

PHYSICAL PROCESSES IN WESTERN LAKE ONTARIO DURING A TASTE AND ODOUR EPISODE

M G Skafel and R R Yerubandi
NWRI, Environment Canada,
Burlington, ON, L7R 4A6

ABSTRACT

Over five million people rely on western Lake Ontario for potable water. Each summer there is an episode of earthy taste and odour in the drinking water that forces local utilities to spend millions of dollars on systems to ameliorate the problem. The earthy taste and odour is caused by geosmin, a secondary metabolite of some Cyanobacteria and Actinomycete bacteria. Recent extensive field studies were undertaken to document the lake physics before and during the taste and odour event to understand better the processes controlling the delivery of geosmin to the water treatment plant intakes. Using current meters and fixed temperature profilers at several sites, a downwelling event was documented along the northwestern shore of the lake during the period of elevated geosmin concentration in the intake waters from Cobourg to Grimsby. The event was characterized by elevated water temperatures nearshore coincident with onshore and cyclonic alongshore circulation. In 2002, the downwelling was relatively poorly developed off Cobourg where the geosmin concentration was the least elevated. The downwelling event was stronger off Mississauga and Grimsby, where the geosmin concentrations were higher. The flow regime supports the hypothesis that the elevated geosmin concentrations originated in the warm offshore waters driven inshore and alongshore during a downwelling event.

RÉSUMÉ

L'eau potable de plus de cinq millions de personnes provient de l'ouest du lac Ontario. Chaque été, on enregistre un épisode où l'eau a un goût et une odeur désagréables de terre qui force les services d'eau de la région à dépenser des millions de dollars pour solutionner le problème. Ce goût et cette odeur de terre sont dues à la géosmine, une substance provenant du métabolisme secondaire de Cyanobactéries et d'Actinomycètes. Des études poussées ont été entreprises récemment sur les lieux pour recueillir des données sur les caractéristiques physiques du lac avant et durant un tel épisode dans le but de mieux comprendre les processus qui interviennent dans la production de géosmine dans l'eau prélevée par les stations de traitement de l'eau. Les appareils de mesure et notamment les appareils fixes qui enregistrent le profil vertical de température déjà installés à plusieurs endroits ont permis de déceler une plongée des eaux le long de la rive nord-ouest du lac durant la période de concentration élevée de géosmine dans l'eau prélevée à Cobourg et à

Grimsby. Cette plongée des eaux était caractérisée par des températures élevées de l'eau près de la rive qui coïncidaient avec la circulation cyclonique de l'air sur la rive et le long de la rive. En 2002, la plongée était relativement peu développée au niveau de Cobourg où la concentration de géosmine était la moins élevée. Par contre, au niveaux de Mississauga et de Grimsby, où la plongée était plus forte, la concentration de géosmine était plus élevée. Le régime d'écoulement appuie l'hypothèse que la concentration élevée de géosmine provient d'eaux chaudes du large qui se dirigent vers la rive et le long de celle-ci durant un événement de plongée des eaux.

INTRODUCTION

Lake Ontario is an important source of drinking water for over five million consumers. During late summer drinking water from Lake Ontario is susceptible to undesirable properties of earthy taste and odour (T/O). The occurrence of objectionable taste and odour is caused by both anthropogenic and naturally produced chemicals (Ridal et al. 2000). The most commonly identified biological causes of taste and odour events are two moderately volatile metabolites of certain micro-organisms, geosmin and 2-methylisoborneol (MIB). These metabolites can be produced by cyanobacteria and/or actinomycetes in diverse aquatic and terrestrial habitats. Both geosmin and MIB are discernable at extremely low threshold levels (Young et al. 1996) and are widely occurring in lakes and rivers. They resist oxidation and are therefore difficult to remove with typical drinking water treatment.

In the Great Lakes, both production and transport of these metabolites are influenced by large scale meteorological forcing, watershed, basin, diffuse/point source loading and hydrological processes. In response to severe T/O episodes in 1998 and 1999 in western Lake Ontario, a multi-disciplinary research team (Watson et al. 2002) was established to identify the biological sources and environmental triggers of these events, and to develop predictive and remedial tools. Early work identified an abrupt increase in geosmin concentration coinciding with T/O problems in drinking water along the northwestern shores of Lake Ontario. Geosmin production is observed to be indigenous, peaks annually, but only periodically at nuisance levels, and is hypothesized to originate from offshore planktonic cyanobacteria. Based on the evidence of geosmin concentrations and water temperatures at the intakes it was hypothesized that the strong downwelling may favour the transport of geosmin produced at offshore locations to nearshore areas causing the T/O problem.

