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Characterizing patterns of nearshore water temperature variation in the North American Great Lakes and assessing sensitivities to climate change

Justin Trumpickas [a,*], Brian J. Shuter [a,b,1], Charles K. Minns [b,c,2], Hélène Cyr [b,3]

[a] Aquatic Research and Monitoring Section, Ontario Ministry of Natural Resources and Forestry, 2140 East Bank Drive, Peterborough, Ontario K9J 7B8, Canada
[b] Department of Ecology and Evolutionary Biology, University of Toronto, 25 Harbord Street, Toronto, Ontario M5S 3G5, Canada
[c] Great Lakes Laboratory for Fisheries and Aquatic Science, Fisheries and Oceans Canada, PO Box 5050, 867 Lakeshore Road, Burlington, Ontario L7R 4A6, Canada

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ABSTRACT

Nearshore waters are among the most biologically productive and anthropogenically developed in the North American Great Lakes. We examined site-to-site differences in the pattern of variation in the daily water temperatures observed at water intakes located in nearshore regions of the Great Lakes. Data from 28 nearshore sites spread across all five lakes were analyzed. At each site, daily differences between nearshore and lake-wide surface water temperatures varied systematically with season, and these seasonal patterns varied systematically from site to site. We characterized these patterns using an index derived from quantile regression. Index values were related to site-specific factors such as depth, fetch and exposure. We broadened these empirical analyses to develop a tool for extending, to nearshore water temperatures, previously published projections of climate change impacts on lake-wide mean surface water temperatures. This tool provided projections of the possible impacts of increasing surface water temperatures on nearshore water temperatures under a climate change scenario for the Great Lakes region. Projections were generated for nearshore sites characterized by a range of depth and fetch values representative of those found throughout the Great Lakes. Projected impacts varied with site characteristics, with likely implications for biological activity and human use.

Introduction

Nearshore regions of lakes are important for anthropogenic uses and biological productivity. For example, nearshore waters contain municipal water intake facilities, electricity generating stations and recreational sites (Edsall and Charlton, 1997). In 2011, consumptive uses of water amounted to 7.8 billion liters per day or 4% of the total water use in the Great Lakes basin (Great Lakes Commission, 2013), with public intakes accounting for 27.8%, nuclear power 18.8%, irrigation 18.3% and industry 17.4% of consumptive uses. The remaining 96% of total usage is devoted to hydroelectric power generation. Nearshore waters are productive habitats for many aquatic organisms including plankton, benthic invertebrates and fishes (Roseman et al., 2005; Ostrovsky et al., 1996; Kilgour et al., 2000). The temperatures of these waters impact the benefits humans derive from them, as well as their productivity. Therefore, it is of both economic as well as ecological interest to develop projections of how nearshore water temperatures might be affected by future climate change. Importantly, findings by McCormick and Fahnenstiel (1999), Jones et al. (2006) and Austin and Colman (2008) suggest that warming trends are already evident at some shallow nearshore sites in the Great Lakes, as well as declines in ice cover (Howk, 2009).

Due to the interaction of wind-driven mixing and transport with basin boundaries, gravity and the rotation of the earth, complex patterns of thermal structure are found in the Great Lakes (Huang et al., 2010; Rao and Schwab, 2007; Rao and Sheng, 2008). In the spring, nearshore surface waters warm up sooner than offshore surface waters resulting in the formation of a thermal bar at 4 °C separating coastal and offshore waters (Mortimer, 2006). In the summer the lakes stratify, permitting intermittent wind events to generate horizontal gradients in surface temperatures as warmer, lighter waters are pushed downwind and cooler, heavier waters upwell upwind (Csanady, 1977; Simons and Schertzer, 1987). In the fall, inshore and offshore waters can become thermally distinct again as shallower, inshore waters cool more rapidly than deeper offshore waters (Chubarenko and Hutter, 2005). Water intakes for municipal and other uses are typically sited at various depths in the nearshore zone or in the inshore portion of the coastal boundary layer, and they can be differentially affected by the complex of water motions.

