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Characterisation of water temperature variability within a harbour connected to a large lake

Bogdan Hlevca [a,*], Steven J. Cooke [b], Jonathan D. Midwood [b], Susan E. Doka [c], Rick Portiss [d], Mathew G. Wells [a]

[a] Department of Physical and Environmental Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON M1C 1A4, Canada
[b] Fish Ecology and Conservation Physiology Laboratory, Department of Biology, Carleton University, 1125 Colonel By Dr., Ottawa, ON, K1S 5B6, Canada
[c] Department of Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries & Aquatic Sciences, 867 Lakeshore Road, Burlington, ON L7R 4A6, Canada
[d] Toronto and Region Conservation Authority, Restoration and Environmental Monitoring Section, Kortright Centre for Conservation, 9550 Pine Valley Dr., Woodbridge, ON L4L 1A6, Canada

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ABSTRACT

Many coastal embayments in the Laurentian Great Lakes have highly variable temperatures due to pronounced movements of the thermocline in the nearshore zone. As an example, we document the diverse thermal regimes in Toronto Harbour, which is also the site of some of the most extensive fish habitat restoration activities in Lake Ontario. Toronto Harbour is characterised by considerable thermal variability as a result of diurnal heat fluxes and large amplitude movements of the thermocline of Lake Ontario. During the ice-free period from April–November 2013, an array of benthic and surface temperature loggers were deployed to obtain the spatio-temporal distribution of water temperatures. Complementary measurements of stratification were made in Lake Ontario at a site 5 km offshore. The dominant periods of short-term thermal variability were 12, 17, and 24 h, reflecting both diurnal heat fluxes and inertial oscillations of Lake Ontario's thermocline. The thermocline in Lake Ontario was observed to oscillate by as much as 15 m, around a mean depth of 9 m, which is comparable to the mean depth of Toronto Harbour. Cold intrusions were found to quickly flow from the lake into the harbour and lead to rapid drops in temperature (e.g., as much as 15 °C in less than 4 h). Such "cold shock" events may be associated with a variety of negative effects on many aquatic organisms, especially warm-water fishes. We consider the potential impacts of the observed temperature variability on cool and warm-water fish species that are the target of restoration activities.

Introduction

Temperature is widely regarded as the "master factor" influencing the biology of fishes (Brett, 1971) and as such is viewed as an ecological resource (Magnuson et al., 1979), driving the productivity and distribution of fish populations (Lapointe et al., 2014). Therefore, the suitability of aquatic habitat for numerous fish species in coastal embayments of the Laurentian Great Lakes is strongly dependent upon their thermal regime (Wismer and Christie, 1987). During summer, the nearshore zone of the Great Lakes is characterised by very active movements of the thermocline, which results in a highly dynamic temperature regime along the lake's boundary (Rao and Schwab, 2007; Trumpickas et al., 2015). Given that temperature changes are known to affect the distribution, growth, reproduction, and survival of fishes and other aquatic organisms (Casselman, 2002, and Donaldson et al., 2008; Shuter et al., 1980), it is important to understand thermal dynamics in coastal embayments.

In the coastal areas of the Great Lakes, thermal variability is the largest during the summer stratified period (Trumpickas et al., 2015; Wells and Parker, 2010). There are several physical mechanisms that are known to be responsible for thermal variability in the coastal areas of large stratified lakes, such as diurnal insolation effects in shallow and confined water bodies (Zhang and Nepf, 2009), near-inertial internal Poincaré waves in deeper bodies of water, internal Kelvin waves, and wind-driven upwelling events (Rao and Schwab, 2007; Troy et al., 2012). Large amplitude movements of the thermocline are a common feature in the Great Lakes region during the summer, and upwelling of cold hypolimnetic waters and downwelling of warm epilimnetic waters have been reported in many lakes (Coman and Wells, 2012; Hawley and Muzzi, 2003; Troy et al., 2012, and Wells and Parker, 2010) resulting in significant temperature variability in the water column. Thus, the temperature variability in a complex harbour is likely to be a function of depth and connectivity of the various embayments and will show thermal variability on a range of timescales.

During periods of thermal stratification the movements of the thermocline in the Great Lakes are dominated by high-amplitude internal waves that have frequencies close to the inertial period of around 17 h at 45°N (Hamblin, 1982). These large amplitude internal waves with anticyclonic phase propagation, known as Poincaré waves, have been documented in Lake Ontario (Rao and Murthy, 2001), Lake Erie (Bouffard et al, 2012), Lake Michigan (Hawley and Muzzi, 2003), Lake Huron

* Corresponding author. Tel.: +1 905 943 7483.
E-mail address: bogdan.hlevca@utoronto.ca (B. Hlevca).

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(Murthy and Dunbar, 1981), and Lake Superior (Austin, 2013). Poincaré waves are dispersive near-inertial oscillations (periods slightly less than $T = 2\pi/f$, where the Coriolis Parameter $f = 2\ \Omega\ \sin\varphi$, Ω is the rotation rate of the Earth, and φ is the latitude), which is a period of approximately 17.4 h for Lake Ontario. In the Great Lakes, a large spectrum of internal waves has been observed, but the near-inertial period is dominant and has been identified from both temperature and velocity records (Csanady, 1975; Mortimer, 2004; Murthy and Dunbar, 1981). In shallow and more confined coastal embayments, solar insolation can lead to pronounced changes in water temperature (up to 10 °C) over a 24-h period (Andradóttir and Nepf, 2000; Monismith et al., 1990; Wells and Sealock, 2009). This rate of thermal change may dominate many shallow bodies of water, but the diurnal heating rate would be insignificant from a thermal variability perspective for deeper areas of typical Great Lakes' harbours, where the average depth is 10 m or more. Furthermore, in the Great Lakes, large-scale movements of the thermocline, known as upwellings and downwellings, are often observed for periods of up to 3–4 days. Upwelling events are produced by a combination of alongshore or offshore winds and the Coriolis effect-driven Ekman transport (Csanady, 1975; Rao and Murthy, 2001; Troy et al., 2012). During upwelling events, cold water is brought to the surface, replacing the warmer and usually nutrient-depleted surface water and results in dramatic drops in nearshore water temperatures. These upwelling events can be quite large in both spatial and temporal dimensions (Mortimer, 2004). For instance, on the north-eastern shore of Lake Ontario, Huang et al. (2010) reported frequent upwellings of cold water, induced by the prevailing westerly winds, which typically covered a 100 km section of coastline around Toronto Harbour, with the cold front extending 5–10 km offshore.

In the context of large stratified lakes, numerous studies have found strong coupling between thermal variability associated with movements of the thermocline and biotic responses. In an extreme event reported in Lake Huron, rapid cooling due to upwelling of cold hypolimnetic waters caused mortalities in benthic species, such as sculpin and crayfish (Emery, 1970). Cold-water upwellings have also been implicated in lower densities of quagga mussels in exposed areas of Lake Ontario (Wilson et al., 2006), more nutrient-enriched waters in Lake Michigan (Nalepa et al., 2005) and to a larger diversity in algal species due to larger temperature variability (Cyr, 2012; McCabe and Cyr, 2006). Movements of the thermocline have also been known to influence the distribution of fish and survival of individuals and species alike. For example, Levy et al. (1991) found a strong correlation between the position of the thermocline and the vertical distribution of sockeye salmon in Quesnel Lake, BC, Canada. This does not imply that fish are not found outside their optimal range, but thermal habitat partitioning seems to be pervasive in aquatic systems (e.g., Brandt et al., 1980), particularly those with modest thermal structure.

A goal of many fish habitat restoration efforts is to create specific habitat for different life stages of important fish species (e.g., Hondorp et al., 2014). Coastal embayments provide important spawning, nursery, and foraging habitat for the majority of fishes found within the Great Lakes basin (Jude et al., 2005; Jude and Pappas, 1992; Wei et al., 2004). This is largely due to the protection they provide from open-lake processes likely resulting in higher productivity (Klumb et al., 2003). Within Lake Ontario, suitable spawning and nursery habitats can be found along most of the southern nearshore zone. On the north shore, due to frequent upwelling events of cold water, fishes are highly dependent upon embayments for suitable thermal habitat (Klumb et al., 2003). As a result, protected nearshore areas like those located in the large freshwater harbour adjacent to the Toronto Region are often the focus of restoration activities that aim to address these issues. The success of these restoration efforts depends, in part, on creating the correct thermal regime, or at least understanding how temperature may constrain restoration activities for certain thermal guilds. It is, therefore, critical to understand the magnitude of thermal variability in coastal embayments at different scales.

Toronto Harbour is listed by the International Joint Commission as a key Area of Concern (AOC) where ecologically beneficial uses are being restored with a goal of de-listing by 2020 (Mortsch et al., 2006; Toronto and Region Conservation Authority, 2011). One of the key components of de-listing Toronto Harbour as an AOC is developing a self-sustaining fisheries through the creation and rehabilitation of habitat, particularly embayments that can support cool- and warm-water fishes.

This paper describes the thermal variability along Lake Ontario's northern shore and inside Toronto Harbour's embayments that is affected by large-scale upwelling events, Poincaré waves, and modified by diurnal heating. Our research quantifies the distribution of thermal variability within the embayments of Toronto Harbour, classifies the thermal zones of the harbour based on their thermal characteristics, links the variability with physical processes, and discusses some of the potential implications of this variability for aquatic organisms, specifically cool- and warm-water fishes. New observations in this paper will greatly extend previous temperature observations made by Murphy et al. (2012) in the Toronto Harbour, while also describing the mechanisms behind the observed temperature variability. We hypothesise that shallow areas will be dominated by the 24-h diurnal heating cycle, while deeper and more connected areas in the harbour will be dominated by periods associated with movements of the thermocline in Lake Ontario. Future work will aim to correlate the results of this study with fish habitat selection determined by a companion telemetry study of spatial and temporal variability in fish movements in Toronto Harbour.

Materials and methods

Field site description

To better understand the temperature variability experienced by coastal embayments in the Laurentian Great Lakes, we performed a focused study of water temperatures in the various embayments within Toronto Harbour, during the ice-free season of 2013. Toronto Harbour is a large and complex embayment system (18 km^2) located on the northern shore of Lake Ontario at 43° 38′ N, 79° 22′ W (Fig. 1). The harbour has a mean depth of 10 m and consists of a commercial port and several natural and artificial embayments used for recreational purposes. Most large harbours in the Great Lakes are dredged to similar minimum depths corresponding to the minimum "Seawaymax" draft of 7.92 m for the large freight ships using the St. Lawrence Seaway. Hence, many of the general features of Toronto Harbour are similar to many others ports in the Great Lakes and we expect that many of the features of temperature variability in this harbour to be of general relevance to large embayment systems throughout the Great Lakes.