In 2000 an intensive field investigation was undertaken in the western end of Lake Ontario to gain new information about the source and distribution of geosmin in the coastal waters. As part of that investigation, current meters and temperature sensors were deployed in the vicinity of several water treatment plant intakes as well as other locations. That investigation is reported in Rao et al. 2003, and confirms the correlation of a T/O event (albeit at low concentrations) with a downwelling event along the northwestern shore.

In 2002 another intensive investigation was carried out, and again current meters and temperature sensors were deployed at selected locations. This paper documents the circulation and thermal regime and provides another data set to test the hypothesis of offshore produced geosmin being transported onshore during a T/O event.

GENERAL PHYSICAL BACKGROUND

The thermal structure and circulation in the Great Lakes generally depends on the season because of the large annual variation of surface fluxes (Boyce et al. 1989). In the summer and fall there is a distinct thermocline in the upper 30 m in most of the lakes, which makes them stratified. During this period of stratification, significant wind events will cause upwelling and downwelling of the thermocline along the shore. The scale of the offshore distance over which these events takes place depends on the wind stress and nearshore bathymetry, and is typically of the order of 5 to 10 km, hence within the coastal boundary layer. During the summer stratified season the temperature variations along the northwest shore of Lake Ontario were found to be linked to the wind, with winds from the westerly direction causing upwelling and cooling, and easterly winds inducing downwelling and warming. Previous studies revealed that the flow and structure within the coastal boundary layer along the north shore of Lake Ontario presents a complex scenario during upwelling and downwelling episodes. The upwelling events are characterized by relatively weak easterly flow, and downwelling events with strong westward currents, sometimes associated with the propagation of internal Kelvin waves due to thermocline oscillations (Simons and Schertzer 1989, Rao and Murthy 2001).

FIELD DEPLOYMENT

During the summer of 2002 three pairs of stations were established, one pair each off Cobourg, Mississauga and Grimsby, see Figure 1. Each pair comprised an inshore and offshore station, with a current meter and fixed temperature profiler (FTP) at each. An Acoustic Doppler Current Profiler (ADCP) was deployed at each station except inshore at Grimsby where a Nobska MAVS single point acoustic meter was deployed. Similarly, temperature loggers were typically located at 5 m intervals on FTPs except inshore at Grimsby where the temperature sensor on the MAVS current meter was used. Details of the stations are given in Skafel and Yerubandi (2003). The reported accuracy of the ADCPs is $0.25\% \pm 2.5$ mm/s and that of the MAVS is ± 3 mm/s. Several different temperature sensor types were used on the FTPs, but all are accurate to $\pm 0.15^\circ\text{C}$ or better. All sensors recorded data at time intervals of 20 minutes or one hour. The velocities were resolved into alongshore and cross-shore components, with positive alongshore values to the east and positive cross-shore values onshore. With this convention, the onshore values at Grimsby are southerly in contrast to the other two stations where they are northerly.

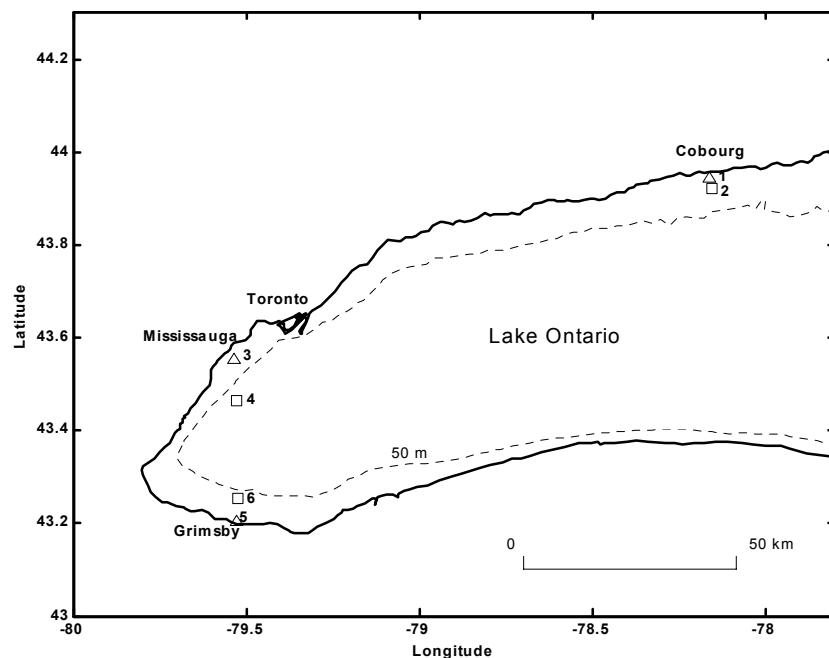


Figure 1. Locations of current meters and FTPs in 2002 off Cobourg, Mississauga and Grimsby, Lake Ontario.

