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PAGES 313–324

Lake Erie Hypoxia Prompts Canada-U.S. Study

PAGES 313, 319

Because of its size and geometry, the central basin of Lake Erie, one of North America's Great Lakes, is subject to periods in the late summer when dissolved oxygen concentrations are low (hypoxia). An apparent increase in the occurrence of these eutrophic conditions and 'dead zones' in recent years has led to increased public concern. The International Field Years for Lake Erie (IFYLE) project of the Great Lakes Environmental Research Laboratory (GLERL, a U.S. National Oceanic and Atmospheric Administration (NOAA) laboratory), was established in 2005 in response to this increase.

This project is investigating the causes and consequences of hypoxia in the lake. As part of the effort, scientists from the United States and Canada conducted an extensive field study in 2005 to gather more information on the duration and extent of the hypoxic zone and its effects on the biota in the lake. This article gives a brief history and description of the problem and presents initial results from the field study.

Preliminary results from 2005 indicate that, when compared with data collected in the past 25 years, the hypoxic region was one of the largest (approximately 10,000 square kilometers) ever documented in the lake. This is about half the maximum size of the hypoxic area in the Gulf of Mexico [*Rabelais et al.*, 1999] and about five times larger than the maximum hypoxic area in the Chesapeake Bay [*Hagy et al.*, 2004].

Background on the International Field Years

The central basin of Lake Erie (Figure 1a) has a large area where the water depth is 20–25 meters. The water is deep enough to stratify during the late summer, and the ratio of surface area to hypolimnetic volume (the volume of colder water below the thermocline) is relatively large. These factors make the central basin susceptible to the development of hypoxia/anoxia. Near-equilibrium saturation of oxygen (13 milligrams O_2 per liter) occurs during the late winter–early spring, but isolation of the hypolimnion to re-aeration occurs as thermal stratification becomes established. The reservoir of oxygen within the hypolimnion then begins to be consumed by the settling and decomposition of sedimentary organic matter.

Hypoxia (less than two milligrams O_2 per liter) is considered stressful for all organisms, while concentrations below four milligrams O_2 per liter are stressful for fish. Anoxia (zero milligrams O_2 per liter) is not only deadly for biota, but is also a condition that initiates different microbial and geochemical reactions. The most pernicious of these reactions is the release of phosphorus from the large inventories in the bottom sediments. This may produce eutrophic conditions that are favorable for the development of harmful algal blooms.

Restoration of year-round aerobic conditions in the bottom waters of the central basin is one of the goals of the Great Lakes Water Quality Agreement negotiated between the United States and Canada in 1972. To accomplish this goal, the two governments agreed to reduce phosphorus loads to the lake to 11,000 metric tonnes per year. These goals were achieved by the late 1980s, when the magnitude of hypoxic events was reduced and the issue of oxygen depletion appeared to be solved.

By the 1990s, however, surveillance data collected by both the U.S. Environmental Protection Agency (EPA) and Environment Canada began to show both an increase in total phosphorus in the lake and an increase in the severity of hypoxic events. The reappearance of these conditions coincided with the establishment in the lake of zebra mussels, an exotic and fast-growing species. It was suggested that the zebra mussels were the cause of the changed conditions. However, other possible causes, including higher temperatures due to climate change, reduced water levels, and natural variability, may be equally important.

IFYLE originated largely from research hypotheses, ideas, and needs generated at the Lake Erie Science Planning Workshop in