The harbour has three distinct zones with different hydrodynamic characteristics, namely the Outer Harbour, the Inner Harbour, and thirdly the sheltered Tommy Thompson Park area (hereafter TTP; formerly known as the Leslie Street Spit) and the channels inside the Toronto Islands (Fig. 1). The Outer Harbour is connected directly to Lake Ontario through a wide opening and it is characterised by steep bathymetric slopes on the northern shore due to the presence of the navigation channel (10 m depth). The second zone, the Inner Harbour, contains the commercial harbour and is characterised by a quasi-uniform depth (10 m), with vertical walls on the northern shore and milder bathymetric slopes along the Toronto Islands. The Inner Harbour is connected to the Outer Harbour through the Eastern Gap channel and to the west to Lake Ontario's Humber Bay through Western Gap channel. Based upon measurements made in 1977, Haffner et al. (1982) estimated the mean daily bidirectional exchange rate between Lake Ontario and Toronto Harbour to be 97 m^{3}s^{-1}, which for the inner part of the harbour (the volume of which is approximately 40×10^6 m^3) results in a residence time of approximately 5 days. Much of this circulation is wind driven and predominantly flows into the Western Gap from Lake Ontario and out of the Eastern Gap (Dewey, 2012; William Snodgrass,

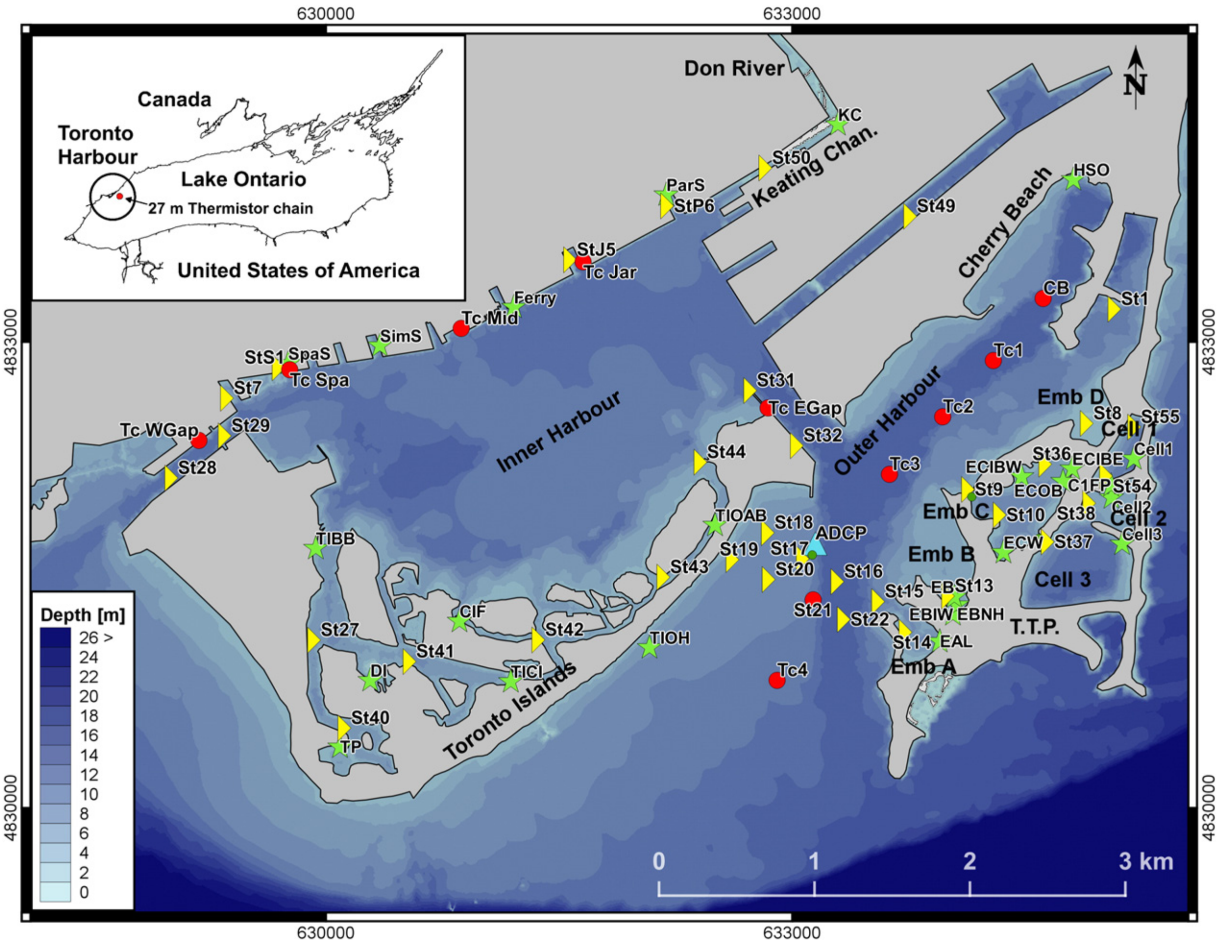

Fig. 1. Field observation locations for thermistors are shown over the bathymetry of Toronto Harbour and its adjacent embayments, Lake Ontario, Canada. The placement of University of Toronto benthic chain thermistors is shown with red dots, the thermistors associated with telemetry stations deployed by Carleton University with yellow triangles, and the thermistors deployed by the Toronto and Region Conservation Authority with green stars. The location of the acoustic Doppler current profiler is marked by a light blue triangle in the proximity of Station 17. All thermistor loggers that were used in the field work were Onset HOBO U22 Water Temp Pro V2. The location of Toronto Harbour and that of the 27 m long offshore thermistor chain are shown on the map inset. T.T.P. marks Tommy Thompson Park.

personal communication, May 30, 2014). Less than 8% of the total volume flux is driven from inflows from sources discharging into the harbour, such as the Don River (Dewey, 2012; Haffner et al., 1982), which has an average flow under 4 m^3s^{-1}. Therefore, usually the river has little influence on the circulation or the thermal structure within the Harbour and the dynamics of the Don River will not be mentioned in this study. The third zone is composed of the shallower artificial embayments of TTP and the channels inside the Toronto Islands. This zone is sheltered from lake water intrusions and is characterised by slower currents and finer sand and mud substrates. A further noteworthy feature of the entire harbour is the close proximity of very deep water in Lake Ontario. Immediately outside the 10–12 m deep Outer Harbour, there is a steep underwater escarpment that drops off to 75 m depth within 600 m of the end of TTP, making the harbour especially sensitive to upwelling hypolimnetic waters from Lake Ontario.

Instrument deployments

During the periods April–November in 2012 and 2013 and continuing in 2014, a large array of over 200 individual thermistor loggers (122 used in this study) and several thermistor chains were deployed throughout Toronto Harbour (Fig. 1). In this paper, we will focus only on data from 2013. Several short thermistor chains were deployed in the benthic zone on the longitudinal transect of the Outer Harbour and five longer thermistor chains were deployed in the Inner Harbour slips and in the shipping channels (Eastern and Western Gaps; see Table 1) to capture the water column stratification at strategic points of the harbour. The thermistors were arranged at 1 m intervals on ropes kept vertical by submerged buoys. The thermistors used were the Onset HOBO U22 Water Temp Pro V2, which have an accuracy of ±0.1 °C, an annual drift under 0.1 °C, and recorded the temperature every 10 min. In addition to our thermistor deployments, we have used temperature data collected by the Toronto and Region Conservation Authority (TRCA), which had deployed an array of subsurface (1 m above the bottom) single-thermistor stations (Onset HOBO U22 Water Temp Pro V2) along most of the harbour's coastal area (Fig. 1). It must be noted that, due to navigation restrictions in this active commercial harbour, we could not deploy thermistor chains in the main navigation channel of the Outer Harbour, and those placed on the longitudinal axis were limited to two loggers (one on the bottom and the second one at 1 m above the bottom). This setup allowed us to determine the benthic temperature variability but not the full water column stratification along the longitudinal transect. For the same reason, the thermistor placement in the Inner Harbour was limited to its perimeter. The full water column stratification within the Inner Harbour was captured by two thermistor chains situated 2 km apart; one in the Eastern Gap that covered the water column from the surface to a depth of 5 m and a thermistor chain in the Jarvis Dock, which had loggers installed from a depth of 5 m to the bottom (9 m). In order to complement the temperature data from sources located on the perimeter of

Table 1
Location of the deployed thermistor loggers. All thermistor loggers that were used in the field work were Onset HOBO U22 Water Temp Pro V2. All loggers had a sampling interval of 10 min. The symbol identifies thermistor logger placement in Fig. 1. The water depth placement for thermistor loggers was measured at deployment time but varied with the water level. LO is a thermistor chain with 24 loggers in Lake Ontario 5 km offshore of Scarborough Bluffs. Toronto and Region Conservation Authority (TRCA) thermistor loggers are not listed individually as 24 were deployed at standard depths throughout the harbour. All TRCA loggers were deployed at 1 m from the bottom and 1 m from the surface. Their location can be seen in Fig. 1.

Symbol	Location name	Embayment	Water depth [m]	Logger depth [m]	Number of loggers
LO	Scarb. Bluffs	Lake Ontario	27	3–27	24
TRCA	Entire Harbour	Toronto Harbour	2	1	24
CB	Cherry Beach	Outer Harbour	10.5	8.5,9.5,10.5	3
Ferry	Ferry Terminal	Inner Harbour	9	1	1
S1	Station 1	Outer Harbour	7	6.5	1
S7	Bathurst Dock	Inner Harbour	6	6	1
St8	Embayment D	Sheltered TTP	1.5	1.5	1
St10	Embayment C	Sheltered TTP	5	4.5	1
St13	Embayment B	Sheltered TTP	3	2.8	1
St14	Embayment A	Sheltered TTP	5	4.5	1
St15–20	Station 15–20	Outer Harbour	9,11,7,5,4,7	9,11,7,5,4,7	6
St21	Station 21	Outer Harbour	9.5	8.5,9.5	2
St22	Station 22	Outer Harbour	12	12	1
St27	Toronto Islands	Inner Harbour	3.5	3	1
St28–29	Western Gap	Inner Harbour	6,7	5.5,6.5	2
St31–32	Eastern Gap	Inner Harbour	4.5,6	4,5.5	2
St36	Embayment C	Sheltered TTP	3	3	1
St37	Cell 3	Sheltered TTP	5	4	1
St38	Cell 2	Sheltered TTP	4	3.5	1
St40–44	Toronto Islands	Inner Harbour	3,4,3,3,3.5	3,4,3,3,3.5	5
St49	Turning Basin	Inner Harbour	5.5	5	1
St50	Keating Chan.	Inner Harbour	5.5	5	1
St54–55	Cell1	Sheltered TTP	4,4	4,4	1
StFD5	Ferry Dock	Inner Harbour	5	5	1
StJ5	Jarvis Dock	Inner Harbour	6	6	1
StP6	Parliament Dock	Inner Harbour	5	5	1
StS1	Spadina Dock	Inner Harbour	4	4	1
Tc1	T-Chain 1	Outer Harbour	10.1	9.1,10.1	2
Tc2	T-Chain 2	Outer Harbour	10.2	9.2, 10.2	4
Tc3	T-Chain 3	Outer Harbour	10.7	9.7, 10.7	4
Tc4	T-Chain 4	Outer Harbour	6.5	5.5, 6.5	3
Tc Spa	Spadina Dock	Inner Harbour	5	1,3,5	3
Tc Jar	Jarvis Dock	Inner Harbour	9	5,6,7,8,9	5
Tc EGap	Eastern Gap	Inner Harbour	5	1,2,3,4,5	5
Tc Mid	Middle Dock	Inner Harbour	5	1,3,5	3
Tc WGap	Western Gap	Inner Harbour	5	1,2,3,4,5	5

