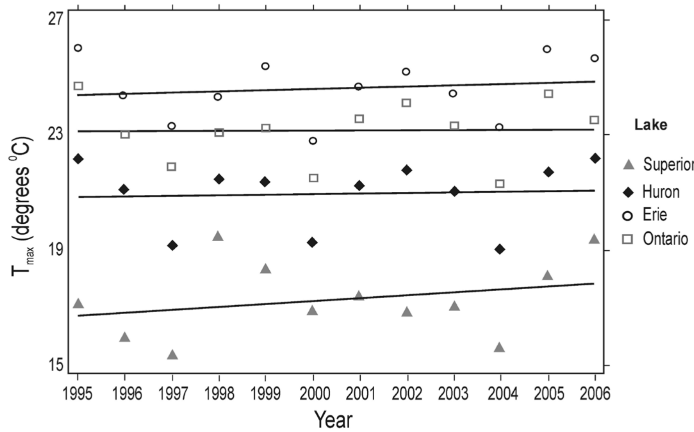

Figure 4. Changes in Tmax values from 1995 to 2006 for Lake Superior, Lake Huron, Lake Erie, and Lake Ontario. Tmax values did not increase significantly over this time span (ANCOVA, p = 0.3816). Tmax represents the median of the ten highest temperatures observed in a lake during the year.

Table 1. Fitted slopes for the rates of change in fall and spring surface water temperatures.

Lake	Season	Slope[a]	Adjusted R^2
Superior	Spring Fall	0.22448 -0.13947	0.8442 0.9098
Huron	Spring Fall	0.19197 -0.16170	0.8281 0.9478
Erie	Spring Fall	0.19409 -0.16211	0.9022 0.9530
Ontario	Spring Fall	0.19268 -0.17516	0.8050

[a] All fitted models were significant at p < 0.0001.

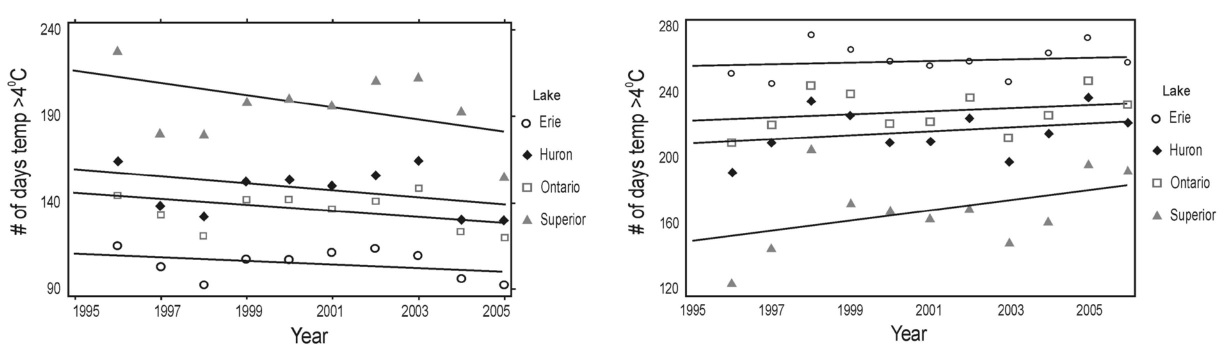

Figure 5. Lengths of the winter (temperature <4°C) and spring, summer, and fall (temperature >4°C) periods from 1995 to 2006 for Lake Superior, Lake Huron, Lake Erie, and Lake Ontario. Winter length decreased significantly (ANCOVA, *p* = 0.0036), and the length of the ice-free period increased significantly (ANCOVA, *p* = 0.0268).

