PAPER

Societal Benefits of the Real-Time Coastal Observation Network (ReCON): Implications for Municipal Drinking Water Quality

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ABSTRACT

Environmental conditions on Lake Erie in summer 2006 produced hypoxic waters (1.2 mg/l dissolved oxygen), with characteristic low pH (7.2), low temperature (18°C) and high manganese levels, negatively impacting water processing at the Cleveland Water Department. A ReCON system deployed in 2005 recorded the onset of similar conditions and is used to explain the episodic nature of the event. Internal waves initiated by winds can propagate around the central basin of Lake Erie for several days explaining the cyclical nature of the event. Future deployments of a ReCON buoy system in Lake Erie's central basin will provide real-time observations of temperature and dissolved oxygen to water department managers. The buoy will function as an early warning system for the detection of low oxygen and the onset of internal waves responsible for delivering hypoxic waters to water intakes, thus ensuring the quality of drinking water for approximately 1.5 million residents of Cleveland, OH.

Introduction

The development and application of coastal observing system technology is a major national need identified by Ocean.US (Ocean.US, 2002). Real-time observations are needed to provide resource users with information on the current status of the ecosystem to reduce public health risks (Oceans.US, 2006). The next generation of national coastal observation buoys must be designed with networking technology concepts (Ruberg, Brandt et al., 2007) to keep up with the increasing demands of observation requirements and benefit from technological advances.

Recently, the Marine Technology Society addressed marine technology applications that provide environmental, economic, and societal benefit (Kohanowich, 2007). The ReCON project, real-time networking technology developed for marine coastal observations (Ruberg, Muzzi et al., 2007), is currently engaged in collaborative research to create ecosystem forecasting tools in the Great Lakes benefiting a wide range of regional constituents. The Great Lakes contain approximately 19% of the world's surface liquid freshwater (Beeton, 1984) and roughly 40 million people in the United States and Canada derive drinking water from these freshwater inland seas. The implications of marine technology employed to ensure safe drinking water in the Great Lakes are being explored in collaboration with the Cleveland Water Department (CWD) under the ReCON project by implementing a buoy-based hypoxia early warning system in the central basin of Lake Erie near Cleveland, OH. The ReCON system will augment existing sensors used by CWD by providing real-time observations of changing Lake Erie conditions.

CWD operates four drinking water treatment plants (WTP) serving approximately 1.5 million people in Northeast Ohio. Water intake locations are shown in Figure 1. From west to east, the Crown, Morgan, Baldwin, and Nottingham WTPs have water intake pipes ranging between 3 and 4.8 miles from the south coast of Lake Erie's central basin near Cleveland. It is well established that Lake Erie central basin stratification beginning in the late spring and typically persisting until early fall, results in the development of hypoxia in the hypolimnion by late July or early August (Bertram, 1993).

On August 9, 2006 the hypoxic waters from the hypolimnion reached the WTP intakes at the CWD. Lake Erie water with low temperature, low pH, and discoloration was pumped into three of the four WTPs and into the distribution system for about 10-12 days. At the Crown WTP, temperature, dissolved oxygen (DO), and pH dropped drastically, while turbidity rose. A couple of days later, similar but less severe hypolimnetic conditions were observed at the Morgan WTP. At the Nottingham WTP, temperature and pH decreased, while odorous algae accumulated on the intake screen and required manual removal. The Baldwin WTP had less significant signs of ingestion of hypolimnetic waters from its intake due to its proximity to the surface. The hypolimnion continued to intermittently reach the Crown intake until August 13, 2006 and the Nottingham intake until August 19 or 20, 2006.

FIGURE 1

Bathymetric map of Lake Erie near Cleveland, OH showing CWD water intakes (indicated with black dots) and NOAA ReCON buoy location in 2005 (indicated by the “X”). The 20 m contour is labeled.

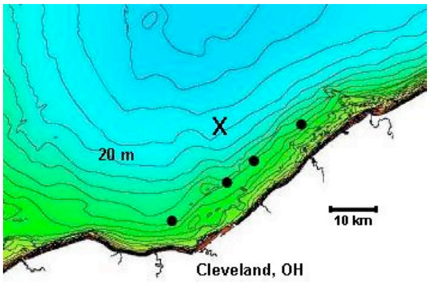


FIGURE 2

Current ReCON shore stations allowing buoy deployment within an approximate 4300 square km area. The Ann Arbor operations center controls data collection platforms and transfers sensor data for web display, archive, research, and forecast applications (after Ruberg et al., 2007).