the Inner Harbour and to understand if its spatial temperature variability is significant, we sampled the entire basin with an RBR XR-620 conductivity, temperature, and depth (CTD) sonde. The details about this field observation can be found in Electronic Supplementary Material (ESM) Appendix S1. The temperature variability in the nearshore of Lake Ontario was recorded by a 27 m long thermistor chain, using 24 Onset HOBO U22 Water Temp Pro V2 loggers, arranged from the bottom up to 3 m beneath the surface, at 1 m intervals. The rope was kept in vertical position by a submerged buoy. Due to heavy vessel traffic into Toronto Harbour, this could not be deployed immediately outside the harbour but rather was deployed in 27.5 m of water at 43° 42′ 17.52″ W, 79° 10′ 14.15″ N, which is 17 km east of the harbour and 4.5 km from the shoreline. This spatial offset is sufficient to capture the timing of the large upwelling events in Toronto Harbour. Observations of Huang et al. (2010) showed that the cold upwelling events typically occur along a 100 km stretch of the north-eastern coastline of Lake Ontario and are centred on the Toronto Region. Similarly, while there is considerable temporal variation in the depth of the thermocline in Lake Ontario, at any given time the depth does not vary significantly over a spatial scale of 17 km along the shore. All the thermistor loggers from Carleton University, University of Toronto, and TRCA have been tested in laboratory conditions before deployment.

In addition to the thermistor stations, one acoustic Doppler current profiler (ADCP) has been deployed in the Outer Harbour from 25 June 2013 to 18 August 2013 (DOY 175–230). The broadband ADCP was an RD Instruments 600 kHz deployed at a depth of 8 m, mounted looking upward; the 1 min ensembles were recorded every 3 min in 1 m bins between 1 m and 8 m above the bottom.

Data analysis

To evaluate thermal spatial variability in the harbour, we developed a series of interpolated spatial maps of the benthic temperatures using an inverse cost weighting interpolation algorithm with boundary conditions. In addition, an animation assembled from hourly temperature maps was used to capture the temporal variability during a 12 day period (see the video in the ESM). Data from the entire grid of benthic thermistors were used to create the spatial temperature variability maps. Data were divided in three distinct periods: pre-stratification, during stratification, and post-stratification. The top quartile temperature values were used to estimate the maximum values at each thermistor location, and the bottom quartile temperature values were used to estimate the minimum values. The same method was used for the mean temperature maps and for the maps showing hourly rates of temperature change. Furthermore, spatial thermal variability was also determined by calculating the frequency of several categories of hourly rates of temperature changes at select locations for the entire monitoring interval. The results were represented in histograms with 1 °C h^{-1} wide bins. The temperature profiles were made from the data recorded by vertical temperature chains, located within the harbour, and at a location 17 km east of the harbour. Additionally, the various areas of the Toronto Harbour have been thermally classified based on the temperature range during the stratified season, mean temperatures, the magnitude of the rates of hourly temperature changes, and the frequency of such rates of temperature change events.

In order to determine the relationship between wind data and upwelling events, we estimated the wind stress following Pingree and Griffiths (1980)

$$\tau = \rho_a C_{10} |U_{10}| U_{10} \quad (1)$$

where ρ_a is the density of the air, $C_{10} = 0.00129$ is the drag coefficient for wind stress (Kraus, 1972), and U_{10} the wind velocity at a height of 10 m. The direction of the wind was projected on a direction along the coast (blowing from southeast), where positive values of τ favour upwelling events and negative values favour downwelling events. The stress force of wind gives the initial velocity of the water in the direction of the wind, but the Coriolis effect due to the Earth's rotation exerts an acceleration proportional to velocity at right angles to the direction of motion. In the northern hemisphere, the resulting Ekman transport is 90° to the right of the wind direction, therefore, in Lake Ontario, prevailing southwesterly winds induce frequent upwellings by pushing the water upper layers offshore. In addition, we performed a calculation of the time lag between wind events and upwelling events by adjusting the time lag for a maximum correlation coefficient. The time lag between the wind times series and water temperature time series was calculated using windowed cross-correlation and peak picking methods (Boker et al., 2002). The initial time lag is evaluated from the raw time series using the correlation equation

$$R(X,Y,\delta) = \frac{1}{N-\delta} \sum_{i=1}^{N-\delta} \frac{\left(x_i - \acute{X}\right)}{sd(X)sd(Y)}, \quad (2)$$

where $\acute{X}$ and $\acute{Y}$ are the grand means of the respective time series and $sd(X)$ and $sd(Y)$ are the standard deviations of X and Y, respectively, and N is the number of samples. This equation is a Pearson correlation between the two time series lagged by δ observations (a time interval corresponding to δ times s, the sampling interval). Furthermore, an incremental windowing procedure was used to analyse how the strengths and lags of association between the two time series change over time. This allowed us to only make an assumption about the local stationarity rather than assuming stationarity over the whole time series.

The fast Fourier transform (FFT) was used to determine the dominant frequencies of the temperature time series at thermocline and close to the surface levels. The significant peaks were matched with the signature of the major temperature variability drivers outside and within the embayments. Fluctuations in signal amplitude can induce noise in simple FFT analysis, which can be reduced by smoothing. The trade-off is that the frequency resolution is severely reduced because fewer data points are available for each FFT calculation. The loss in frequency resolution was diminished by using Hanning windowed data segments with 50 % overlap (Welch, 1967). The 95 % confidence intervals for the averaged multi-tapered power spectral densities S_{xx} were approximated by

$$\left[\frac{\nu S_{xx}(\omega)}{\chi^2_{(1-\alpha/2,\nu)}}, \frac{\nu S_{xx}(\omega)}{\chi^2_{(\alpha/2,\nu)}}\right] \quad (3)$$

where $\chi^2_{(1-\alpha/2,\nu)}$ and $\chi^2_{(\alpha/2,\nu)}$ are the 0.975 and 0.025 % points of the χ^2 distribution for $\alpha = 0.05$ (assuming a Gaussian process) with ν equivalent degrees of freedom (Priestley, 1981; Welch, 1967). The equivalent degrees of freedom were estimated based on the 50% overlap of the segmented periodograms and the windowing function used (Welch, 1967). A further increase in the overlap percentage for a Hanning data taper did not increase the number of equivalent degrees of freedom, ν, and therefore did not reduce the sampling errors, nor decreased the width of the confidence intervals. The spectral analysis method that typically is performed on integrated potential energy of the entire water column (Antenucci et al., 2000) was also considered. However, their method is more appropriate for analysis of internal waves and did not capture the temperature signals at specific depths, which is necessary in areas with complex water circulation and considerable diurnal heating, such as Toronto Harbour. We performed the single-sided amplitude spectrum (SSAS), instead of the typically used power density spectrum (PSD), because it gives a direct measure of the temperature variability (°C). The SSAD estimates the amplitude for each frequency by taking the absolute value of the FFT of the temperature time series, $T(f)$, divides it by the length of the time series, N_{series}, and then multiplies it by 2 ($\alpha(f) \simeq 2|T(f)|/N_{series}$, where α is the amplitude of the oscillation and f is the frequency).

Results and discussion

Despite the economic and environmental importance of Toronto Harbour, there are only a few previous studies that describe some of the physical processes driving water movements and temperature variability (e.g., Dewey, 2012; Haffner et al., 1982; Murphy et al., 2011, 2012). The observations of Murphy et al. (2012) described how cold upwelling events in Lake Ontario likely corresponded to drops in water temperature in the more exposed embayments of Toronto Harbour, but they noted that the shallowest embayments were largely unaffected and provided valuable habitat for warm-water fishes. Our study, which focused on benthic temperatures, shows that even though some shallow protected embayments can reach 30 °C in the summer, typical of wetlands, with the exception of the most remote ones (e.g. Cell1 in TTP; Fig. 1), they are still subjected to drops in temperature of more than 10 °C during large upwelling events. Furthermore, rather than evaluating thermal variability using a statistical approach based on indices that are compared with simulated inland lake temperatures (e.g., Murphy et al., 2011), we characterise each harbour area of the initial three broad thermal zones based on quantifiable physical characteristics, such as mean temperature, thermal range, rate of hourly temperature change events and their frequencies (Table 2), while taking in account the influence of topographical characteristics, such as bathymetry and connectivity orientation in relation to main water currents.

The waters of Toronto Harbour are characterised by considerable variability in temperature, both in space and time. For instance, during the stratified season, there were frequent upwellings (8 in 2012 and 9 in 2013) of cold water that rapidly propagated into the base of the harbour from Lake Ontario and were associated with rapid cooling of the deeper regions of the harbour (Fig. 2). The shallow waters of the harbour tended to be warmer, and the temperature variability in these regions was largely driven by diurnal heat fluxes. We present below the specific details of temperature variability in Toronto Harbour.

The nearshore waters of Lake Ontario showed very large temperature variations during the stratified period. This variability in water temperature was driven by a combination of changes in wind direction and speed and changes in air temperature. Periods of strong winds (Fig. 2a) blowing from west-southwest (Fig. 2b) lead to considerable stresses along the shore oriented along the coastline of Lake Ontario (Fig. 2c; estimated using Eq. (1)) that were followed by drops in water temperature at a depth of 10 m (Fig. 2d). For example, during DOY 202–203 and 243–244 westerly and southwesterly winds with speeds over 30 km h^{-1} determined positive wind stresses of 0.6 Pa and 0.5 Pa, respectively, that were followed by upwelling events. Rao and Murthy (2001) found that similar values of 1–2 dyn cm^{-2} (0.1–0.2 Pa) eastward wind stresses induced thermocline rises in Lake Ontario. The correlation between wind and thermocline movements is difficult to discern visually due to the smaller oscillations and time lag, therefore, we used the windowed time lag cross-correlation technique from Boker et al. (2002) (Eq. (2)) that found that the best fit was obtained for an approximately 2-day time lag between the wind stress peaks and the upwelling events ($R^2 = 72\%$).