Wind data were obtained from routine observations at Toronto Island Airport, Kingston, Trenton, Cobourg, Burlington, and Port Weller collected by the Meteorological Service of Canada, Environment Canada. The data from the Toronto Island Airport were used as the primary wind data set. The wind stress at the water surface was computed by the quadratic law given as $\tau = \rho_a C_d |W|W$, where $\rho_a = 1.2 \text{ kg/m}^3$ is the air density, W is the wind velocity [m/s]. In general, the drag coefficient C_d increases with the wind speed and is estimated as $C_d = (0.8 + 0.065 W) \times 10^{-3}$ for $W > 1 \text{ m/s}$ (Wu 1980). The stresses were decomposed into alongshore and cross-shore using the general orientation of the shoreline as 80°T at Toronto Island Airport.

Geosmin concentrations in raw water collected at water treatment plants at Cobourg, Toronto (R L Clark) and Grimsby were measured over the summer and fall. The sampling interval was approximately weekly. The samples were analyzed for geosmin by high resolution mass spectrometry using the Ontario Ministry of the Environment standard method for taste and odour compounds (Palmentier et al. 1998).

Figure 2 shows the time series records of geosmin concentration at the intakes of the water treatment plants. Both Toronto and Grimsby show a clear peak between Day 246 and 253. The concentrations peaked at only about 10 ng/L , marking a relatively minor taste and

odour event. At Cobourg, the event was almost non-existent; no values were reported above about 4. In 1998 and 1999 values of geosmin over 100 ng/L were recorded so while 2002 was not a severe year the time profile of the event nevertheless had the same character as these two severe years.

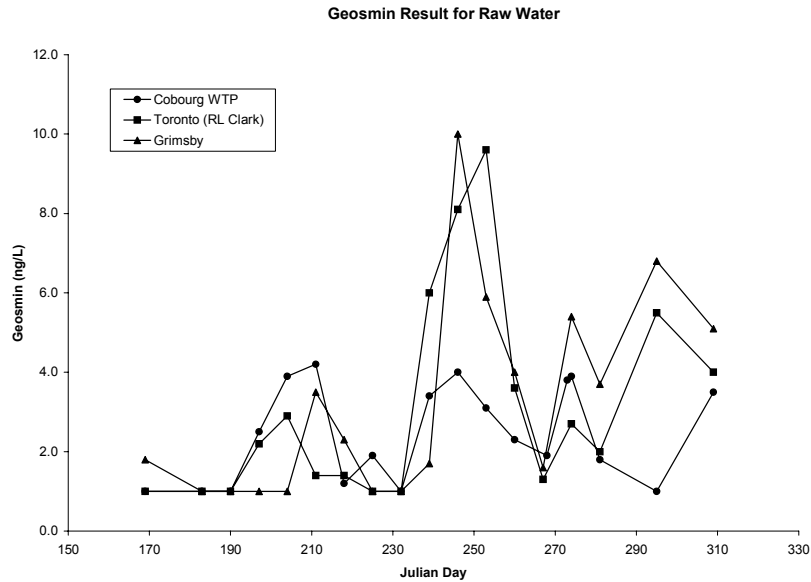


Figure 2. Geosmin concentrations at the intakes of the Water Treatment Plants, Lake Ontario, 2002.

FIELD DATA AND DISCUSSION

As noted in Rao et al. (2003), the geosmin peak in drinking water typically occurs in late August or early September. Therefore in this paper, the currents and the thermal structure of the lake were analyzed from Julian Day 220 to 270 (8 August to 27 September). Following Rao et al. (2003), the 10°C isotherm is used to identify upwelling and downwelling events.