Due to hypolimnetic waters reaching the CWD intakes, pre-treatment operations were disrupted, and corrosion control strategies were affected by changes in temperature and pH. In addition, reduced and dissolved forms of iron and manganese from the hypolimnion did not settle and went into the distribution system resulting in numerous customer water quality complaints about discolored water. The complaints were primarily from customers served by the distribution system closest to the affected WTPs. Customers served by distribution systems fed from storage appeared to be unaffected by hypolimnetic waters (e.g., no complaints were received).

Methods

The ReCON System

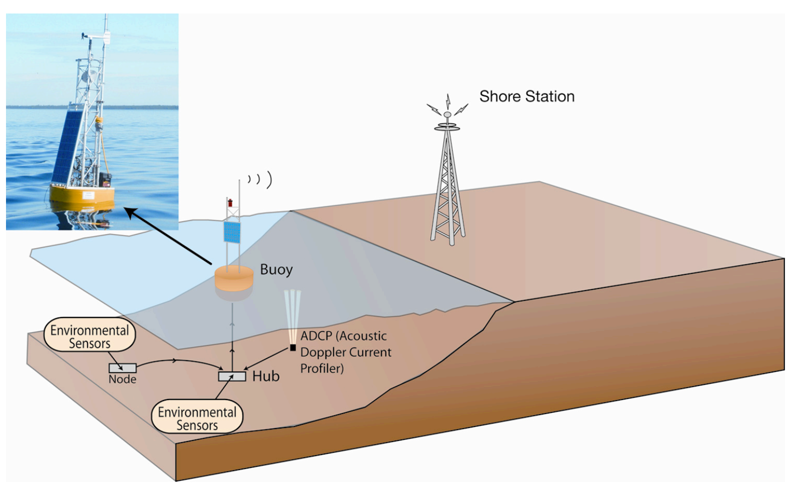
The ReCON system is a universal, broadband buoy system for seabed to sea-surface coastal observations designed to take advantage of rapidly advancing commercial internet technology (Figure 2). The system consists of multiple Ethernet-based, portable buoys (Frye, 2000) and fixed stations deployed within an approximate 24 kilometer radius from the shore station node. Surface wireless and wired underwater guest ports (Austin, 2002) provide an opportunity for installation of a wide range of sensors from any regional institution without incurring the expense of a buoy development and deployment program. Recent deployments have demonstrated the system’s capacity to provide long-term observations and the ability to respond to episodic events (Ruberg et al., 2007). Providing information to drinking water managers in time to respond to the effects of changing environmental conditions in Lake Erie demands long-term observations of dissolved oxygen over several weeks coupled with observations of pH and temperature variation over only a few hours. The system, consisting of a network control center, shore stations, buoys and permanent stations with surface sensors, and underwater hubs with sensors, is able to provide marine measurements at time scales required to provide early warning of conditions impacting drinking water processing for communities along the southern coast of Lake Erie.

ReCON utilizes off-the-shelf technology to implement a surface communications network implemented with wireless IEEE802.11b/g radios (Figure 3). Within line of sight, buoys will choose the shortest path to shore station nodes. System range can be extended beyond line of sight by relaying data through a buoy that is within range of shore stations. Underwater hubs can be connected to additional hubs, within power limitations. Maximum deployment range and system throughput vary depending on signal amplification and antenna heights.

Control center commands are sent through the commercial internet to shore station nodes where they are transferred using wireless internet to offshore buoys. Power control and data acquisition commands for specific devices are sent through a robust underwater Ethernet cable connecting the underwater hub to the surface buoy. The underwater hub has up to eight analog or serial ports to enable connections to a wide variety of instruments. Instruments capable of serial communications are connected directly to an internet addressable serial port server in the underwater hub. Analog sensors are connected to the same network port server through an analog to serial converter.

FIGURE 3

Picture of ReCON buoy and an illustration of the ReCON hub, buoy and shore station configuration. The system is capable of providing a wireless Ethernet connection to offshore buoys and instrumentation up to 24 km from shore and buoy to buoy connections beyond shore station line of sight.