Table 2
Thermal variability classification at select locations in Toronto Harbour (June 18–September 30, 2013: DOY 169–273). Location type is classified by four parameters. The first parameter is the thermal regime: warm (W), cold (C), and intermediate (I). The second parameter represents thermal variability: variable (V), quasi-constant (C) temperature. The third parameter represents the depth: deep (D) and shallow (S). The fourth parameter represents the connection type to Lake Ontario: sheltered (S) and exposed (E). Horizontal dashed lines separate Tommy Thompson Park, Inner Harbour, and Outer Harbour stations. Warm area type is assumed if mean temperatures are above 18 °C, maximum benthic temperature is over 23 °C, and minimum temperature over 13 °C. Cold areas are assumed if mean temperatures are under 10 °C, maximum temperature is under 20 °C, and minimum under 7°C. Intermediary area are those which don't fall within these categories. Variable areas (V) are those with higher than 10 high rates of temperature change events per season. Constant temperature areas are those that have low rates of temperature change that or experience just occasional low rates (~2 °C h^{-1}, 1–4 times during the entire period, most likely during stronger upwelling events.

Station	Location type	Max rate [°Ch^{-1}]	Min rate [°Ch^{-1}]	No. events $\lvert\Delta T\rvert > 4°Ch^{-1}$	No. events $\lvert\Delta T\rvert > 2°Ch^{-1}$	Mean temp [°C]	Max temp [°C]	Min temp [°C]	Sensor depth [m]
St13	W, V, S, E/S	2.88	−2.66	0	10	18.8	26.4	13.83	2.8
St14	I, V, S, S	2.63	−3.46	0	14	15.4	22.56	9.88	4.5
St37	W, V, D, S	2.94	−2.81	0	15	18.1	25.1	14.84	4
St38	W, C, S, S	1.43	−1.68	0	0	20.4	27.57	15.71	3.5
St8	W, C, S, E/S	1.56	−1.39	0	0	22.0	29.99	15.83	1.5
St27	W, C, S, S	1.79	−1.53	0	0	18.2	23.11	14.19	3
St41	W, C, S, S	1.41	−1.27	0	0	18.61	23.45	14.98	4
St44	W, V, S, E/S	3.25	−4.13	3	24	18.0	26.89	13.28	3.5
St28	I. V, D, E	4.66	−4.19	5	86	13.88	22.75	8.64	6.5
St32	I. V, D, E	6.14	−8.64	21	160	13.8	22.39	7.72	5.5
St49	C, C, S/D, S	1.7	−2.81	0	2	11.54	19.89	7.73	5
Tc Jar	C, V, D, S	5.4	−4.21	6	38	11.10	20.55	7.04	9
CB	C, C, D, E	1.2	−2.94	0	1	9.97	17.49	6.43	9.5
St21	C, V, D, E	6.0	−5.16	6	33	12.8	19.87	6.95	8.5
TC1	C, C, D. E	0.83	−2.85	0	2	9.81	16.49	6.33	9.1
TC2	C, C, D, E	1.1	−3.21	0	4	10.03	16.83	6.25	9.2
TC3	C, C, D, E	1.09	−2.99	0	4	10.26	17.77	6.18	9.7
TC4	I, V, S/D, E	3.44	−4.65	2	34	13.14	22.39	6.72	6.5

During the observation period, the mean thermocline depth in the nearshore was 9 m (Fig. 2e), while the mean depth in the navigation areas of the harbour is 10 m. Consequently, thermocline oscillations propagated unobstructed in the harbour at their full amplitude and the water temperatures in Toronto Harbour (Fig. 2f) followed closely the variations of the neighbouring Lake Ontario (Fig. 2e). Because of

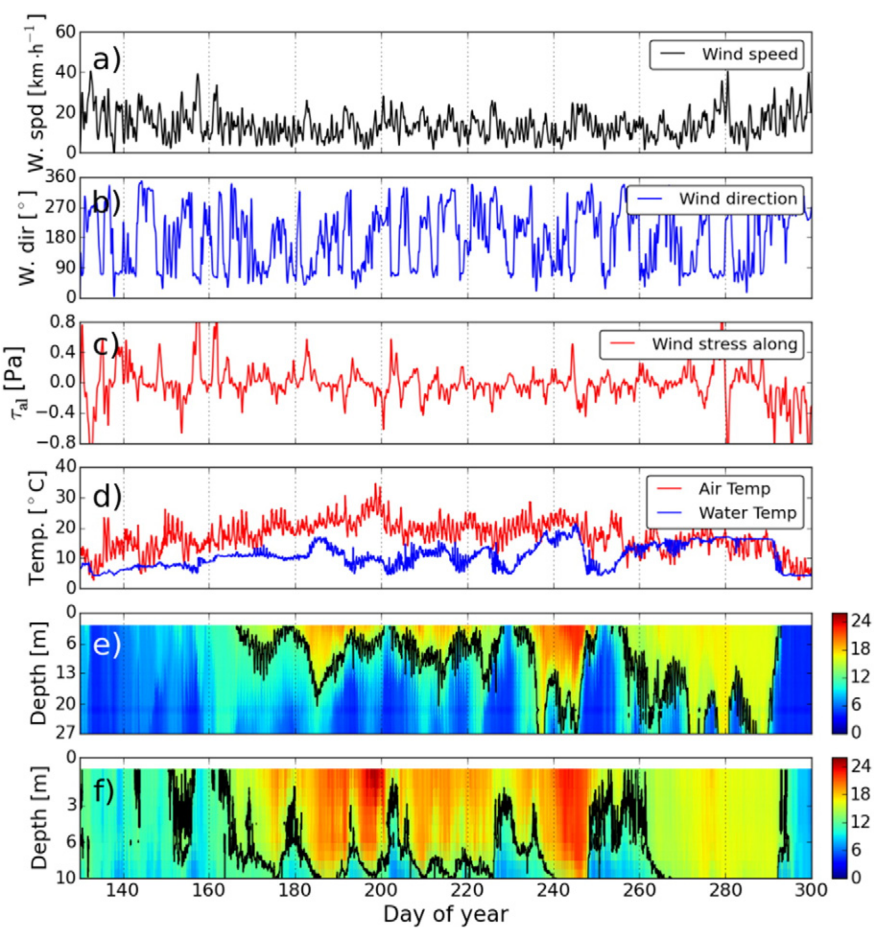

Fig. 2. Observations of stratification in Lake Ontario and Toronto Harbour and wind speed between May 1 and October 30, 2013 (DOY 122-303). a) Recorded wind speed at Toronto City Airport. b) Recorded wind direction. c) Calculated wind stress. d) Air temperature and water temperature at 10 m depth in Lake Ontario. e) Thermal stratification in Toronto Harbour. f) Thermal stratification in nearshore in Lake Ontario. The thermocline position is shown with a black line.

the navigation restrictions on logger placements, Fig. 2f has been constructed by concatenating the records of temperatures from two different locations that are 2 km apart (Eastern Gap and Jarvis Dock). The temperature profiles (Fig. 2e) recorded during the summer of 2013 in the nearshore of Toronto Harbour show quasi-regular upwelling events (an average period of 12 days) for most of the stratified season (June to September). This was also confirmed by our Lake Ontario thermistor chain field observations in 2012 (not shown) and is consistent with the prevailing southwesterly winds experienced in Lake Ontario during summer (ESM Figure S1). The mean thermocline depths at our nearshore location were around 9 m in July and August and considerably lower in September at about 18–20 m. The amplitude of the upwelling oscillations averaged 11 m; however, the maximum amplitudes exceeded our measuring range that was limited to 27 m water depth.

In addition to the large and long-term swings of the isotherms during upwelling events, along the Lake Ontario thermocline, one can observe a strong higher frequency oscillation (Fig. 2e). The evident periodicity of the oscillation ($T \sim 17$ h) is close to the local inertial period of 17.4 h at 43° N (Mortimer, 2006), suggesting a Poincaré wave signature. The amplitude of the Poincaré waves averaged at this location between 3 and 4 m. The Poincaré wave signature can also be observed in the deep temperature data records from the Outer Harbour stations, but there is little evidence of their presence at any of the Inner Harbour and sheltered embayments stations in TTP.

Water flows, upwelling propagation and temperature gradients

The rapid advancement of cold upwelling events from Lake Ontario was captured by the benthic thermal variation along the longitudinal axis of the Outer Harbour. Pairs of temperature values recorded by the thermistors vertically stacked at each of the stations along longitudinal transect of the Outer Harbour were represented on the y-axis in Fig. 3a, starting from the nearest station to Lake Ontario then proceeding towards Cherry Beach at the bay's head. Thus, the y-axis represents benthic temperatures measured at six stations over a total distance of 3.5 km. During the upwelling events, the temperature was the same at all benthic temperature stations, irrespective of their depth, suggesting that intrusion of hypolimnetic 5 °C water from Lake Ontario had been able to spread through the whole harbour, including at the shallower stations (e.g., Tc4). The mean velocities of the upwelling front were found to vary from 0.28 m s^{-1} to 0.11 m s^{-1}, with the highest values between stations Tc3 and Tc1 and slowest at the Cherry Beach station (ESM Table S1). These speeds are similar to those of upwelling fronts observed on the gently sloping southeastern benthos of Lake Simcoe (Cossu and Wells, 2013). When observing the temperature patterns over shorter time periods (Fig. 3b and c), the propagation of the cold front is clearly indicated by the slope of the isotherm. Among the several upwelling events that took place during the stratified season, two of the strongest occurred between 13th and 14th of August (DOY 225–226), and 2nd and 3rd of September (DOY 245–246), respectively, when the temperature dropped by more than 15 °C in less than 4 h. Because the benthic thermistor chains on the longitudinal axis of the Outer Harbour were not all deployed at the same depth, the plot (Fig. 3) shows an apparent anomaly (inversion) in the benthic temperature distribution. Very high thermal variability was observed at all the benthic thermistor chains along the longitudinal axis of the Outer Harbour (Fig. 1 and Table 1). The highest gradients were observed at the outermost thermistor chain (Tc4; Fig. 4a). The large vertical temperature gradients recorded between the benthic thermistor and the thermistor placed at 1 m above the bottom reached values as high as 9 °C m^{-1} and occurred when the thermocline in Lake Ontario was dropping (Fig. 2; DOY 157, 178, 194, 205, 217, 230, 245 267, 283). In contrast, during upwelling events, small temperature inversions of the order of −0.1 °C could be observed (Fig. 4b; see ESM Figure S5 for even larger values). These temperature inversions seemed to last for several hours during the initial phase of the upwelling event and are indicative of sustained convective mixing. While these −0.1 °C to −0.4 °C temperature inversions are near the accuracy of the Hobo U20 loggers, they occurred at all the benthic moorings during upwellings, and the timing and magnitude of these inversions are very similar to observations of convective mixing beneath upwelling cold bores that were made by Cossu and Wells (2013) using thermistors with high accuracy.