The wind stress for the Toronto Island meteorological station, filtered with a 24 hour low pass filter, is plotted in upper panel of Figure 3. The alongshore wind stress was typically stronger than the cross-shore stress, except for the event on Day 255 when there was a very strong northerly wind. There were two strong easterly wind events, on Days 234-237 and Days 240-242 that were important in the development of the downwelling along the north shore, followed by three smaller events up to Day 247. The strong events were evident in all met stations at the west end of the lake, but were weaker at the met stations at the east end. This suggested that the wind field was relatively homogeneous at the western end of the lake during these events, but was diminished in strength towards the eastern end of the lake.

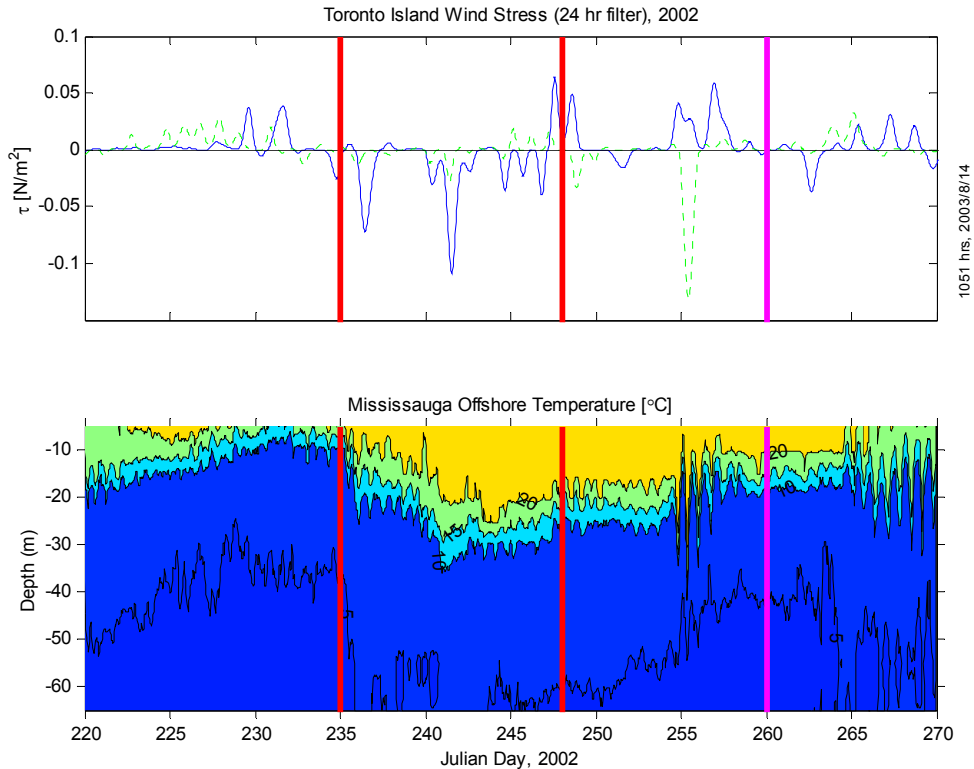


Figure 3. Upper Panel: Filtered shore parallel (solid line) and shore normal (broken) wind stress at the Toronto Island Airport. Lower Panel: Isotherms at the offshore station off Mississauga, 2002.

In the lower panel of Figures 3, the thermal structure at Mississauga is shown. Of the three stations monitored, it portrays best the response of the thermocline to wind events and is used in this paper to define the conditions in western Lake Ontario (full details of the field data are given in Skafel and Yerubandi, 2003). Comparison of the wind stress and temperature data shows that the variability of the thermal structure is associated with the prevailing winds. Upwelling events are caused by winds from the west and downwelling events caused by winds from the east. Starting about Day 235, in response to the easterly wind event (starting on Day 234), there was a depression of the thermocline at Mississauga, indicating a downwelling event. There was a slight relaxing about Day 248 in response to the westerly wind. A second westerly wind event starting at about Day 255 marked the end of the downwelling event and the start of an upwelling event at all three stations, although Grimsby lagged behind the other two. The isotherms show oscillations at about the inertial period (~ 17 hours) throughout the observation period, which is common during the summer stratified season. Based on the easterly wind events and temperature data, the downwelling event was defined to occur from Day 235 to Day 248 (red vertical lines in Figure 3) in terms of the physical processes, even though the warm waters persisted near shore longer and the elevated geosmin data (Figure 2) continued to about Day 260 (magenta vertical line in Figure 3).

The isotherms off Mississauga on Day 248, developed from four profiles taken that day are shown in figure 4. The depression of the isotherms adjacent to the bottom indicates that the warm surface water was being forced downward at the shoreline, characteristic of a downwelling event.