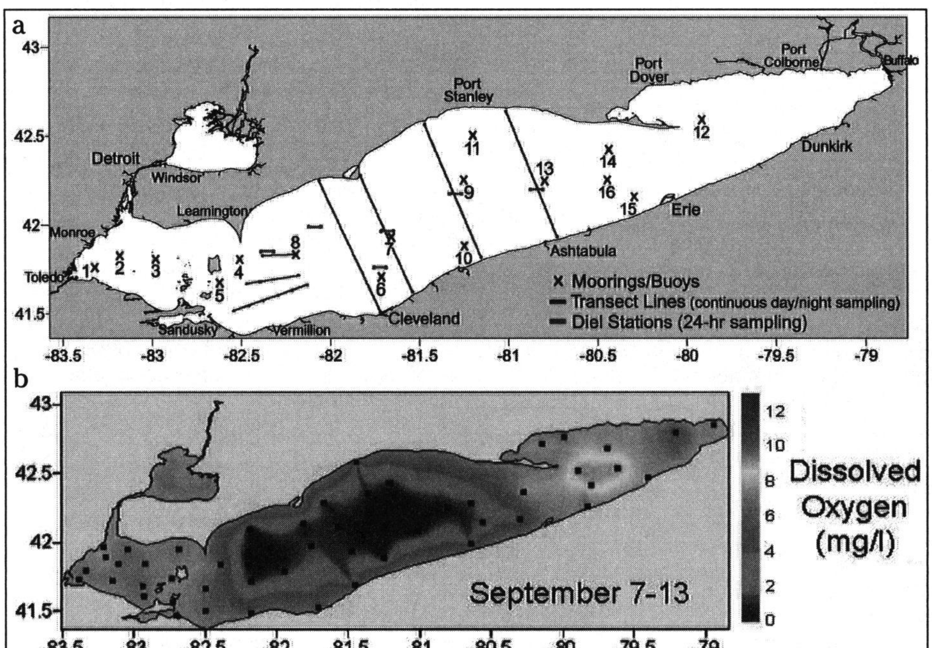

Fig. 1. (a) Map showing the locations of time series moorings (numbered crosses), transect lines (blue), and diel stations (red). (b) Map showing the locations of the fixed stations and the extent of hypoxia in September 2005. Original color image appears at the back of this volume.

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2004. Many of these ideas and hypotheses are based on monitoring data collected by the EPA and Environment Canada over the past 25 years, and on research performed by members of the Lake Erie Millennium network. One of the main goals of the program is to determine the causes and consequences of the apparent increase in hypoxia in the central basin. Other parts of the program (not reported here) address harmful algal blooms and the coupling of lake physics with forecasts of fish production. The program includes field measurements as well as the development of numerical models.

The 2005 Field Program

Efforts in 2005 were directed primarily toward a large field measurement program designed to collect data to (1) quantify the spatial extent of hypoxia across the lake and gather information that can help forecast its timing, duration, and extent, and (2) assess the ecological consequences of hypoxia to the Lake Erie food web. Four types of cruises were conducted each month from May to October. Figures 1a and 1b show the locations of the stations during the four cruise types.

Water samples were collected at 55 stations during the fixed-station cruises and analyzed for nutrients, size-fractionated chlorophyll, microbial communities, and other limnological characteristics such as temperature, dissolved oxygen, and light levels. Data from these cruises provide a synoptic picture of how conditions changed throughout the lake over time. During the transect and diel cruises—the latter being cruises during which samples are taken at the same station throughout the course of a 24-hour period—scientists sampled fish as well as their zooplankton and benthic macro-invertebrate prey. The buoy cruises were devoted to deploying and maintaining the array of moorings used to make time series observations of meteorological conditions, waves, currents, water temperature, dissolved oxygen, vertical mass flux, and water clarity.

The timing and spatial extent of thermal stratification and hypoxia were mapped during each of the fixed-station cruises. Thermal stratification was pronounced throughout the central basin starting in June, and hypoxia was observed at a subset of stations in the west central basin. Stratification strengthened throughout the summer, but hypolimnetic thickness varied considerably among stations, ranging from 0.9 to 5.3 meters in the central basin during September. The areal extent of hypoxia dramatically increased after August, and at its peak in September the hypoxic zone covered about 10,000 square kilometers, which includes most of the central basin where the water depth is greater than about 15 meters (Figure 1b).

The hypolimnetic oxygen depletion rate measured at 18 central basin stations averaged 0.12 milligrams per liter per day from July to September. This is well within the range of rates measured in previous years [*Rosa and Burns*, 1987] and suggests that the depletion rate has not changed significantly with time. However, the large spatial and temporal variations in oxygen depletion rates, as well as in hypolimnetic thickness, between individual stations did not allow us to determine the relationship between these parameters. Variations between individual stations confirm the need to use basin-scale surveys for comparing trends in hypoxia development over time.