The flows in the Outer Harbour were predominantly oscillatory with mean velocities along the longitudinal axis up to 30 cm s^{-1} (Fig. 5a).

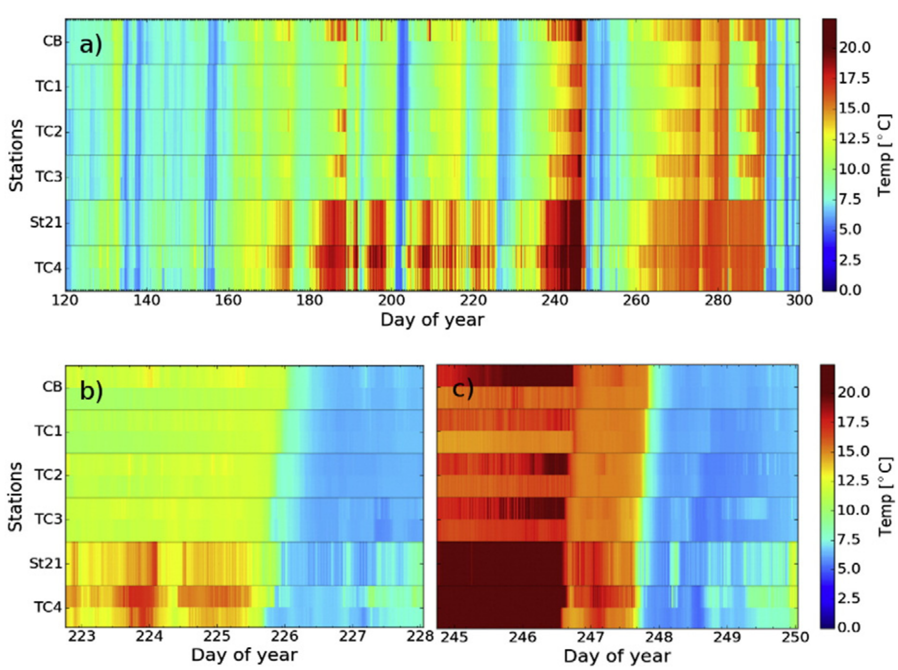

Fig. 3. Observations of benthic water temperatures in the Outer Harbour during May 1–October 30, 2013 (DOY 122–303). a) Temperature records along the six benthic thermistor chains located along the longitudinal transect (Cherry Basin to Tc4) shown in Fig. 1. b) Detail of a strong upwelling event occurred between 12 and 24 August 2013 (DOY 224–236), which is also featured in an animation in the Electronic Supplementary Material section. c) A strong upwelling event captured in September 2013 when the temperature dropped by more than 15 °C in less than 6 h at all stations, including the shallower, sheltered locations.

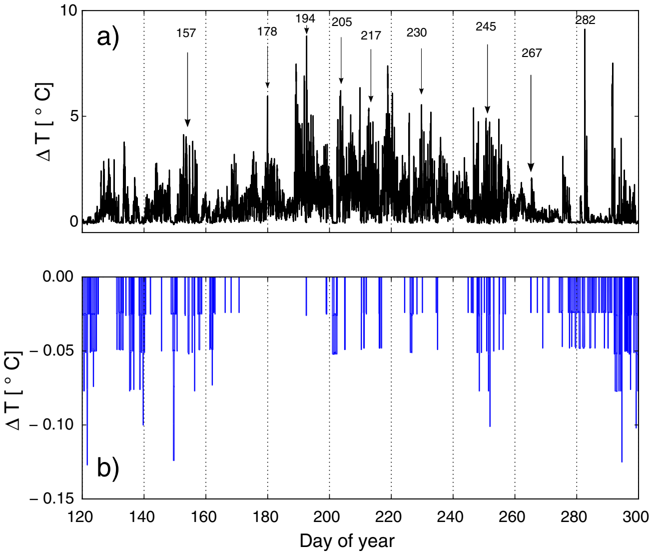

Fig. 4. Time series of vertical temperature differences at the base of the water column recorded between the thermistor 1 m above bottom and the benthic thermistor at the outermost thermistor chain station (Tc 4). a) The arrows mark times of recorded upwelling events. b) Detail of negative vertical temperature differences. Similar temperature differences were obtained at all thermistor chains along the longitudinal transect (see ESM Appendix S1).

Cross channel velocities were smaller (Fig. 5b), as expected, and did not exhibit the same oscillatory pattern. The values of the vertical gradient, dV/dz (Fig. 5c), had the largest values in the upper layer induced by wind shear, but very small values in the water column except for periods that correspond to upwelling events (e.g., DOY 194, 205). The vertical velocity profiles (Fig. 5a) and vertical gradient (Fig. 5c) show clearly that the flows are bidirectional, with the whole water column moving in the same direction most of the time (the gradient has the same sign throughout the water column). The velocity shear is weak and it is mostly due the presence of bottom drag and wind stress, indicating predominantly barotropic processes, unlike the Hamilton Harbour where persistent baroclinic flow exchanges that create strong vertical gradients were observed (Wu et al., 1996). There were, however, several instances where the bottom layer moved to the opposite direction to the upper layer, which match periods with strong upwelling events (e.g., DOY 194, 205) and relaxation (e.g., DOY 209–210). In a companion study, Hlevca et al. (unpublished) have analysed the circulation and flushing times in the harbour and have shown that the velocities have strong diurnal and hourly components. The diurnal oscillations were found to be predominantly caused by barotropic processes rather than density-driven currents. The water level and water currents oscillations with period $T = 1$ h match the natural frequency of the harbour system and were caused by resonant excitation of water level fluctuations, similar to those described by Hlevca et al (2015).

Temperature variability drivers

To identify the other major drivers of temperature variability, we analysed data from the three zones with distinctive topographic and hydrodynamic characteristics. A fast Fourier transform was applied to the temperature data recorded at a depth of 9 m at three different locations (Fig. 6a): (1) at the nearshore mooring in Lake Ontario; (2) at the Jarvis dock mooring, inside the Inner Harbour; (3) at the thermistor chain in the middle of the Outer Harbour (Tc3). We observed a very strong peak at a frequency 1/17 h (0.058 cycles per hour) in the Lake Ontario spectrum, corresponding to the inertial frequency at this latitude. A secondary strong peak of energy is present at a frequency of 1/15.2 h (0.066 cycles per hour, 14% less than the inertial period) that is often seen accompanying large amplitude Poincaré waves (Mortimer, 2006).

In addition, three prominent peaks with periods of 13.6, 12.6, and 11.5 h were also observed, which are most likely the signatures of internal Poincaré modes 6, 7, and 8 (Mortimer, 2006). The superposition of these oscillations may have an important modulation effect on major thermocline oscillations and increase thermal variability especially in

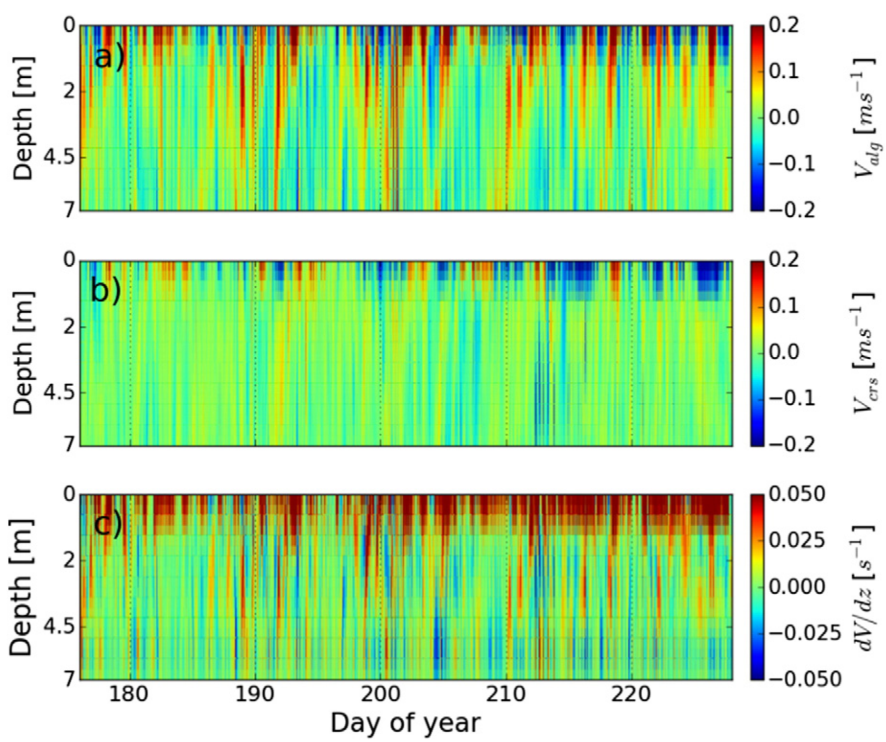

Fig. 5. Velocities from the Outer Harbour acoustic Doppler current profiler. a) Velocity profiles along the longitudinal axis. Velocity in the direction of Lake Ontario has positive values b) Velocities across the harbour. Northwestern direction has positive values. c) Vertical gradient.