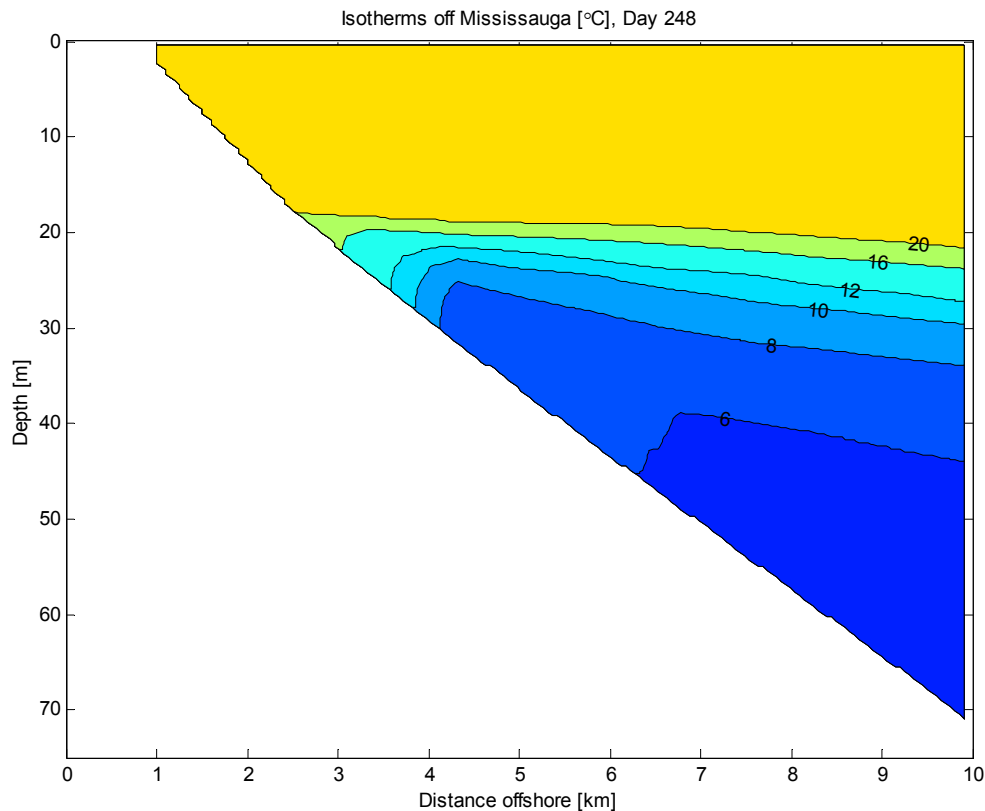


Figure 4. Water temperature off Mississauga on Day 248.

Figure 5 shows the time series of the low-pass filtered (>24 h) currents at 5 m below the surface at the offshore stations at Cobourg, Mississauga and Grimsby. The alongshore currents were comparatively stronger than cross-shore currents at all stations. As in 2000 (Rao et al. 2003), the alongshore currents show that the low-frequency oscillations (>3 days) were dominant and were related to alongshore wind stress. The persistent deepening of the isotherms in Figures 3 from Day 235 to Day 248 are matched by continuous westward and onshore flow in the surface waters at Mississauga and eastward and on shore at Grimsby, as one might expect. However, at Cobourg the westward flow was interrupted by two eastward events (Days 238 and 242), and the onshore flow was not persistent, indicating the downwelling event was not as vigorous there.