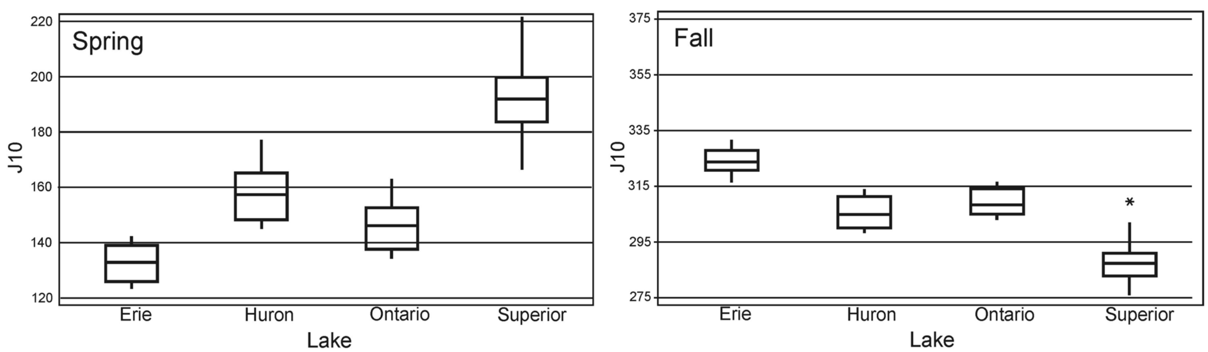

Figure 6. Boxplots showing the variation in spring and fall J10 values for Lake Superior, Lake Huron, Lake Erie, and Lake Ontario from 1995 to 2006. J10 is the day of the year in which the surface water temperature reached 10°C.

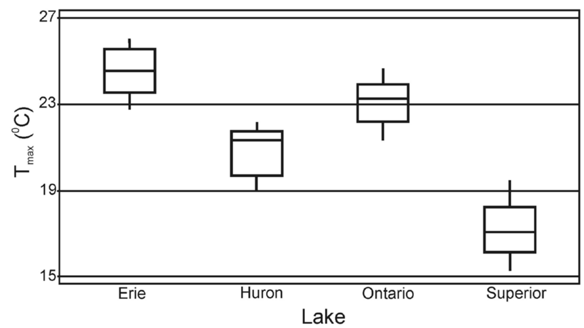

Figure 7. Boxplots demonstrating between-lake and between-year variation in T_{max} values for the four lakes. T_{max} was estimated as the median of the ten highest temperatures observed in a lake during the year.

Lake	Constant	$July_{mean}$	$August_{mean}$	January to $June_{mean}$	P value	Adjusted R2
Superior	8.52	0.20	0.26	0.51	0.0028	0.7422
Huron	1.74	0.54	0.49	0.06	0.0024	0.7515
Erie	3.42	0.56	0.43	-0.18	<0.0001	0.9149
Ontario	1.96	0.44	0.60	-0.01	0.0026	0.7483

Table 2. Regression of median of the ten highest temperatures observed in a lake during the year (T_{max}) versus surface water temperature.

Lake	Constant	$April_{mean}$	May_{mean}	$June_{mean}$	$Oct\text{-}Mar_{mean}$	P value	Adjusted R2
Superior	198.52	-3.91	-0.89	0.14		0.0018	0.8283
Huron	196.19	-2.14	-0.29	-2.65	-4.31	0.0003	0.8956
Erie	218.63	-1.48	-1.48	-2.33	-3.67	0.0011	0.8502
Ontario	244.78	-2.34	-0.61	-4.19	-1.06	0.0033	0.7941

Table 3. Regression of day of the year in which the surface water temperature reached 10°C ($J10_{spring}$) versus surface water temperature.

Lake	Constant	$Sept_{mean}$	Oct_{mean}	$Mar\text{-}Aug_{mean}$	$Sept\text{-}Aug_{mean}$	*P* value	Adjusted R^2
Superior	178.35	2.00	3.44	2.73	2.96	0.0028	0.8042
Huron	273.15	2.03	2.49	-3.22	5.24	0.0507	0.5294
Erie	245.12	2.26	2.94	0.37	-0.18	0.0013	0.8440
Ontario	242.54	2.89	4.44	-4.78	5.69	0.0039	0.7833

Table 4. Regression of day of the year in which the surface water temperature reached 10°C ($J10_{fall}$) versus surface water temperature.

the 2071 to 2100 period, maximum surface temperatures (T_{max}) are expected to rise by 3.7 to 4.4°C under the A2 scenario and by 2.5 to 3.1°C under the B2 scenario. Spring J10 values occur 34.8 to 46.5 days earlier under A2 and 23.8 to 30.7 days earlier under B2. In contrast, the fall J10 values will occur 26.2 to 51.2 days later under A2 and 17.7 to 36.1 days later under B2. These changes translate into a decrease in winter length of from 42 days for Lake Erie under B2 to 90 days for Lake Superior under A2 between the 1971 to 2000 period and the 2071 to 2100 period. (Tables 13 through 16 and Figures 9 and 10 provide the full prediction results.) The overall estimated changes for each lake between the 30-year base period and the 2071-2100 period for the A2 scenario are illustrated in Figure 11. The same overall pattern was observed for the B2 scenario (data not shown).