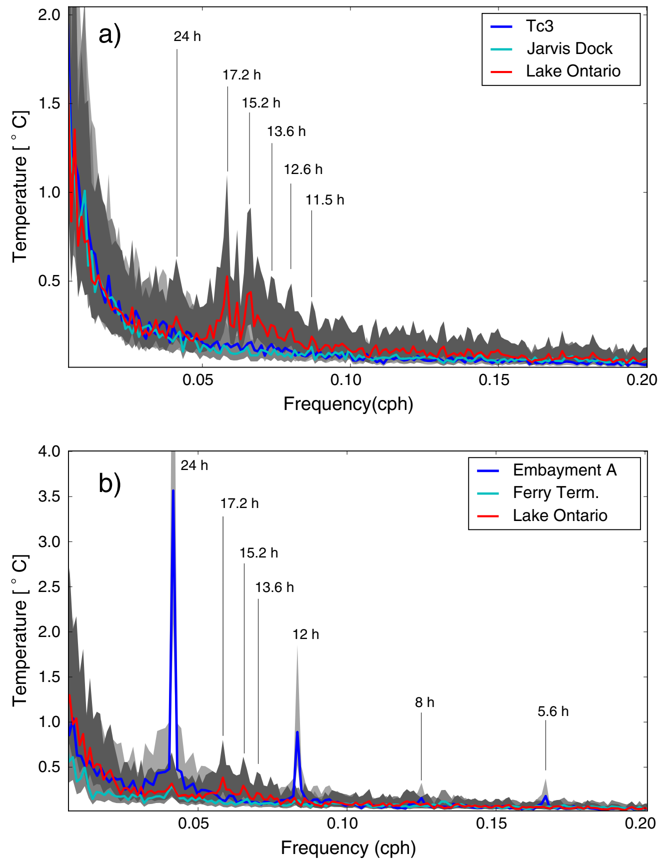

Fig. 6. Spectral analysis of the temperature time series from May 1–October 30, 2013 (DOY 122–303) in Lake Ontario and at two locations in Toronto Harbour. a) A fast Fourier transform of temperature time series recorded at 9 m depths at locations in Inner Harbour (Jarvis Dock), Outer Harbour (Tc4), and at the thermistor chain in Lake Ontario. b) Fast Fourier transform for temperature time series taken close to the water surface (1 m depth) at locations near to those of a). The gray shadings represent the 95% confidence intervals.

the first half of the Outer Harbour (e.g., 11.5 h). These peaks are also visible in the spectra of the two locations inside the harbour, however, with much diminished amplitudes and hardly distinguishable from the background noise. In all spectra, there are significant peaks at frequencies near the diurnal cycle (1/24 h or 0.04 cycles per hour). Prominent spectral peaks can be seen for the subsurface (1 m depth) temperatures spectra (Fig. 6b), with the notable difference that more energy is concentrated at frequencies near the diurnal cycle, especially at locations inside the harbour. The Poincaré wave modes signatures can be observed only in the Lake Ontario spectrum and at locations in Outer Harbour closer to its mouth (e.g., Embayment A).

The spectrum for close to surface temperature time series in Embayment A showed significant peaks for periods of 24, 12, 8, and 5.6 h. The prominent peaks at $T = 12.2$ h and $T = 5.6$ h match the signatures of the semi-diurnal tide and mode 1 Lake Ontario seiche, respectively (Hamblin, 1982). The natural period of Embayment A ($T = 5.4$ h), which was determined from Hlevca et al (2015), is close enough to the lake mode 1 seiche period to determine strong resonant amplification of water level oscillations that increases the exchange with colder lake water. Therefore, Embayment A is the coldest and most thermally variable among the TTP embayments. The very prominent peak at a period of 24 h (Fig. 6b), which was observed in other shallow embayments, suggests that diurnal heating may play a major role in determining the thermal regimes of these sheltered areas. However, several shallow embayments in TTP (e.g., Stations 13, 14 and 37) have a relatively high number of events where the rates of hourly temperature changes exceeded 2 °C h^{-1} (Table 2). These were not seen in the connected embayment farther from the lake (Station 38). This is an indication that the observed thermal variability in the aforementioned locations is produced by cold-water intrusions, while in the succeeding embayment, further from the lake (e.g., Station 38), their influence is diminished and not detected by the 2 °C h^{-1} threshold. Undoubtedly, the diurnal heating has a major role in determining the type of thermal habitat at all these locations, but the temperature changes produced are slow and do not significantly impact the magnitude of short-term (hourly) variability.

Spatial and temporal temperature variability

The degree of spatial and temporal temperature variability differed considerably between the pre-stratified, stratified, and post-stratified periods, with the stratified season showing the most variability. During the pre-stratified period, the time-averaged water temperature in Toronto Harbour embayments (Fig. 7a and b) showed relatively uniform horizontal spatial distribution, with slightly lower temperatures in the Outer Harbour and slightly higher temperatures (2–3 °C) in the more sheltered areas. A similar spatial temperature distribution was observed for the post-stratified period (Fig. 7e and f), with a notable exception that the sheltered areas had slightly higher values for both maximum and minimum recorded temperatures. The stratified season showed the largest spatial benthic temperature variability and range (Fig. 7c and d). During the stratified period, the maximum benthic temperature values ranged between 16 °C in the Outer Harbour to over 29 °C in shallow areas, such as Embayment D and Cell 1. During the same period, the minimum temperatures ranged from 6 °C in the Outer Harbour and 15 °C in sheltered areas. The mean temperatures (Fig. 8a, c, and e) matched the same seasonal patterns found for minimum and maximum temperatures. The pre- and post-stratified periods exhibited a quasi-uniform spatial distribution of benthic temperatures, while the stratified season had large spatial variation in benthic temperatures, with the colder benthic temperatures (9–10 °C) found in the areas directly connected to the lake and much warmer temperatures (20–23 °C) in the sheltered areas, such as in the channels within the Toronto Islands and in the confined embayments in TTP. The highest absolute rates of temperature change (Fig. 8b, d and f) were observed during the stratified season (up to 1.3 °C h^{-1}, averaged over the top 25% absolute rates of change), particularly in the Outer Harbour, close to the harbour's entrance, where stronger benthic thermal changes were associated with a steep change in bathymetry and immediate exposure to the lake water (Fig. 4). The lowest average absolute rates of the temperature change were observed during the non-stratified season, where the rate values were between 0.1-0.4 °C h^{-1}.

The three thermally distinct zones of the Toronto Harbour were subjected to different intensities and frequencies of rates of benthic temperature changes (Fig. 9; Table 2). The thermistors in TTP were deployed in shallower water, with depths ranging between 1.5 m and 4.5 m, whereas those in the Outer Harbour and Inner Harbour were placed at depths ranging from 5 m to 10.7 m and 3.5 m to 6.5 m respectively. There were fewer extreme temperature changes in the sheltered areas (Fig. 9a), compared to either the Outer or Inner Harbours (Fig. 9b and c). In the sheltered areas, the rates of temperature change were close to the estimate of ± 0.4 °C h^{-1} driven by solar insolation. In the Outer Harbour, the maximum hourly temperature change rates were low (-3 °C and 1 °C) except for Station 21 and Tc4, where they reached much higher values (± 6 °C). The histograms show that the majority of the hourly temperature changes are in the sub ± 1 °C h^{-1} range (95%), in agreement with the rates shown on the temperature maps (Fig. 8b, d and f). However, at exposed locations, from over 4000 hourly temperature change events, there were up to 160 instances (4%) with ± 2 °C h^{-1} and over 20 instances (0.5%) with ± 4 °C h^{-1} or more. The largest hourly temperature rates were recorded at locations in the Inner and Outer Harbour and were mostly associated with rapid cooling due to rapid intrusions of cold hypolimnetic water (up to -6 °C h^{-1}; Fig. 4).

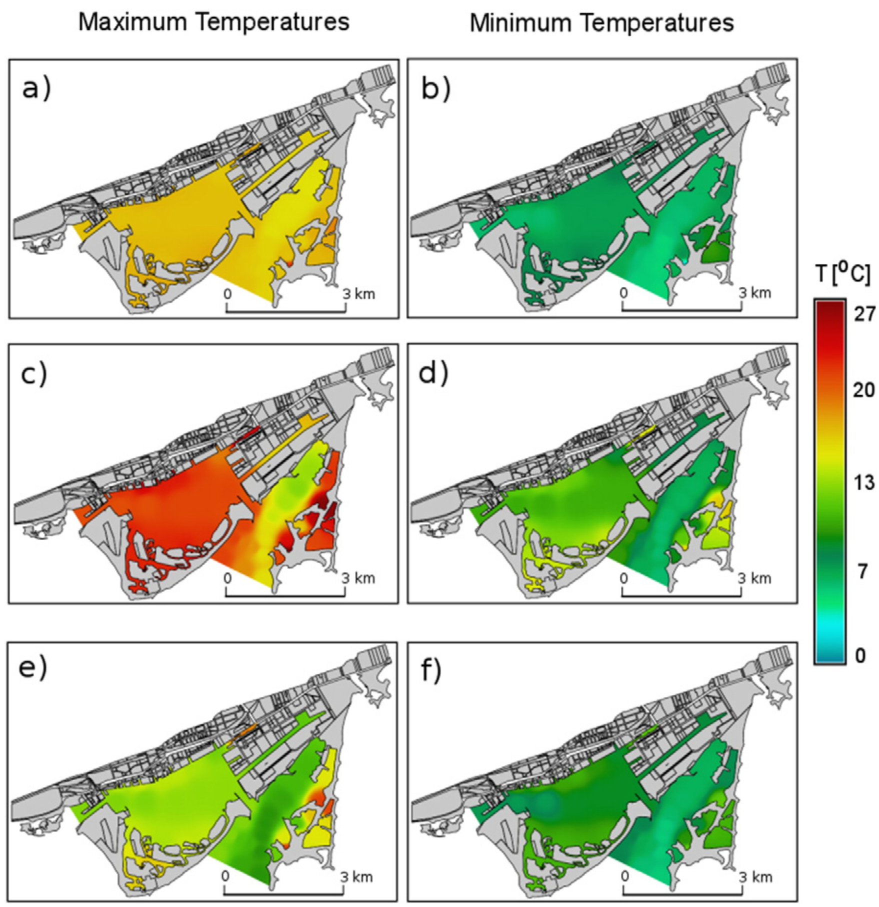

Fig. 7. Spatial distribution of maximum and minimum benthic water temperatures inside Toronto Harbour embayments during the May 1–October 30, 2013 (DOY 122–303) observational period. a) and b) Temperatures during the pre-stratified period (May–June; DOY 122–181. c) and d) temperatures during the stratified period (June–September; DOY 181–256). e) and f) temperatures during the post-stratified period (September–October; DOY 256–303).

We observed extreme variability in water temperatures in both the Inner Harbour and Lake Ontario during a week-long period in the stratified season (June 30 to September 13, 2013; DOY 181 − 256). The difference in the vertical profiles of the time-averaged temperatures in the Inner Harbour and Lake Ontario (Fig. 10a and b) in part reflects the differences in flow dynamics at each location. The greatest range of water temperatures is seen in Lake Ontario (Fig. 10b) at depths between 3 and 9 m where the total variation is between approximately 5 °C and 24 °C. The temperatures at 27 m depth are cooler and vary between 4 °C and 17 °C. Hence, on average, there is a persistent stratification in Lake Ontario. In the shallower Inner Harbour (Fig. 10a), there is a similar range of thermal variability, when compared to similar depths in Lake Ontario; however, the minimum water temperatures in Toronto Harbour remain 1–2 °C warmer than those at comparable depths in Lake Ontario, and the upper layers appear to have much less variability than their equivalent depths in Lake Ontario. Because the mean depth of the thermocline (Fig. 2e) varies around the mean depth of the harbour (10 m), there is not any significant stationary stratification within the harbour, and as such, the stratification here is well described as being a polymictic system. Much of the temperature variability shown in these figures is due to the frequent upwelling events (e.g., Fig. 4). Before one such strong upwelling event (September 2, 2013; DOY 245), the benthic temperatures in the harbour were approximately 18 °C and the harbour had an almost uniform temperature profile (Fig. 10a; red dotted line), whereas after the cold water entered the Inner Harbour (~16 h later; blue dotted line), the temperature difference between the surface and benthos was more than 10 °C and benthic temperatures have dropped by almost 11 °C to around 7 °C. For comparison with these temperature profiles, we note that the preferred average temperature ranges for cold-water fishes are 12 °C ± 2.5 °C, for cool-water fishes are 20 °C ± 3 °C, and for warm-water fishes are 25 °C ± 4 °C (Fig. 10; Casselman, 2002).