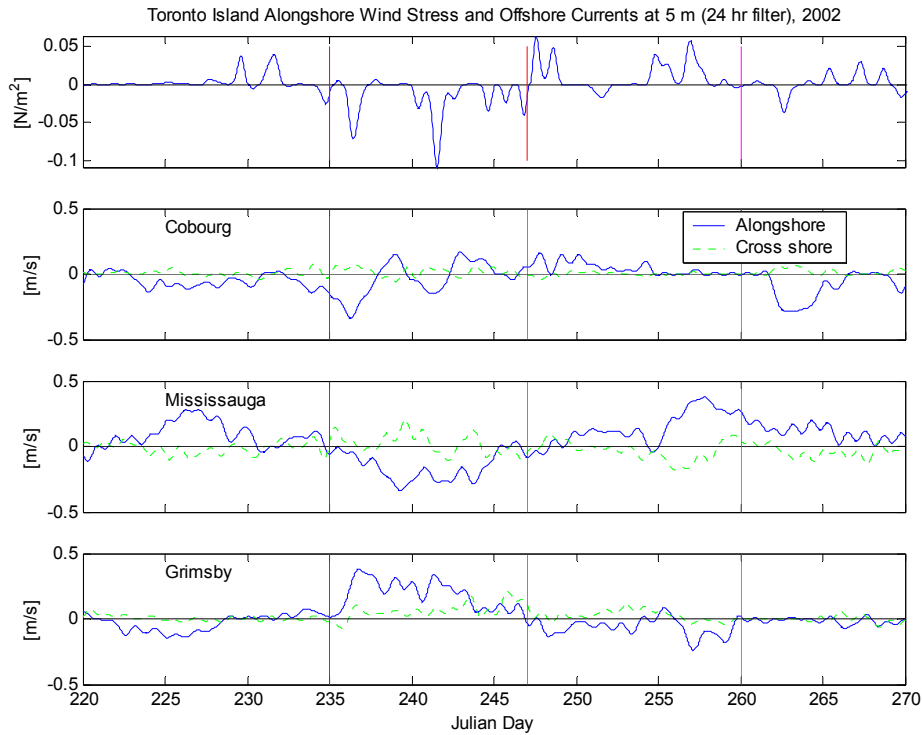


Figure 5. Alongshore wind stress at Toronto (upper panel), followed by the alongshore (solid line) and cross-shore currents (broken) at the three offshore stations at a depth of 5 m.

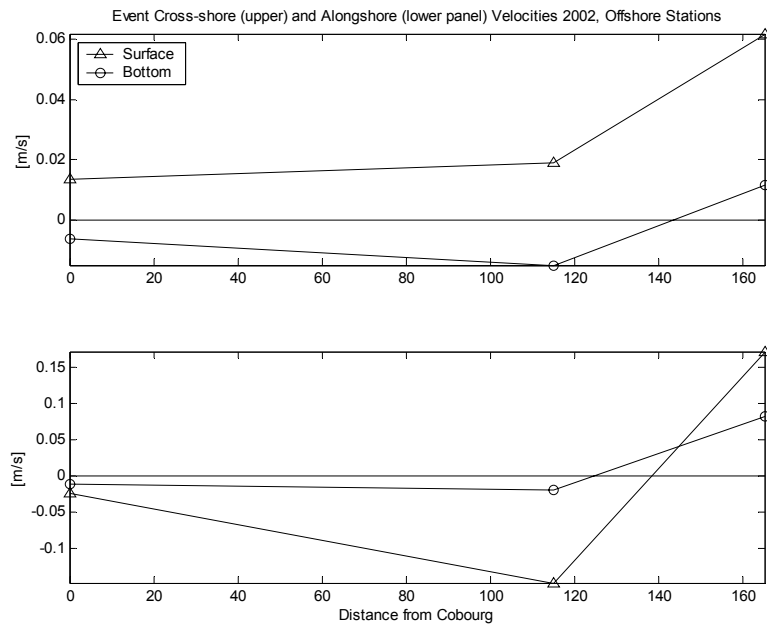


Figure 6. Average surface and bottom currents at the offshore stations during the downwelling event plotted against the distance from Cobourg.

The alongshore flow at the bottom (not shown) was westward at Mississauga and eastward at Grimsby, but mixed at Cobourg during the event time period. The onshore-offshore flows at the bottom were small and mixed in direction at Cobourg and Mississauga, but consistently onshore, although small, at Grimsby.

In Figure 6 the mean values of the velocity components at the offshore stations are shown for the duration of the event, Day 235 to 248. The cross-shore flow at the surface was onshore everywhere, and at depth the mean flow was offshore at Cobourg and Mississauga, but onshore at Grimsby. The onshore flow at Grimsby is in contrast to the offshore flow at Port Dalhousie reported in Rao et al. 2003. The alongshore flow was counterclockwise everywhere although it was very small at Cobourg. (Recall that Grimsby is on the south shore so that positive alongshore current is cyclonic, consistent with the other two stations, and that onshore here is to the south in contrast to the other two stations where onshore is to the north.) The spatial extent of the downwelling feature appears to start somewhere near Cobourg and extend around the western end of the lake to east of Grimsby on the south shore.