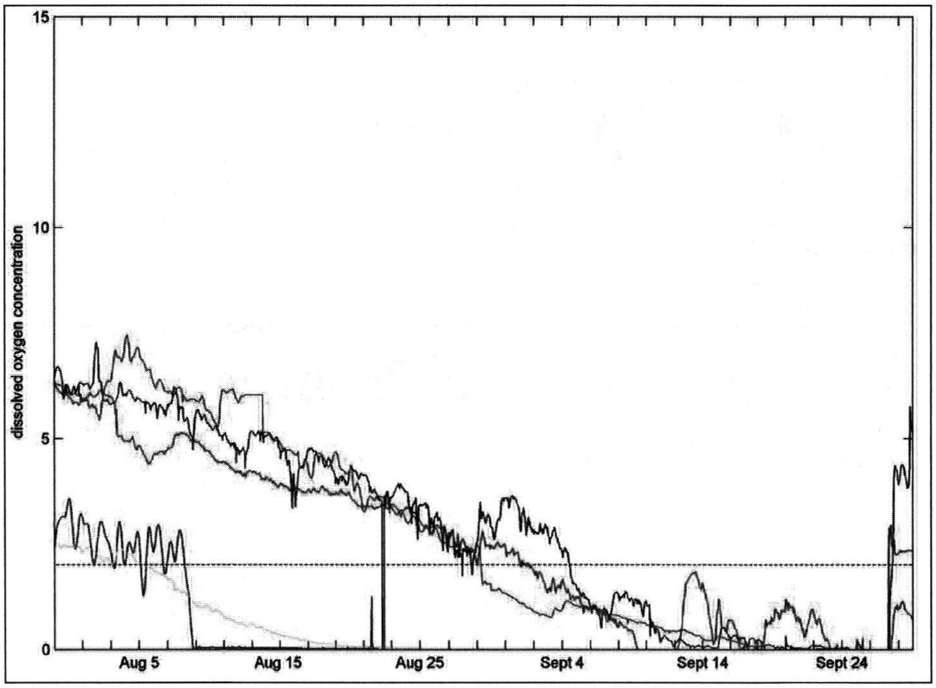

Fig. 2. Hourly measurements of dissolved oxygen concentration, in milligrams per liter, at stations 6 (red), 7 (black), 9 (yellow), 10 (magenta), and 13 (blue), in 2005. The dashed line shows the limit of hypoxic oxygen concentration (two milligrams per liter). Vertical lines indicate gaps in the data. Original color image appears at the back of this volume.

Time series measurements of water temperature and dissolved oxygen concentration were made at five sites in the central basin (stations 6, 7, 9, 10, and 13 in Figure 1a). Temperatures were measured throughout the water column at each station, while dissolved oxygen was measured approximately one meter above the bottom. Temperature data collected during August and September (not shown) indicate that all of the oxygen sensors were in the hypolimnion, the part of the lake below the thermocline. The dissolved oxygen measurements (Figure 2) show that dissolved oxygen concentration decreased to hypoxic levels at all of the stations by 27 August and remained low until late September, when a storm remixed the water column. The water remained mixed during October, and oxygen levels increased to about five milligrams per liter (not shown).

Numerical Modeling

IFYLE's ultimate modeling goal is to develop a coupled hydrodynamic–water quality model for the lake. A numerical model that calculates the currents and water temperature in the lake on a two-kilometer grid already is operational and eventually will be coupled with a water quality model. Daily tributary flows and hourly meteorological observations were retrieved for the years 1994 and 2004 (time series measurements of water temperature were made during these years), and complete hydrodynamic simulations were conducted. Model results for 1994 were combined with realistic phosphorus loadings from the tributaries to spatially and temporally simulate variable phosphorus concentrations in the lake. In addition, a coupled large basin runoff model was calibrated for a number of Great Lakes watersheds. In the future, this model will be interfaced to the hydrodynamic model to simulate tributary loadings of water, solids, and chemicals.