Thermal classification and analysis

We analysed the temperature data during the stratified period (DOY 181–256) and classified select locations from the three distinct zones of the harbour based on temperature range, mean temperature, maximum rates of hourly temperature changes and their frequency, the average depth of the location, and the connection type to the lake (see Table 2 footnotes). We found that connectivity to the lake and depth alone cannot characterise the benthic thermal variability but can determine, in general, the type of habitat (warm, cold, or intermediate). Topography (e.g., orientation of the embayment mouth), lake currents, and even local bathymetry can severely alter such classification. For example, sheltered embayments such as Embayment A (Station 14) and Cell 3 (Station 37) have intermediate thermal variability that can be explained by the local currents, most likely produced by resonant amplification of seiches.

The warm areas with quasi-constant temperatures were in general the shallow and sheltered embayments in TTP (e.g., Stations 8, 38) or Toronto Islands' channels (e.g., Stations 27 and 41). However, as mentioned above, some sheltered embayments (e.g., Embayment A), due to their specific topography, have relatively high variability and can be classified as intermediate from the thermal habitat perspective. Furthermore, shallow, but more exposed areas, such as Station 13, are also warm habitats, but have enhanced variability. The most thermally stable regions of the harbour are the channels between the

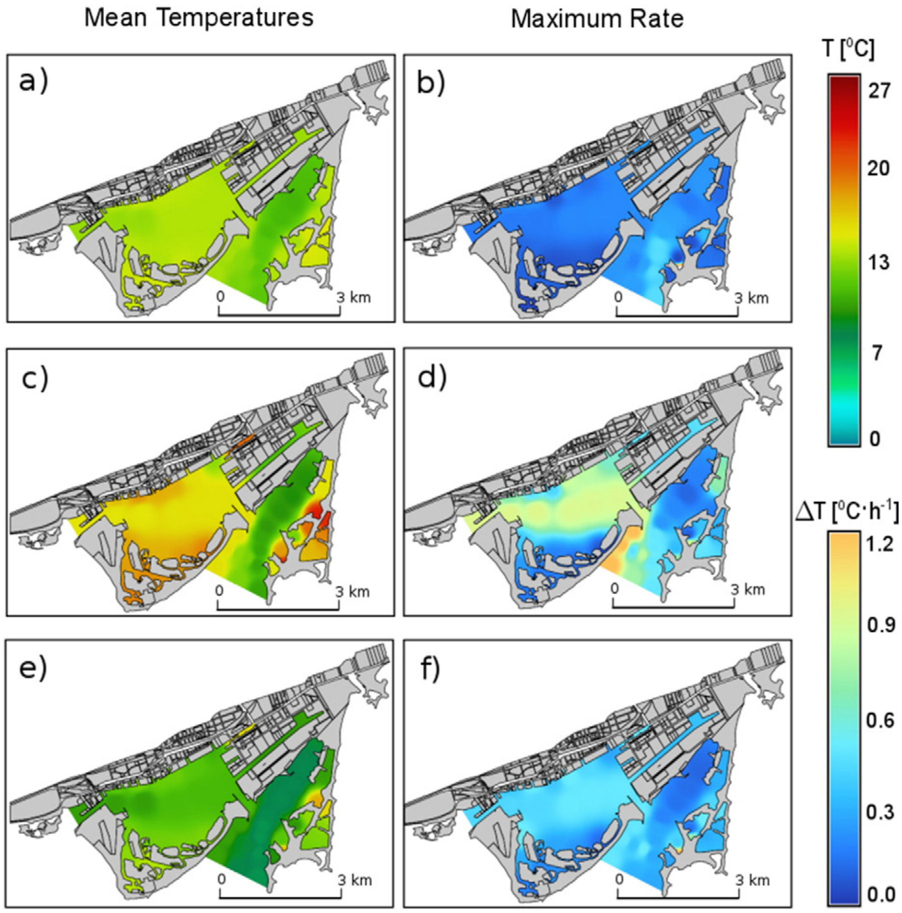

Fig. 8. Spatial distribution of mean benthic temperatures and absolute values of hourly rates of temperature change inside Toronto Harbour during the May 1–October 30, 2013 (DOY 122–303), observational period. a, c, e) Temperatures and b, d, f) absolute values of the hourly rates of temperature change during the pre-stratified period (May–June; DOY 122–181), during the stratified period, (June–September; DOY 181–256), and during the post-stratified period (September–October; DOY 256–303).

Toronto Islands. They are warm (average temperature ~18 °C) and have small temperature variability. Like the embayments in TTP, the Toronto Islands channels are protected from the direct action of the lake's physical processes; however, they are narrow enough to not be susceptible to strong diurnal heating, possibly mediated by a mature riparian zone that provides shade and shelter from wind-driven mixing and solar radiation.

The deep, sheltered areas such as Cell 3 (Station 37) have benthic habitats that can be generally considered warm, but they are moderately variable, most likely due to the more frequent cold-water intrusions that do not always reach the upper layers. On the contrary, deep, and arguably sheltered, locations such as the Inner Harbour's docking slips (e.g., Jarvis Dock) have high temperature variability and can be characterised as cold-water habitats (mean temperatures of 11–12 °C) and high variability. This is a good indication that the strong currents, which travel between Western Gap and Eastern Gap and flush the Inner Harbour, keep a relatively uniform spatial temperature distribution inside the Inner Harbour and stratification structure similar to that of neighbouring Lake Ontario. This fact was confirmed by our temperature profile measurements with CTD, which showed that the stratification structure in the Inner Harbour does not vary much from its centre to its perimeter (1–1.5 °C), especially when compared with the deeper northern shore (see ESM Figure S3).

The deep exposed benthic zones of the Outer Harbour (e.g., Tc1, Tc2, and Tc3) are cold; however, they are thermally stable, with only few rates of hourly temperature change events of over ± 2 °C, which most likely occurred during the strongest thermocline upwellings or relaxations. Notwithstanding their position in the main flow, stations Tc3 to Tc1 have low thermal variability, which can be explained by their location in the deep and flat navigation channel (to Cherry Beach) that favours unobstructed flow of cold hypolimnetic water. Conversely, the zones that are closer to the Toronto Islands' southern shelf (e.g., station Tc4 and St21) exhibit the greatest range of thermal variability, which is induced by the interaction of the moving thermocline with the neighbouring sloping bottom. A noteworthy fact is the striking asymmetry in stratification on the shelf between very stable stratification during downwellings and unstable benthic stratification during the process of "shear induced convective mixing," where the velocity shear that existed near the boundary either advected colder water above warm during upwelling leading to the apparent prolonged periods of small inversion, or strained existing stratification during downwelling. While this process has been previously described in Lake Simcoe, Ontario (Cossu and Wells, 2013), and Lake Alpnach, Germany (Lorke et al., 2005), the frequency of very strong vertical temperature gradients in Toronto Harbour is striking ($\Delta T \sim 10$ °C m^{-1} compared to 4–6 °C m^{-1}; Fig. 4a). In part, the difference is due to Lake Ontario being very much larger than either Lakes Alpnach or Simcoe, so that wind-driven thermocline movements are larger. Additionally, Toronto Harbour experiences an enhanced thermocline upwelling effect due to the large escarpment at the end of the Outer Harbour. While the magnitude of the temperature variability on the Toronto Harbour shelf is exceptionally large, sizable variability has been also observed in the nearshore of the Great Lakes. Wells and Parker (2010) found water temperature changing at a rate as much as 5 °C per hour and 10 °C in a 12–24 h in the offshore of Georgian Bay and Lake Huron. Rao and Murthy (2001) recorded decreases in water

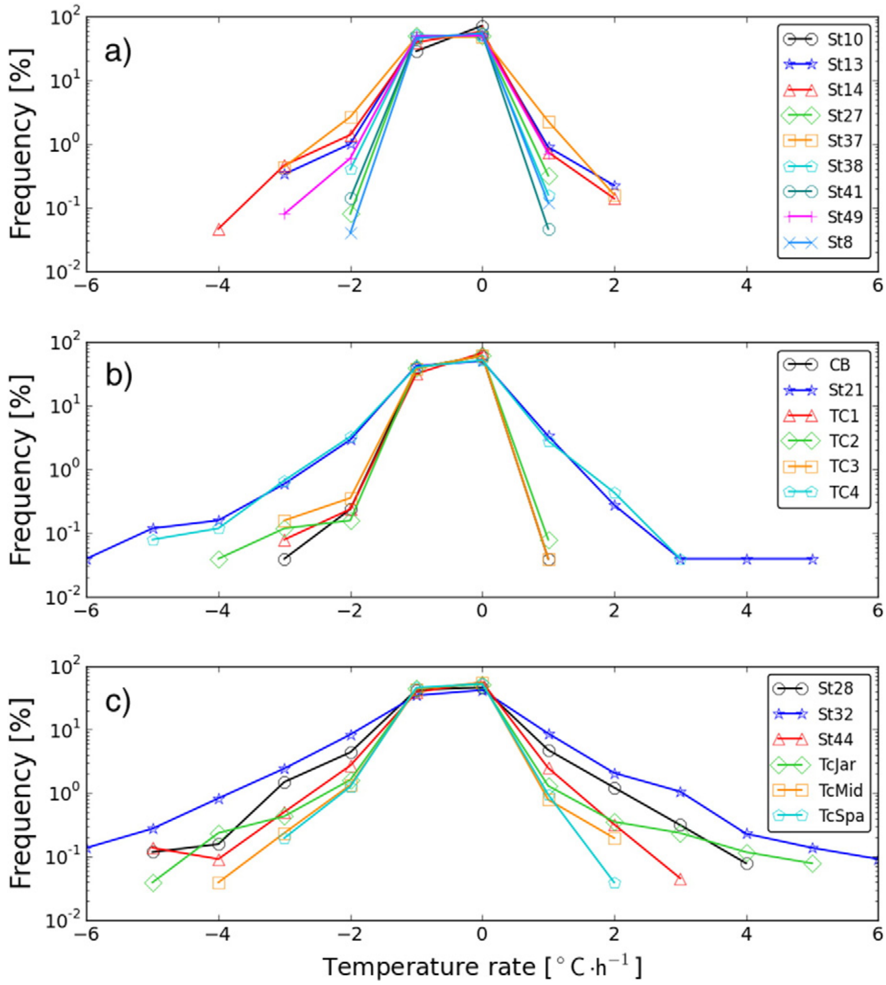

Fig. 9. Frequency distribution of hourly rates of benthic temperature change in units of °C per hour. The y-axis represents the relative frequency of hourly rates of temperature changes, during the entire May 1–October 30, 2013 (DOY 122–303), observation period (4368 events), at various locations inside Toronto Harbour. The temporal changes in temperature are calculated over 1 h. a) Sheltered areas inside Tommy Thompson Park. b) Outer Harbour. c) Inner Harbour.

temperatures of 10–12 °C in 2 days during an upwelling event at a nearshore mooring at Darlington, Lake Ontario. Troy et al. (2012) observed thermal fluctuations in excess of 10 °C, over 3 h at a nearshore mooring near Michigan City, Lake Michigan. Therefore, the results of this study may serve as a model for understanding other systems around the Great Lakes. The values of the observed inversions were too small to have any significance from the fish biology perspective and are close to the instrument accuracy; therefore, they involve a large margin of error and uncertainty. However, studies of mixing in bottom boundary layers, employing higher resolution instruments, may find Toronto Harbour a good site for exploration.