The mean velocity profiles for the whole summer (about Day 110 to 290) and for the event period (Day 235 to 248) are shown in Figure 7 for the offshore stations. Examining the cross-shore flow first, at Cobourg over the summer the flow was onshore to 25 m and

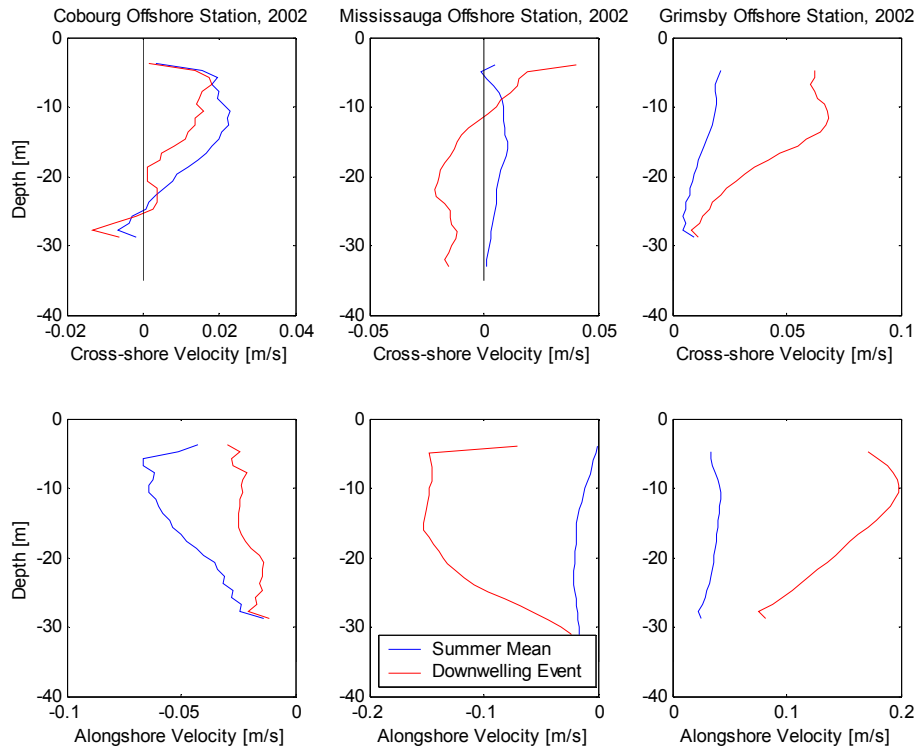


Figure 7. Velocity profiles for the whole summer and the downwelling event at the three offshore stations.

modestly offshore below that. During the event period the flow was similar but at lower intensity onshore and slightly higher offshore at the lower depths. At Mississauga the summer flow was small and onshore; during the event there was a pronounced onshore flow near the surface reversing to offshore below about 10 m. At Grimsby there was a modest onshore flow all summer which was greatly enhanced during the event. The alongshore flows were westward both for the whole summer and the event period at Cobourg and Mississauga and eastward at Grimsby. At Cobourg the alongshore flow was much less during the event than the summer mean. In contrast at Mississauga and Grimsby the event flow was much stronger than the whole summer mean flow.

The surface temperatures of Lake Ontario are shown in Figure 8 for Day 246. The surface waters are above 20°C along the north shore, around the west end of the lake, and along the south shore as far east as the mouth of the Niagara River. There is evidence of cool upwelling waters along the southeast shore. The lake wide surface temperature distribution is consistent with the temperature observations made during this study.

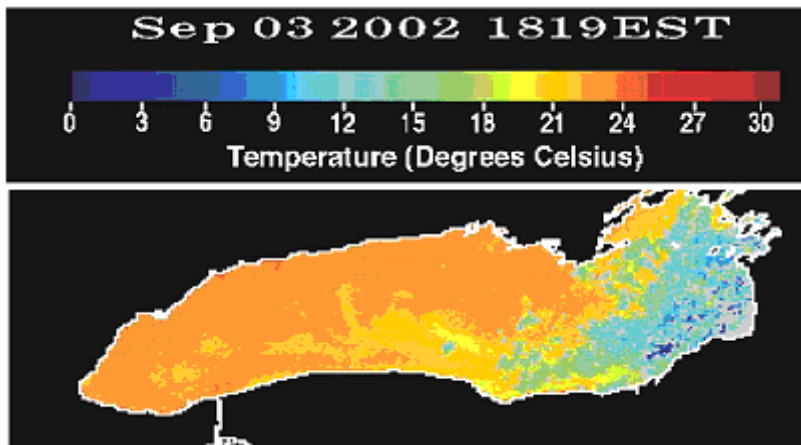


Figure 8. Lake Ontario surface temperature on 03 September (Day 246). The western portion of the lake was above 21°C, cooler temperatures prevailed in the southeast.