Future Work

In 2006, primary efforts will focus on analyzing the massive amount of information collected in 2005 and developing plans for additional field work in 2007. Results from the model simulations will be compared with the field measurements for 1994, a hydrodynamic simulation for 2005 will be conducted, and the development of a coupled hydrodynamic-water quality model will continue. The runoff model will be modified to include sediment erosion and deposition, transport of sediment and chemicals, and nonpoint-source distributions of materials, and the results will be compared with observations from selected Lake Erie watersheds.

Some preliminary results from the 2005 field program were presented at the Fourth Biennial Lake Erie Millennium meeting, held in Windsor, Ontario, 28 February–2 March 2006, and additional results were presented at the 49th meeting of the International Association of Great Lakes Research in Windsor on 22–26 May 2006. Specific hypotheses to be tested in 2007 will be developed as the data from 2005 become available. Additional information can be found at http://www.glerl.noaa.gov/ifyle

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Argo Floats Complement Biological Remote Sensing

PAGES 313, 320

Within the past decade, satellite observations of ocean color have provided a global view of biology within the ocean's surface layer and revealed how phytoplankton abundance varies in response to various physical forcings ranging from the large scales of seasonal cycles and the El Niño-Southern Oscillation, to planetary waves, eddies, and coastal filaments at smaller scales. The maturing Argo network of profiling floats now provides a way to put these remote sensing measurements into a vertical context.

The true test of any scientific discipline is prognostic capability. In physical oceanography, the ocean dynamics are fairly well understood, and their prediction hinges on the measurement of key variables at the proper spatial and temporal scales so as to validate and initialize models. Remote sensing coverage of these key parameters, such as sea surface temperature and height anomalies, has been available for 30 and 15 years, respectively. As a result, recent advances in numerical modeling are bringing operational forecasting of ocean circulation within reach.

However, many current and pressing problems in ocean sciences, such as those concerning anthropogenic impacts on the ocean and climate, also involve biological and chemical processes that have traditionally not been observed as extensively as physical ones.

At present, the only biological variable that can be resolved globally at close to its intrinsic scales of variability is chlorophyll concentration derived from satellite ocean color. Thus, it is often the only representation of ocean biology that can be coanalyzed with other satellite data sets to study such things as the forcing of biological variability by physical processes or the influence of biologically mediated environmental factors on the physical circulation.

The ready availability of chlorophyll data has helped make chlorophyll concentration an important variable in nearly every space-resolving ecological model, despite ongoing challenges in data assimilation and in converting pigment concentration to productivity or biomass units. However, the most significant limitation of remote sensing measurements is that they reflect only the conditions at the very surface of the ocean. Even ocean color is a heavily surface-weighted average of the first few tens of meters. Thus, interpreting data is challenging, especially with biological systems, because so much of their variability is associated with vertical processes that supply nutrient-rich waters from below to offset losses due to sinking particulate material.

The maturing Argo network now is alleviating this limitation. Argo complements satellite remote sensing because it provides in situ vertical information with some of the operational features that users have come to expect from remote sensing data: (1) Data are freely available from a single source; (2) Argo provides nearly global coverage at a spatial and temporal resolution suitable for many uses; and (3) data have consistent file structure for ease of use.

A Case Study Using Argo Floats

Argo is an international effort to seed the deep basins of the global ocean with some 3000 vertically profiling floats. As of late July this year, there are over 2480 active floats almost uniformly covering all ocean basins. (A global map of float locations can be viewed at http://www.argo.ucsd.edu) The floats drift at a nominal 1000-meter depth for nine days, then drop briefly to 2000 meters and rise to the surface, measuring temperature and salinity profiles along the way. Upon surfacing, location and profiles are transmitted via satellite to one of the data centers and made publicly available within hours.

While the intended purpose of the Argo array is to improve data coverage for physical oceanography and meteorology, especially for climate-related studies, there are many other uses that would benefit from its 10-day sampling period and average spatial separation of three degrees. The use of individual Argo profiles to supplement interdisciplinary remote sensing imagery is illustrated in Figure 1 with a time series of the 2004 spring bloom in the North Atlantic Ocean. Quick Scatterometer (QuikSCAT) wind stress is shown in the top plot of each panel as a proxy for wind mixing. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) five-day composite images show chlorophyll concentration (Chl) as a measure of the phytoplankton biomass, and temperature profiles from Argo floats give the depth of the mixed layer.