Table 5. Predicted surface water temperatures for Lake Superior.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$ (DOY)	$J10_{fall}$ (DOY)
1971-2000	Base	16.7	195.8	280.4
2011-2040	A2	18.0	185.8	295.5
	B2	18.1	183.4	297.1
2041-2070	A2	19.3	174.0	310.1
	B2	18.9	178.2	305.0
2071-2100	A2	21.2	157.5	331.7
	B2	19.8	169.8	316.6

[a] IPCC CO2-equivalent scenarios

Table 6. Predicted surface water temperatures for Lake Huron.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$ (DOY)	$J10_{fall}$ (DOY)
1971-2000	Base	20.6	164.6	298.8
2011-2040	A2	22.1	156.5	306.9
	B2	21.9	154.8	307.8
2041-2070	A2	23.1	144.8	315.6
	B2	22.7	148.2	312.4
2071-2100	A2	25.0	129.4	325.7
	B2	23.5	140.5	319.5

[a] IPCC CO2-equivalent scenarios

Table 7. Predicted surface water temperatures for Lake Erie.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$ (DOY)	$J10_{fall}$ (DOY)
1971-2000	Base	24.2	136.2	320.6
2011-2040	A2	25.3	125.2	327.1
	B2	25.0	124.5	327.2
2041-2070	A2	25.8	115.3	335.5
	B2	25.9	118.8	333.0
2071-2100	A2	27.9	101.4	346.9
	B2	26.7	112.4	338.3

[a] IPCC CO2-equivalent scenarios

Table 8. Predicted surface water temperatures for Lake Ontario.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$ (DOY)	$J10_{fall}$ (DOY)
1971-2000	Base	22.6	152.7	302.0
2011-2040	A2	23.9	142.7	308.9
	B2	23.8	140.4	309.0
2041-2070	A2	24.9	127.1	320.2
	B2	24.7	131.4	316.8
2071-2100	A2	27.0	106.2	332.7
	B2	25.5	122.0	325.7

[a] IPCC CO2-equivalent scenarios

Table 9. Predicted changes in surface water temperatures from the 1971-2000 average for Lake Superior.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$	$J10_{fal}$
2011-2040	A2	-10.0	+1.3	+15.0
	B2	-12.4	+1.4	+16.6
2041-2070	A2	-21.8	+2.6	+29.6
	B2	-17.6	+2.1	+24.5
2071-2100	A2	-38.3	+4.4	+51.2
	B2	-26.0	+3.1	+36.1

[a] IPCC CO2-equivalent scenarios

Table 10. Predicted changes in surface water temperatures from the 1971-2000 average for Lake Huron.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$	$J10_{fal}$
2011-2040	A2	+1.4	-8.1	+8.1
	B2	+1.3	-9.8	+9.1
2041-2070	A2	+2.4	-19.8	+16.8
	B2	+2.1	-16.5	+13.7
2071-2100	A2	+4.3	-35.2	+26.9
	B2	+2.9	-24.1	+20.7

[a] IPCC CO2-equivalent scenarios

Table 11. Predicted changes in surface water temperatures from the 1971-2000 average for Lake Erie.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$	$J10_{fal}$
2011-2040	A2	+1.1	-11.0	+6.5
	B2	+0.8	-11.6	+6.6
2041-2070	A2	+1.6	-20.8	+14.8
	B2	+1.7	-17.4	+12.4
2071-2100	A2	+3.7	-34.8	+26.2
	B2	+2.5	-23.8	+17.7

[a] IPCC CO2-equivalent scenarios

Table 12. Predicted changes in surface water temperatures from the 1971-2000 average for Lake Ontario.[1]

Period	Scenario[a]	T_{max} (^{0}C)	$J10_{spring}$	$J10_{fal}$
2011-2040	A2	+1.2	-10.0	+6.9
	B2	+1.1	-12.2	+7.0
2041-2070	A2	+2.2	-25.6	+18.2
	B2	+2.0	-21.3	+14.8
2071-2100	A2	+4.3	-46.5	+30.7
	B2	+2.9	-30.7	+23.7