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* Corresponding author. Tel.: +1 705 755 5199; fax: +1 705 755 1559.
E-mail addresses: justin.trumpickas@ontario.ca (J. Trumpickas), brian.shuter@utoronto.ca (B.J. Shuter), ken@minns.ca (C.K. Minns), helene.cyr@utoronto.ca (H. Cyr).
[1] Tel.: +1 416 978 7338.
[2] Tel.: +1 416 927 8671.
[3] Tel.: +1 416 978 0975.

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Besides a range of water quality measurements to meet safety and environmental regulations (Edsall and Charlton, 1997), water temperature has been monitored daily often for decades at many municipal water intakes, for example, the data records examined by McCormick and Fahnenstiel (1999) for evidence of climatic trends. While the temperatures seen at shallower intakes typically track nearshore surface conditions, temperatures at deeper intakes also show evidence of the intermittent effects of upwelling (Trumpickas et al., 2009), similar to the surface patterns reported by Howell et al. (2012) at sites in the nearshore of Lake Ontario when upwelling events penetrated to the lake surface. Howell et al.'s (2012) observations also exhibit both advanced warming of nearshore surface waters in spring and advanced cooling in fall, relative to lake-wide mean surface temperatures, provided by the National Oceanic and Atmospheric Administration's Great Lakes Surface Environment Analysis (GLSEA) program (http://coastwatch.glerl.noaa.gov/statistic/statistic.html) (Schwab et al., 1999). While the GLSEA provides an estimate of lake-wide mean surface temperatures, the estimates largely reflect offshore conditions because (i) >75% of the area of each Great Lake is over depths >20 m (with the exception of Lake Erie, with ~41% of its area over depths of >20 m) (based on lake morphometry data from the Great Lakes Information Network http://coastwatch.glerl.noaa.gov/statistic/physical.html) and (ii) GLSEA pixels (taken on a 2.5 km scale) overlapping the shoreline are removed from the GLSEA water temperature estimate, further decreasing the influence of nearshore areas on the estimate of the overall lake-wide mean surface water temperature (Schwab et al., 1999). Furthermore, Schwab et al. (1999) showed high similarity between in-situ water temperatures recorded at eight offshore buoys across the Great Lakes and GLSEA temperatures measured at the buoy locations (mean temperature differences between buoy and GLSEA temperatures were <0.5 °C for all buoys), showing that the GLSEA program accurately measures offshore temperatures, but its relevance for nearshore temperatures is unknown.

Trumpickas et al. (2009) used empirical models linking air temperatures to GLSEA temperatures to project how climate change might affect future Great Lakes lake-wide surface water temperatures. These water temperature projections have proved useful in assessing possible impacts of climate change on Great Lakes' fish ecology and fisheries management (Lynch et al., 2010) and on regional biodiversity (Hall, 2012). In exploratory analyses, Trumpickas et al. (2009) showed that there were marked differences in seasonal water temperature patterns among specific nearshore sites. They hypothesized that these among-site differences were related to site-specific characteristics which affect both seasonal warming/cooling patterns and the influence of offshore hypolimnetic water (Trumpickas et al., 2009). These hypotheses are supported by recent empirical findings that: (i) link nearshore water temperature patterns to site bathymetry and offshore temperatures (Murphy et al., 2011; Wells and Parker, 2010) and (ii) demonstrate temporally consistent (i.e. over 36 years) statistical associations between Lake Superior offshore water temperatures and a nearshore site located in the lake's outflow (Austin and Colman, 2008).