Sensor data transfer software includes Linux shell and Kermit scripts to schedule and transfer serial data from instrumentation. These scripts are run on a Linux processor located on the surface buoy or in the underwater hub. Specific instruments used to provide observations of temperature profiles and hypoxic (low oxygen) waters were the YSI 6600 multi-probe and the Fondriest TS110 temperature string. The YSI 6600 multi-probe hosted a dissolved oxygen sensor (YSI 6562 pulsed polarographic, range of 0-20 mg/L, and an accuracy greater than ±2% of reading or 0.2 mg/L) and temperature sensor (YSI 6560, range of -5-60ºC and an accuracy of ±0.15ºC. The Fondriest TS110 temperature thermistors have a range of 0-50 ºC and an accuracy of +/- 0.1 ºC. The TS110 was deployed at a depth of 21.5 m with Thermistor 1 located approximately 0.3 m height above bottom (hab), and Thermistor 2 collocated with the YSI 6600 at 0.8 m hab. The remaining nine thermistors were located at 1.3 m, 1.8 m, 2.3 m, 3.3 m, 5.3 m, 7.3 m, 8.3 m, 9.3 m, and 10.3 m hab. This arrangement provided a high resolution profile of the hypolimnion, metalimnion, and epilimnion during the summer 2005 deployment. Wind speed and direction are measured by an R.M Young Anemometer located 2.3 m above the lake surface at 5-minute averaged intervals; wind speed resolution is 0.1 m/s and accuracy is +/- 1.0 m/s, and wind direction resolution is 1.0 degrees and accuracy is +/- 10 degrees.

A web-based data management system permits access to real-time marine conditions for municipal drinking water processing mangers through real-time tables and data plots. Data for these applications are stored on the buoy and at the shore station node until the control center Linux computer transfers data for archiving.

Cleveland Water Department Instrumentation

Sensors used to detect the ingestion of hypoxic waters at the CWD water intake were a Fisherbrand Bimetal Dial Thermometer with a short (probe) sensor, a range of 0-100 ºC, and accuracy of +/- 1%, and a Fisher Scientific Accumet Model AB15 pH/ion/Conductivity meter with a resolution of 0.1/0.01pH, a range of -1.99-19.00 pH units, and an accuracy of +/- 0.01 pH units. Dissolved oxygen readings were observed at the water intake with a Fisher Scientific Accumet Basic Model AB40 DO meter with a range of 0-60 mg/L and an accuracy of +/- 0.1 mg/L.

Wind speed and direction during 2006 were obtained from NOAA's National Data Buoy Center (NDBC) 3 meter discuss buoy 45005 located approximately 60 km west northwest of the study area at 41°40'36" N 82°23'54" W. The redundant R.M Young Anemometers located 5 m above the lake surface provided hourly 8-minute averaged wind speed with a resolution of 0.1 m/s and an accuracy of +/- 1.0 m/s, and wind direction with a resolution of 1.0 degrees and an accuracy of +/- 10 degrees.

Observations and Discussion

CWD Water Treatment Plant Data during the August 2006 Event

The most complete set of water quality data was collected from the Crown WTP, the western most intake. Figure 4a represents the temperature at the Crown WTP intake for August 2006. The temperature dropped from around 25°C to 18°C on August 9. On the 11th, it increased to 23°C before returning to 18°C for a few days. On August 13th, the temperature began a steady increase back to 24°C for the remainder of the month.

Figure 4b is a plot of pH data from the Crown WTP for August 2006. The pH values dropped from 8.2 to 7.6 between August 5–7. The pH values temporarily returned to a more typical value of 8.1 on the 8th but again dropped to 7.2 on August 9th. The pH remained below normal levels between August 9–17, increasing to normal levels after the 19th.

The plot in Figure 4c represents DO concentrations at the Crown WTP intake in August 2006. The lowest concentration was 1.2 mg/L observed on the 12th, and the average concentration between August 9–13was 2.8 mg/L. Normal DO values range between 8 and 10 mg/L. The highest DO value was 6.5 mg/L, observed on the 18th and 19th.

Water temperature, pH, and DO varied over the time period when water from the hypolimnion reached the Crown intake. This could indicate that the hypolimnion was intermittently reaching the intake during this period. The exact time at which the parameters fluctuated over this period was not consistent. This could be a result of either samples being collected at different times of day or analytical error.

In addition to the water intake sensor observations shown in Figure 4, water samples were analyzed for iron and manganese concentrations by certified analysts applying approved drinking water analyses under the Ohio Environmental Protection Agency. Both iron and manganese concentrations increased above typical values observed at the WTP intakes and were also observed at elevated concentrations in samples taken at the tap (data not presented). Manganese concentrations at the Crown WTP intake exceeded the secondary standard of 0.05 mg/L (50 µg/L) during this time period. Iron concentrations observed at the intakes were not above the secondary standard of 0.3 mg/L (300 µg/L).