On 1 April (Figure 1a), spring bloom had already started on the continental shelf, but at the location of the profiles, stronger wind forcing has kept the mixed layer deeper than 100 meters, which reduced the average light level experienced by phytoplankton and prevented a bloom. After a period of calmer winds, on 10 April (Figure 1b) a warm, shallow surface layer developed and phytoplankton multiplied within it. By 22 April another storm deepened the mixed layer down to about 100 meters (Figure 1c). This drastically reduced the surface Chl but also replenished nutrients in the surface layer: In the affected area, spring bloom was ongoing by 5 May (Figure 1d) while it was almost over elsewhere.

By B. M. Uz

Page 313

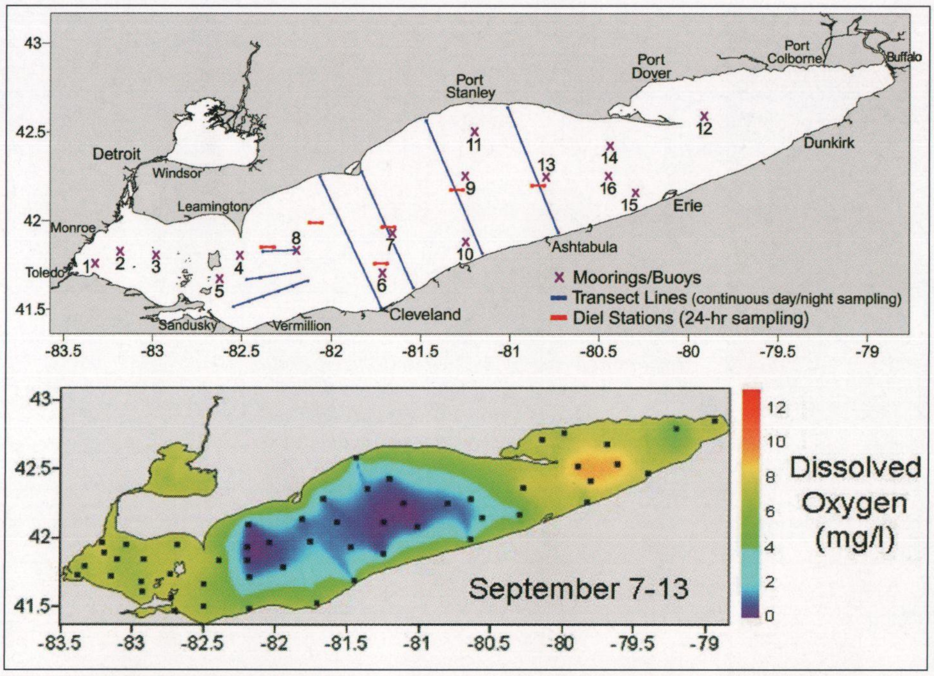


Fig. 1. (a) Map showing the locations of time series moorings (numbered crosses), transect lines (blue), and diel stations (red). (b) Map showing the locations of the fixed stations and the extent of hypoxia in September 2005.

Page 317

Fig 1. Crusader wall trending east-west was displaced by about 2.1 meters by an earthquake in 1202 A.D. at the Vadum Jacob archeological site. The two parallel lines bracket the Dead Sea fault zone.