While there is usually some stratification in the Toronto Harbour during the summer period (June–September; DOY 181–256), it is highly variable (Fig. 10). As expected, the minimum benthic temperatures recorded are almost the same at all depths (~5–6 °C) reflecting the cold water associated with full upwelling of hypolimnetic water from Lake Ontario. Rather than being a well-defined and stable epilimnion, metalimnion, and hypolimnion, there are large ranges of temperatures at all depths, reflecting the dynamic movements of the thermocline in Lake Ontario. Thus, while Lake Ontario is well characterised as a dimictic system, it makes more sense to treat Toronto Harbour as a polymictic system that responds strongly to thermal variability due to upwelling events in Lake Ontario, and atmospheric heat fluxes. Clearly, fishes residing in various areas of the harbour are likely to be differentially influenced by such contrasts in thermal dynamics that create many thermal habitats.

Implications of thermal regime on fish habitat in Toronto Harbour

In the embayments, open nearshore waters, and tributaries in and around Toronto Harbour, 50 different species of fishes (including 10 non-native species) have been identified (Dietrich et al., 2008). This community is predominantly composed of species that fall within warm- to cool-water thermal guilds, dominated by white sucker (*Catostomus commersonii*) and the non-native common carp (*Cyprinus carpio*). The presence of a range of species across multiple different thermal guilds suggests that there is thermal habitat-partitioning in the harbour, which has potential implications for fish metapopulations and community interactions as well as for the development of embayment remediation strategies that prevent cool-water "traps" for warm-water fishes (Murphy et al., 2012). Furthermore, rapid changes in water temperature, which may result from cold-water upwellings (i.e., cold shock), can cause detrimental physiological changes in fishes and result in sub-lethal changes and, in extreme cases, mortality (reviewed in Donaldson et al., 2008). Based on the observed temperature variation in Toronto Harbour and its rate of change, it is likely that these temperature fluctuations influence the distribution of fishes and may also influence individual growth rates and system productivity. The temperatures within the warm zones of the harbour (defined in the previous subsection) fall within the optimal temperature range for most warm-water fishes as well as the upper limits of the optimal temperature range for coolwater fishes. As might be expected, these regions are also some of the most productive in the harbour in terms of both

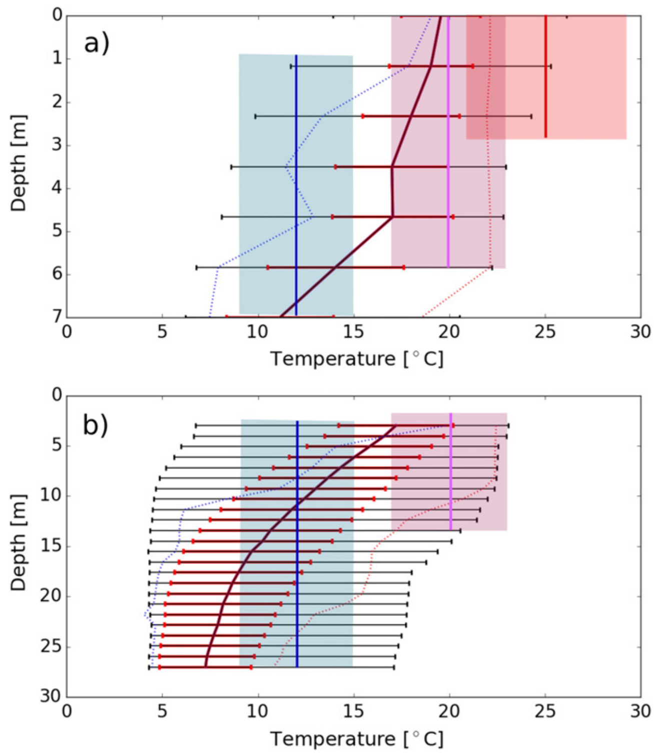

Fig. 10. Averaged temperature in the water column in Toronto Harbour and Lake Ontario during the stratified period (June 30–September 7, 2013; DOY 182–251). The bold error bars represent the standard deviation and the thin error bars represent the total temperature range at each depth for a) the Inner Harbour and b) the water column in Lake Ontario. The dotted lines represent the temperature profile at the beginning of a strong upwelling event (September 2, 2013; DOY 245; red dotted line) and during the upwelling event (September 3, 2013; DOY 246; blue dotted line). The filled areas indicate the generalised preferred thermal niche of cold-, cool-, and warm-water fishes, respectively. The filled areas are centred on the estimated optimal temperature for each fish guild: in blue colour (12 °C ± 3 °C) for cold-water fishes, in magenta colour (20 °C ± 3 °C) for cool-water fishes, and in red colour (25 °C ± 4 °C) for warm-water fishes (Casselman, 2002).

total catch and species richness during electrofishing surveys (Adam Weir, personal communication, August 8, 2014). However, despite the optimal temperatures during summer, rapid temperature declines associated with upwelling events can influence all but the most isolated of these comparatively protected regions (e.g., Cell 1). Such periodic drops in water temperature may act to reduce growth rates for warm-water species such as bluegill (*Lepomis macrochirus*) and may establish an overall limit on the productivity of nearshore habitats within Toronto Harbour (e.g., Murphy et al., 2011).

Given the regular periodicity of upwelling events in the harbour during the stratified season, it is possible that fishes that survive within the harbour have adapted to these cycles of cold-water intrusion. Indeed, acclimation to thermocycles has been observed in the lab in largemouth bass (*Micropterus salmoides*), which actually had more rapid growth as a result of increased foraging at warm temperature and reduced metabolic rates during cold temperatures (Diana, 1984). From a behavioural perspective, fish may actively avoid cold currents or preferentially select habitats that are not as frequently or severely affected by cold-water intrusion. However, fishes are unlikely able to predict when and where cold-water intrusion will occur such that some fishes are likely subjected to dramatic variation in temperature over short time scales. Assuming that fishes do not die as a result of cold shock, it is possible that growth may be impaired in the short term due to lost feeding opportunities (see Donaldson et al., 2008). Compensatory growth is common in fishes (Fraser et al., 2007), but the frequency and magnitude of cold shock events may determine the extent to which that phenomenon may occur. By pairing the results from the current study with data on fish habitat selection and movement within the harbour, it will be possible to evaluate the extent to which fishes either actively avoid cold-water intrusion events or select warmer habitats. A companion telemetry study of fish movements within the harbour offers an excellent opportunity to link physical process (i.e., rate of temperature change) with fish life history characteristics (e.g., selection of spawning habitats, behavioural response to upwelling events; see Veilleux (2014) for a description of this companion study). In addition, sampling of calcified structures to assess growth impairments or evaluation of stress responses in fish from different parts of the harbour when exposed to simulated cold shock could help to elucidate the biological implications of these physical processes.

Conclusions

This study uses a mechanistic approach to describe the thermal variability along Lake Ontario's northern shore and inside Toronto Harbour and determines the thermal habitat partitioning within the embayments of the harbour system. The findings from our study show that the most important factors in regulating the thermal regimes in Toronto Harbour are the relatively frequent and pervasive cold-water intrusions induced by thermocline upwellings. However, a multitude of other factors, including Poincaré waves, diurnal insolation, seiches, wind fetch, vegetation, topography, and bathymetry are found to contribute to the thermal habitat partitioning of the harbour. We showed that connection width, distance from the lake, and depth alone do not guarantee a specific thermal regime in an embayment and that each of the characteristics of the zone needs to be carefully analysed in order to understand its impact on the thermal habitat. The findings from our study suggest that there is usually some stratification in the Toronto Harbour during the summer period, but it is highly variable reflecting the dynamic movements of the thermocline in Lake Ontario. Thus, Toronto Harbour can be characterised as a polymictic system that responds strongly to thermal variability due to upwelling events in Lake Ontario, and atmospheric heat fluxes. Furthermore, the geometry of the harbour creates very diverse benthic thermal regimes that range from cold habitats in most of the Inner Harbour (mostly variable) and Outer Harbour (quasi-constant) to warm and relatively constant temperatures in the sheltered embayments in TTP and the channels between the Toronto Islands.

The observations from the companion telemetry study of fish movements, which include selection of spawning habitats and behavioural response to upwelling events, are in the process of being correlated with the results from this study. Understanding the impact of large-scale and short-term temperature variability on fish behaviour will help restoration efforts in creating the correct thermal regime for the targeted thermal guilds. Toronto Harbour embayments, in particular those in TTP, are the subject of restoration activities that will culminate with the re-naturalisation of Don River mouth that will create ~100 ha of new wetlands. Combined results from this and the companion study could inform the design of future restoration work by identifying the physical factors, such as geographic location, opening orientation and size, reforestation (shield against wind and insolation), and reef placement, that will help with the creation of efficient, optimal habitats for targeted fish species.

Supplementary field data, results, and figures that complement and support our main results can be found in Appendix_A.docx. An animation of benthic temperature changes before, during, and after a strong upwelling event (12–24 August, 2013). The animation was created from benthic temperature data from all available thermistor stations taken at 1-h intervals. The animation shows the advancement of the cold-water intrusion into the Outer Harbour and eventually spreading to all the remote corners of the area except for Cell 1 and some very sheltered locations inside the Toronto Islands channels. Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jglr.2015.07.013.

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