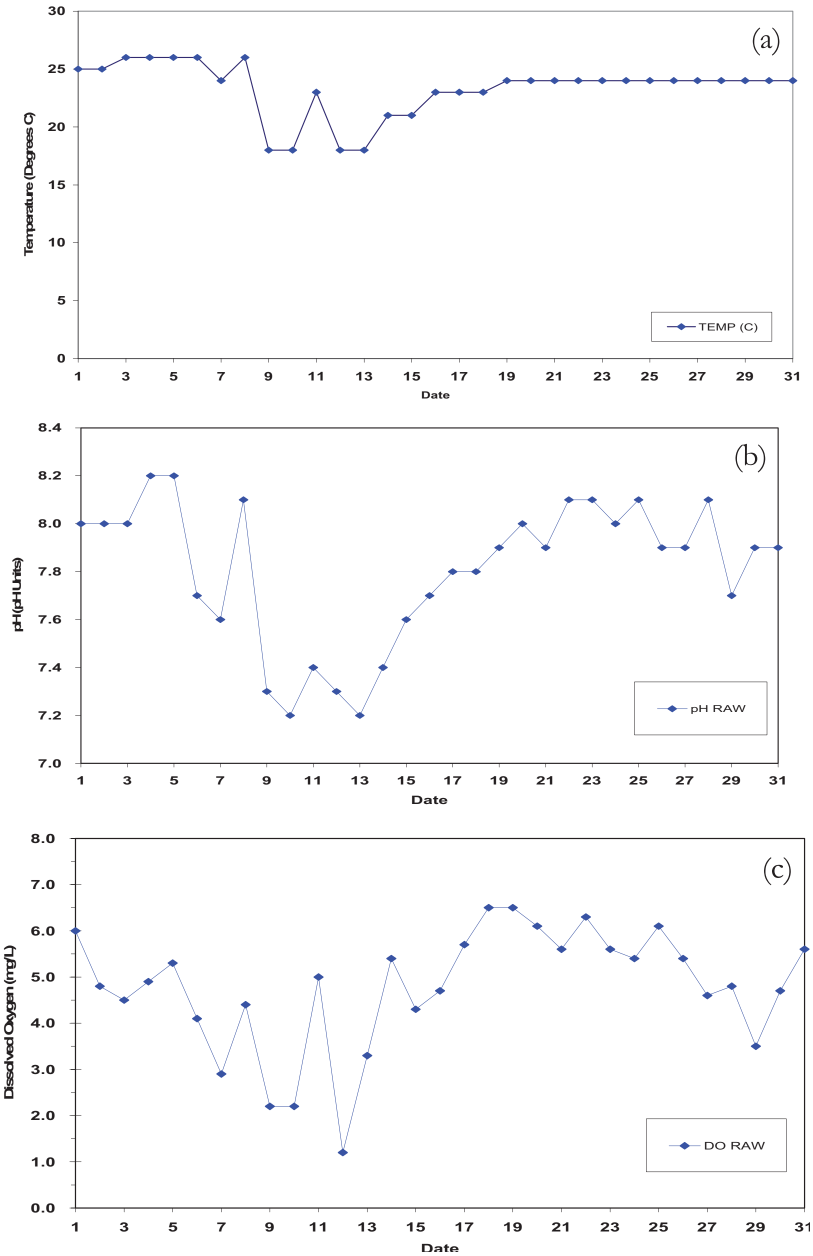
Wind speed and direction obtained from NDBC buoy 45005 (Figure 5) indicate that significant E and NE winds prevailed on August 5–6, with a wind direction reversal to SW winds on August 7 reaching an average speed of 9.3 m/s. On August 8, winds reversed to NE and reached 8.3 m/s. After calm winds on August 9–10, NE winds reached speeds of 10.2 m/s and continued to be strong through August 13th. Oxygen and pH levels on August 7 reached initial low levels, recovered somewhat and then reached the lowest recorded levels on August 13, coinciding with strong NE winds (in the direction of the long axis of lake Erie) recorded on August 12–13.