[a] IPCC CO2-equivalent scenarios

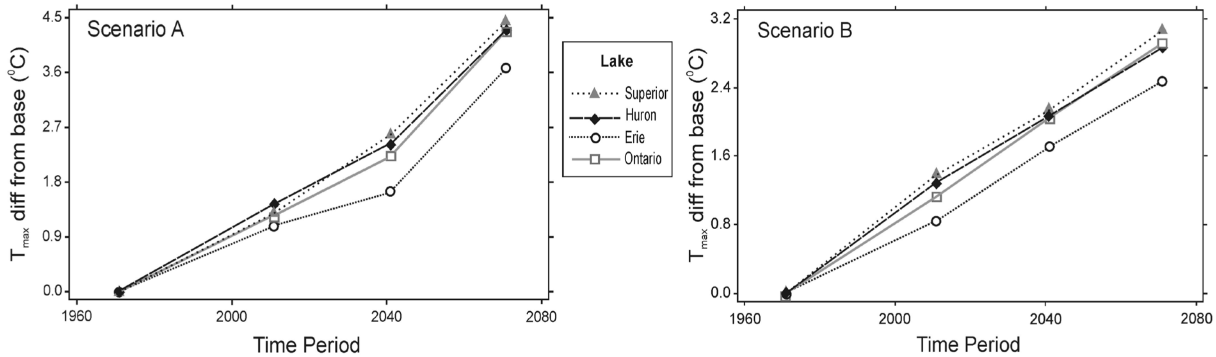

Figure 8. Difference in T_{max} values from the 1971-2000 base during the 2011 to 2040, 2041 to 2070, and 2071 to 2100 periods under IPCC scenarios A2 and B2 CO_2-equivalent warming scenarios. T_{max} is estimated as the median of the ten highest temperatures observed in a lake during the year.

Table 13. Predicted number of days with surface water temperatures <4°C.

Period	Scenario[a]	Lake Superior	Lake Huron	Lake Erie	Lake Ontario
1971-2000	Base	211	163	113	150
2011-2040	A2	186	147	95	133
	B2	181	144	94	131
2041-2070	A2	159	126	77	106
	B2	169	132	83	114
2071-2100	A2	121	101	52	74
	B2	149	118	71	96

[a] IPCC CO2-equivalent scenarios

Table 14. Predicted number of days with surface water temperatures >4°C.

Period	Scenario[a]	Lake Superior	Lake Huron	Lake Erie	Lake Ontario
1971-2000	Base	154	202	252	215
2011-2040	A2	179	218	270	232
	B2	184	221	271	234
2041-2070	A2	206	239	288	259
	B2	196	233	282	251
2071-2100	A2	244	264	313	291
	B2	216	247	294	269

[a] IPCC CO2-equivalent scenarios

Table 15. Predicted differences from the 1971 to 2000 base period in the number of days with surface water temperatures <4°C.

Period	Scenario[a]	Lake Superior	Lake Huron	Lake Erie	Lake Ontario
2011-2040	A2	-25	-16	-18	-17
	B2	-30	-19	-19	-19
2041-2070	A2	-52	-37	-36	-44
	B2	-42	-31	-30	-36
2071-2100	A2	-90	-62	-61	-76
	B2	-62	-45	-42	-54

[a] IPCC CO2-equivalent scenarios

Table 16. Predicted differences from the 1971 to 2000 base period in the number of days with surface water temperatures >4°C.

Period	Scenario[a]	Lake Superior	Lake Huron	Lake Erie	Lake Ontario
2011-2040	A2	+25	+16	+18	+17
	B2	+30	+19	+19	+19
2041-2070	A2	+52	+37	+36	+44
	B2	+42	+31	+30	+36
2071-2100	A2	+90	+62	+61	+76
	B2	+62	+45	+42	+54