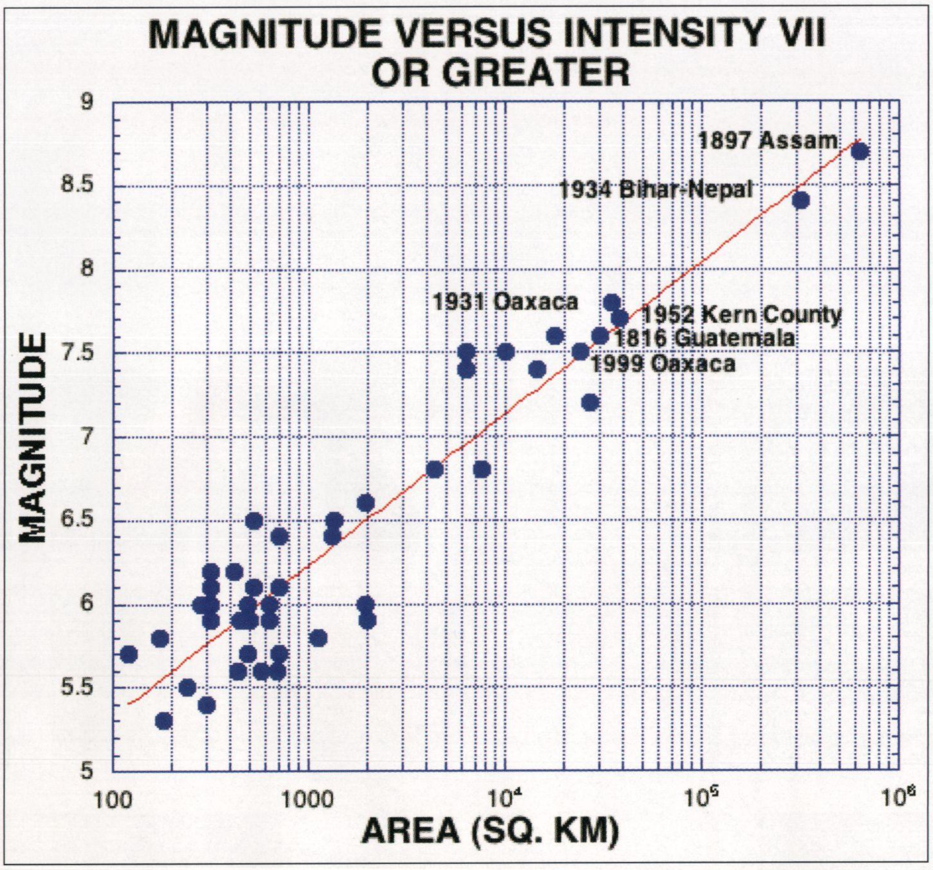
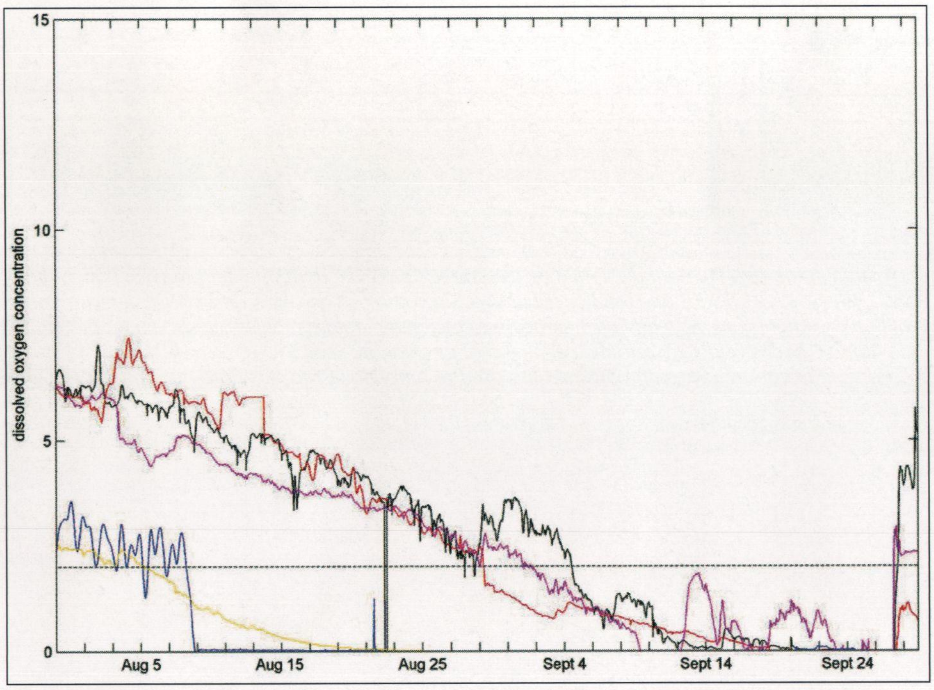


Fig. 2. Magnitude versus area of modified Mercalli intensity contour VII.

Page 317



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Page 319