Internal Waves and Oxygen Conditions Observed during August 2005

Although we have no ReCON buoy observations from 2006, observations made in

FIGURE 4

Plots of Lake Erie Water Temperature (a), pH (b), and Dissolved Oxygen (c) at Crown Water Treatment Plant August 2006.



2005 help explain what probably occurred. The conditions that contribute to water that is hypoxic, and subsequently low in pH and high in manganese levels, most likely resulted from lake stratification and algal decomposition leading to anoxic conditions in the sediment (Beutel et al., 2007). Seasonal stratification varies in Lake Erie's central basin but in general, surface waters (the epilimnion) warm to an approximate depth of 15–18 m. With an average basin depth of approximately 20 m, this results in a 2–5 m hypolimnion (the lower layer) that is cutoff from downward mixing of oxygen-rich waters in the epilimnion due to the density gradient between the two water masses. The epilimnion and the hypolimnion are separated by a thin (1–3 m) layer where the water temperature changes rapidly (the thermocline). Reducing conditions in the sediment lead to mobilization of the reduced compounds into the water above the sediment (Beutel et al., 2007), and microbial activity in the sediments and water column produces CO_2, lowering the pH. Very low oxygen levels interrupt normal chemical equilibrium, and manganese begins to precipitate out of the sediments. The oxygen concentrations and pH serve as excellent, easily measured surrogates indicative of potential trouble. Oxygen decline and temperature, 0.8 m from the bottom, through the August 2005 time period is shown in Figure 6. These show that the hypolimnion water temperature was about 12°C, and that the oxygen concentration decreased from about 6 mg/L to less than 2 mg/L.

The thermocline acts as a barrier between the two water masses and waves can propagate along it, just as waves occur at the air-water interface (Boyce et al., 1989). However, the periods of these internal waves are much longer than those at the water surface. In Lake Erie, many of these internal waves have periods of approximately 18 hours (these are called inertial waves). Other internal waves have much longer periods; the upwelling (when colder epilimnion water approaches the surface and pushes the thermocline upward) and downwelling (when warmer epilimnion water pushes downward and depresses the thermocline) events that are frequently observed in the lake propagate around the lake as internal waves with periods of several days.

Figure 7 shows temperature data recorded by the ReCON buoy in 2005 at three different water depths. The average period of the temperature oscillations at the 16 m sensor was 18.2 hours between August 5–12, 17.4 hours from August 19–22, and 18.1 hours from August 26–31. These temperature oscillations have about the same period as the lake's inertial waves and are undoubtedly caused by the raising and lowering of the thermocline due to the passage of these waves past the sensor located at 16 m. There is also a general rise in the temperature between August 3 and August 11. This rise in temperature is due to the depression of the average position of thermocline from between 14–16 m to between 16–18 m. It is this depression of

FIGURE 5

Wind speed (black) and direction (gray) from NDBC 45005 during August 2006. Wind direction has been smoothed using a 4-hour moving average. The meteorological buoy is located approximately 60 km northwest of Cleveland, OH.