CONCLUSIONS

The current and temperature measurements in 2002 along the north and west shores of Lake Ontario showed upwelling and downwelling of the thermocline. Upwelling was caused by winds from the west generating eastward and offshore flows, and downwelling and strong westward current were caused by winds from the east. The well developed downwelling event from Day 235 to 248 at Mississauga was confirmed by the depressed temperature contours, strong alongshore currents to the west at all depths, and strong onshore flow in the surface waters and offshore flows at depth. This downwelling correlated with the rise in geosmin concentration at the water treatment plant in Toronto. The geosmin peaked on Day 253 (recall that this was a weekly sample), which was after

downwelling had stopped (on about Day 248), but the warm waters remained nearshore because the flows were nearly zero until Day 250). The downwelling at Cobourg was relatively strong in terms of thermocline displacement, but poorly defined in terms of flow. The downwelling at Grimsby was also marked by a depressed thermocline. The cross-shore flows there were onshore throughout the profile and strongest near the surface. Flows alongshore were strongly eastward, which correspond to the westward flow at Mississauga. The geosmin peak at Grimsby occurred on Day 246, within the downwelling event period (235-248).

The 2002 current and temperature data support the hypothesis that a taste and odour event with elevated geosmin concentrations is correlated with a downwelling event along the northwest shore of Lake Ontario. The downwelling was not well established at Cobourg where the geosmin concentrations were low. The downwelling was well established at Mississauga. Although the flow at Grimsby was not classically downwelling, but in a transition between that and upwelling, the flow was of warm surface water flowing onshore and alongshore from the area of strong downwelling around Mississauga, and so also supports the hypothesis.

ACKNOWLEDGEMENTS

The staff of Engineering Services supplied and prepared the instrumentation, and Technical Operations Services deployed and recovered them. One ADCP and the Geosmin concentration data were supplied by T Howell, MOE. The temperature profile data off Mississauga were provided by M Charlton and T Mamone. D Doede provided technical and data reduction support. Partial funding was provided by the Ontario Water Works Research Consortium.

REFERENCES

- Boyce, F M, Donelan, M A, Hamblin, P F, Murthy, C R, Simons, T J 1989 Thermal structure and circulation in the Great Lakes. *Atmos-Ocean*, 27(4), 607-642.
- Palmentier, F P, Taguchi, V Y, Jenkins, W D, Wang, D T, Ngo, K P, Robinson, D 1998 The determination of geosmin and 2-methylisoborneol in water using isotope dilution high resolution mass spectrometry. *Wat Res* 32:287-294.
- Rao, Y R, Skafel, M G, Howell, T, Murthy, C R 2003 Physical processes controlling taste and odour episodes in Lake Ontario drinking water. *J Great Lakes Res* 29(1), 70-78.
- Rao, Y R, Murthy, C R 2001 Nearshore currents and turbulent exchange processes during upwelling and downwelling events in Lake Ontario. *J Geophys Res* 106 C(2), 2667-2678.

- Simons T J, Schertzer, W M 1989 The circulation of Lake Ontario during summer of 1982 and the winter of 1982/83. Environment Canada, Inland Waters Directorate, Scientific Series 171, pp191.
- Ridal, J F, Brownlee, B, Lean, D R S 2000 Is Lake Ontario the source of taste and odour compounds to the Upper St Lawrence River? *J Great Lakes Res* 26(3), 315-322.
- Skafel, M G, and Yerubandi, R R 2003 Physical processes in western Lake Ontario relevant to taste and odour episodes in drinking water: 2002. National Water Research Institute, Contribution No. 03-175.
- Watson, S B, Charlton, M, Brownlee, B, Skafel, M G, Howell, T, Moore, L, Ridal, J, Zaitlin, B 2002 Aquatic odour in Lake Ontario: tracing origins through an environmental maze. 37th Central Canada Symposium on Water Pollution Research, Burlington, 4-5 February 2002.
- Wu, J 1980 Wind-stress coefficients over sea surface near neutral conditions – a revisit. *J Phys Oceanogr*, 10, 727-740.
- Young, W F, Horth, H, Crane, R, Ogden, T, Arnot, M 1996 Taste and odour threshold concentrations of potential potable water contaminants. *Wat Res* 30, 331-340.