[a] IPCC CO2-equivalent scenarios

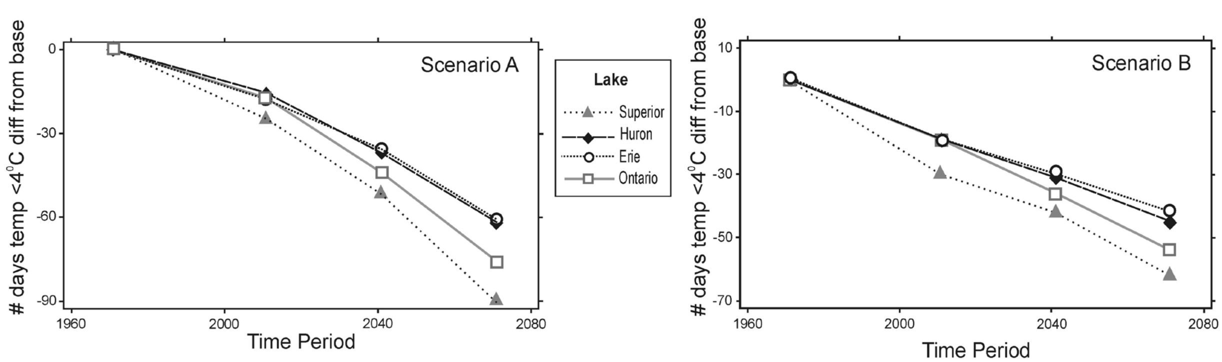

Figure 9. Decreases in the number of days with surface water temperatures <4°C from the 1971 to 2000 base period for the 2011 to 2040, 2041 to 2070, and 2071 to 2100 periods under IPCC scenarios A2 and B2.

For Lake Huron, Lake Erie, and Lake Ontario, J10 values are predicted to change more in the spring than in the fall for all scenarios and all time periods; for Lake Superior, the changes in the two seasons are comparable (Figure 11). This is consistent with the empirical results of McCormick and Fahnenstiel (1999), who found that recent increases in the potential duration of summer thermal stratification (based on the dates when water temperatures rise above 4°C in the spring and decrease below 4°C in the fall) in several of the Great Lakes depended strongly on an earlier transition to spring conditions rather than a later onset of fall conditions.

In general, by the 2071 to 2100 period, the J10 values for Lake Superior will have changed the most, and those for Lake Erie will have changed the least. This reflects the findings of Dobiesz and Lester (in prep), who found that, over their 34-year study period, the greatest increases in water temperature occurred in the colder basins (e.g., in the deep basins of Lake Huron).

The estimated potential increases in surface water temperatures in this study could have important effects on the fisheries and ecosystems of the Great Lakes. For example, the presence of suitable thermal habitats may increase the number of warm-water species capable of invading the Great Lakes and may create problems for reproduction and survival of cold-water species. Moreover, increases in water temperatures may expand the habitat for warm-water species currently residing in the Great Lakes and shrink this habitat for cold-water species. Increases in the length of the growing season for aquatic vegetation due to the presence of warmer temperatures for longer periods will thus have considerable effects on the productivity of the fisheries and on the aquatic ecosystems in the lakes.

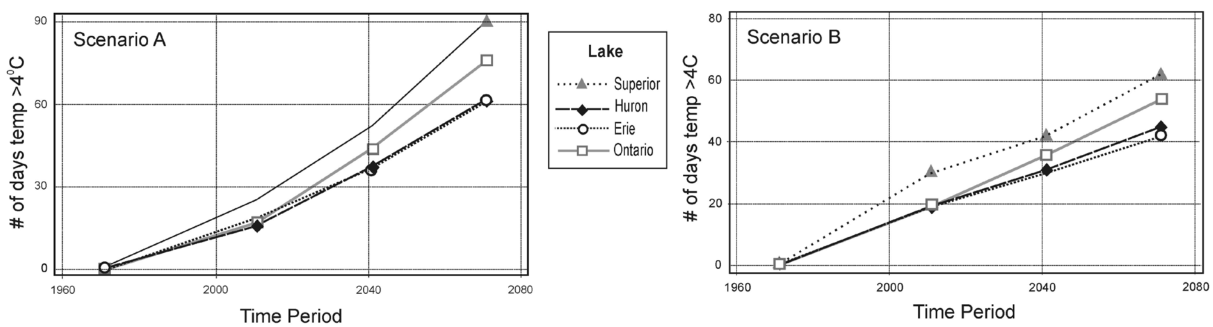

Figure 10. Differences in the number of days with surface water temperatures >4°C from the 1971 to 2000 base period for the 2011 to 2040, 2041 to 2070, and 2071 to 2100 periods under IPCC scenarios A2 and B2.