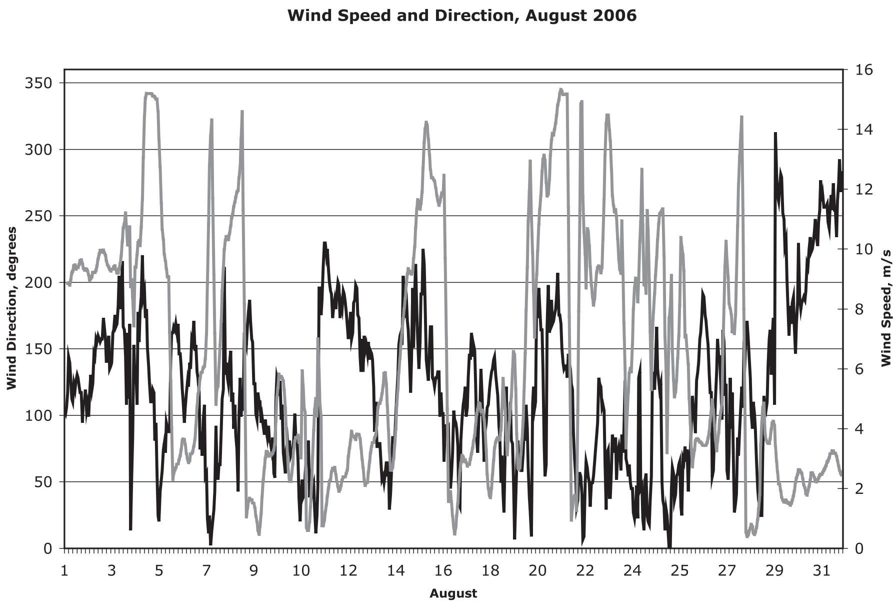
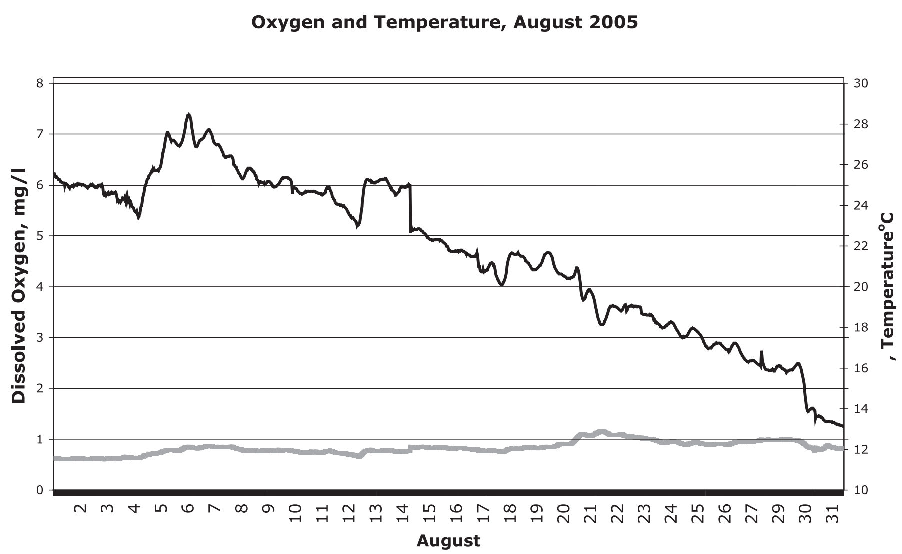


FIGURE 6

Oxygen (black) and temperature (gray) obtained from a YSI 6600 multi-probe deployed at a depth of 20.7 m (0.8 m hab) during August 2005. The instrument was attached to a ReCON buoy approximately 22 km north of Cleveland providing continuous real-time data.



the thermocline that permits the effects of the internal waves to be observed at the 16 m temperature sensor. This longer-term temperature rise is probably caused by the downwelling of warmer epilimnion water. Thus the temperature variations are due to the combined effects of two different processes; shorter-term oscillations caused by the internal inertial waves superimposed on the longer-term temperature rise. Note that the 16 m temperature remains high from 13–19 of August, but that there is some indication of temperature variation at the 18 m sensor during this time. This suggests that the thermocline was depressed to almost 18 m depth during this interval. Temperatures between August 19–21, at the 16 m depth, decreased as upwelling occurred and the thermocline became more elevated (this is the pattern observed at the water intake in 2006). The entire process then repeated between August 21 and August 27, and then started again on August 28.

Figure 8 shows that W and then NW winds on August 4–5 initiate the strong thermocline oscillations during August 5–12. The elevation of the thermocline during this period is due to the downwelling of warmer hypolimnetic water caused by the westward winds during this period. As the winds decreased upwelling occurred and permitted colder epilimion water to approach the surface. We believe that similar processes occurred during 2006 and are responsible for the low water quality observed during August of that year by CWD.

Conclusions

Internal waves observed in the central basin of Lake Erie during August 2005 provide insight into conditions contributing to water quality problems experienced by the CWD during August 2006. While CWD measurements are likely aliased due to undersampling, the variation in oxygen and pH observed at the Crown water intake can be explained by a large amplitude internal wave. Strong and sustained winds beginning on August 11, 2006 likely caused the magnitude of the internal wave to increase. Temperature sensors deployed during August 2005 indicate oscillations resulting in low temperature water reaching the 16 m depth contour; only 1 m in depth away from CWD water intakes.

Hypoxic water not only negatively impacts water quality during the treatment process, but also has the potential to affect the public's confidence in the water distribution system. In response to events in 2006 impacting drinking water quality, future ReCON buoys will be deployed to provide early warning of hypoxic conditions in Lake Erie's central basin. The ReCON real-time data management system will report the onset of hypoxic conditions and hypolimnetic oscillations at the 20 m depth contour so that CWD water processing managers can put measures in

FIGURE 7

ReCON buoy deployed August 2005 recorded time series of temperatures at the epilimnion (black, 14 m), metalimnion (gray, 16 m), and hypolimnion (black, 18 m).