Given the importance of Great Lakes' nearshore waters, there is a need for quantitative descriptions of how nearshore water temperature variability is shaped by nearshore site characteristics and offshore water temperatures. Given the complex physics that must be considered in attempting to mechanistically model the hydrodynamics of nearshore systems (Monismith et al., 1990; Rao and Schwab, 2007; Wells and Sherman, 2001), a formal assessment of the character and strength of the statistical associations linking site-specific seasonal patterns of water temperature variability to local characteristics of nearshore sites would be of value because: (i) it would define constraints on the historical behavior of these systems that would need to be accounted for by future mechanistic modeling and (ii) it would provide simple empirical tools for scoping the possible impacts of increasing surface temperatures due to climate change on nearshore Great Lakes water temperatures — tools that would complement what Trumpickas et al. (2009) developed for lake-wide water temperatures.

The objectives of this paper are to use observed records of daily water temperatures from 28 Great Lakes nearshore sites to: (i) develop a single index that characterizes, for each site, the pattern of day-to-day changes in the historical distribution of nearshore–lake-wide water temperature differences over the period of positive stratification (when surface water temperatures are >4 °C), (ii) provide a quantitative description of how much of the site to site variation in this index is related to easily measured site characteristics like depth and fetch and (iii) use results from steps (i) and (ii) to develop a tool for scoping some of the potential impacts of increasing surface temperatures on midsummer water temperature patterns at nearshore sites around the Great Lakes. This approach will help identify primary drivers of nearshore temperature variation at the basin scale, provide initial forecasts of future nearshore temperature conditions, and identify promising approaches for refining next-generation forecasts.

Methods

Characterizing site-specific seasonal patterns of temperature variation

Data sources and sites

Daily nearshore water temperatures were compiled from 28 water intake sites from across the Great Lakes with 4 to 58 years of data per site (Fig. 1, Electronic supplementary material (ESM) Table S1). Intake data associated with each site include, at a minimum, daily water temperature, the depth of the water intake (the depth at which the temperature was recorded), and a geographical location for the water intake. Some of these data were also used by McCormick and Fahnenstiel (1999) to analyze Great Lakes nearshore temperature trends, but most of the data used here were gathered through direct contact with staff at individual water filtration plants. Each Great Lake was represented by between four and nine intake sites. The earliest water temperature record was from 1943 and the latest from 2000. The 28 intake sites cover much of the range of fetch, exposure and depth values present in the nearshore zone of the Great Lakes — therefore, these sites were considered a representative sample of the nearshore zone of this interconnected set of water bodies. Analyses described in the following sections were completed for all sites across lakes together rather than completed separately for each lake because we expected nearshore water temperature variation to be influenced more by site-level characteristics than lake-level characteristics. This expectation is based on the knowledge that, for all the lakes: (i) thermocline depths are generally similar in stratified regions of the lakes (Boyce et al., 1989; Mazumder and Taylor, 1994); (ii) hypolimnetic temperatures are similar (http://www.glerl.noaa.gov/res/glcfs/); and (iii) prevailing winds are similar (Boyce et al., 1989).

Trumpickas et al. (2009) developed empirical models for lakes Superior, Huron, Erie and Ontario that were designed to estimate GLSEA-based lake-wide daily mean surface water temperatures from daily regional air temperatures for the period of positive stratification (>4 °C). We used the same approach to derive a similar model for Lake Michigan, based on GLSEA data for that lake for the years from 1995 through 2006. We then used these five lake-specific models and local air temperatures for lakes Superior, Huron, Erie, Ontario and Michigan (source: Environment Canada weather stations at Sault Ste. Marie, Sudbury, Windsor and Trenton, http://www.climate.weatheroffice.ec.gc.ca and National Oceanic and Atmospheric Administration National Weather Service weather station in Manitowoc, Wisconsin, compiled by the Goddard Institute for Space Studies http://data.giss.nasa.gov/gistemp/station_data/, respectively), to estimate GLSEA-based lake-wide daily mean surface water temperatures for each lake for all the years for which we had intake data. We had to rely on these indirect estimates of past lake-wide surface water temperatures, rather than direct GLSEA estimates, because the bulk of the data from most of our