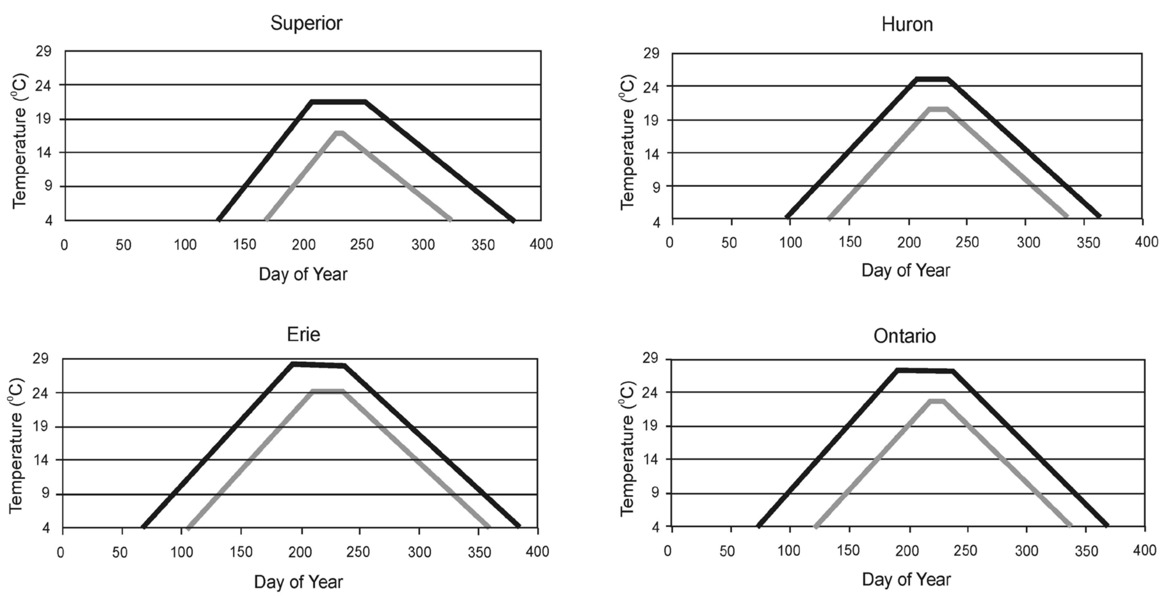

Figure 11. Estimated average annual temperature cycles for Lake Superior, Lake Huron, Lake Erie, and Lake Ontario during the 1971 to 2000 period (grey lines) and during the 2071 to 2100 period under the IPCC A2 CO_2-equivalent scenario (black lines). Changes under scenario B2 were similar, and are thus not shown.

The approach we used in this study focused on predicting whole-lake average SWT. However, significant within-lake variation in water temperatures exists between, for example, shallow embayments and open water. Future work should focus on modelling temperature trends in the shallow basins of the Great Lakes, such as western Lake Erie and the Bay of Quinte in Lake Ontario. In addition, we are compiling more extensive historical data sets for water temperature to develop an independent assessment of the reliability of the SWT predictions generated by our regression models.

Acknowledgements

Funding for this project was provided by OMNR's Climate Change Program under the auspices of Climate Change Project CC-07/08-013. We thank Lisa Buse (OFRI, OMNR) for her editorial advice and Trudy Vaittinen (OFRI, OMNR) for formatting this publication

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Changements possibles, à l'avenir, des températures de l'eau de surface des Grands Lacs en Ontario sous l'effet du changement climatique

La température est un facteur essentiel dans la productivité biologique, car il détermine les vitesses de nombreux processus dans les écosystèmes. Plusieurs études récentes ont démontré que les températures de l'eau dans les Grands Lacs augmentent, possiblement sous l'effet du changement climatique. Notre étude a pour but d'établir un lien entre les changements chroniques de la température de l'eau et ceux de la température de l'air ambiant afin de produire des outils statistiques capables de prévoir les températures futures de l'eau à partir des prévisions des températures de l'air. Des données télédétectées ont été utilisées pour modéliser la configuration annuelle des températures de l'eau en surface dans les lacs Supérieur, Huron, Érié et Ontario. Durant la période sans couvert glaciel, la température en surface subit généralement une augmentation linéaire au printemps, forme un plateau à la mi-été, puis baisse de façon linéaire en automne. Dans un lac, les vitesses de réchauffement et de refroidissement sont similaires au cours des ans, mais le calendrier des périodes de réchauffement et de refroidissement, et des températures de plateau, affiche des variations considérables d'une année à l'autre. Cette variation est bien prévisible en fonction de la variation de la température de l'air ambiant. Des prévisions fondées sur le modèle canadien CGMC2 selon deux scénarios de changement climatique ont été utilisées pour estimer les températures futures de l'eau en surface dans les lacs Supérieur, Huron, Érié et Ontario. Des augmentations élevées des températures sont prévues. Les conséquences sur les processus des écosystèmes et sur les pêches sont étudiées.

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(0.3k P.R., 08 07 15)
ISBN 978-1-4249-3366-2 (PDF)