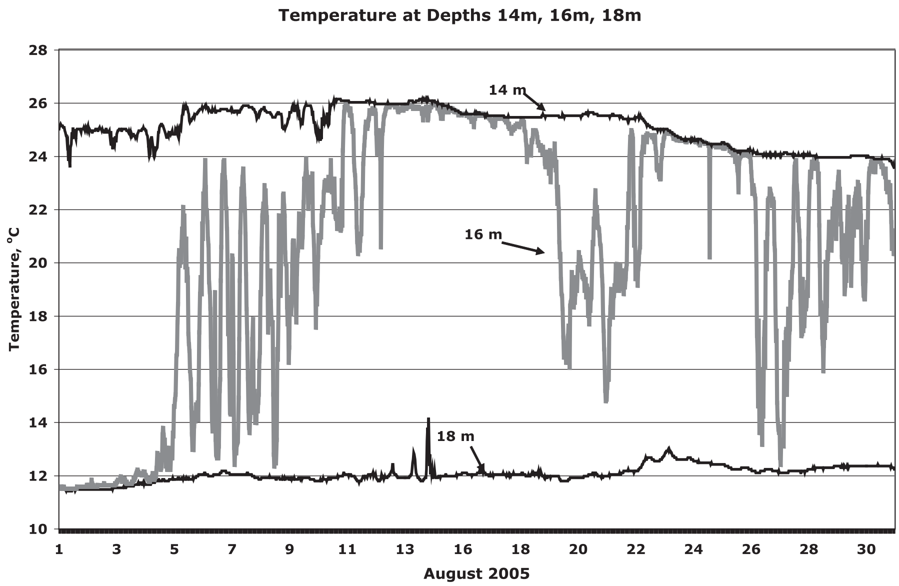
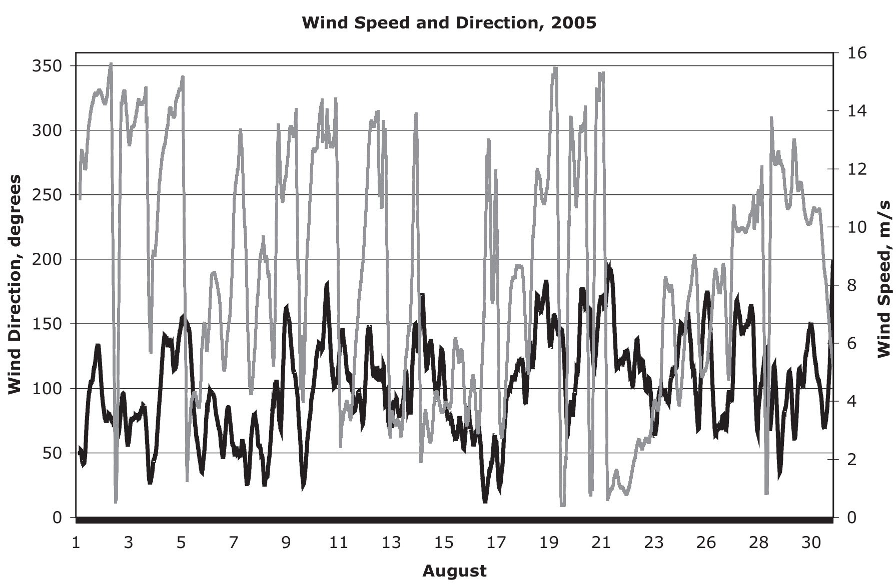


FIGURE 8

Wind speed (black) and direction (gray) from a ReCON buoy located approximately 22 km north of Cleveland in August 2005. Wind speed and direction have been smoothed using a 4-hour moving average.



place to make water treatment possible before a prolonged internal wave event begins to influence water intakes.

Warming climate trends have the potential to extend the period of lake stratification and so increase the probability that internal waves will deliver hypoxic water to municipal intakes along the southern coast of Lake Erie. In addition to Lake Erie, future observing systems would be appropriate for use throughout the Great Lakes providing real-time warnings of sudden environmental changes impacting drinking water processing such as temperature and pH changes, turbidity plumes, and harmful algal blooms. An operational buoy network has strong potential to meet the important societal need of ensuring the quality of drinking water for millions of Great Lakes residents.

Acknowledgments

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