J. Great Lakes Res. 31 (Supplement 2):262–271
Internat. Assoc. Great Lakes Res., 2005

Hypolimnetic Oxygen Depletion Dynamics in the Central Basin of Lake Erie

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ABSTRACT. *Hypolimnetic oxygen depletion has been recognized as a problem in the central basin of Lake Erie since the 1970s. However, recent expansion in distribution of the depletion after several years of low depletion rates in the 1990s has led investigators to explore the factors that influence the extent of the depletion. We have investigated the vertical oxygen budget in the central basin, which is influenced by the following factors: 1) vertical mixing; 2) exchange across the air-water interface; 3) photosynthesis; 4) respiration of plankton; and 5) sediment oxygen demand. We tested the importance of these factors using a 1-D vertical oxygen budget and transport simulations through sensitivity analysis and by estimating vertical mixing parameters using a temperature gradient microprofiler. Epilimnetic factors were found to be robust and the present monitoring efforts are sufficient; while epilimnetic production is ultimately the source of the hypolimnetic oxygen depletion, epilimnetic factors do not directly influence on hypolimnetic oxygen depletion. However, hypolimnetic depletion was sensitive to sediment oxygen demand and hypolimnion respiration, which are the results of primary production in the epilimnion, and hypolimnetic mixing, which is not related to eutrophication. These parameters, especially the physical mixing measurements, and their links with eutrophication and primary production require greater monitoring and analysis because of their influence on the expansion of oxygen depletion in the central basin of Lake Erie.*

INDEX WORDS: *Oxygen budget, Lake Erie, anoxia, hypoxia.*

INTRODUCTION

Periodic hypolimnetic anoxia existed in Lake Erie prior to European settlement (Delorme 1982). However, as early as 1960, cultural eutrophication was linked to increased occurrences of this anoxia in the central basin (Carr 1962). Schindler (1974) demonstrated the importance of phosphorus in freshwater cultural eutrophication, and then confirmed the phosphorus-eutrophication relationship with whole lake enrichment (Experimental Lakes Area ON, Canada; Schindler 1975). The role of phosphorus was similarly shown to be important in Lake Erie, with external loading of phosphorus into the lake from both point source (sewage effluent) and non-point source (agricultural and urban run-off) exceeding 25 thousand metric tons during the late 1960s and early 1970s (Janus and Vollenweider 1981).

Eutrophication, and the water quality issues associated with it including central basin hypoxia, led to the implementation of the Great Lakes Water Quality Agreement (GLWQA, IJC 1978). Bertram (1993) investigated the link between the eutrophication and hypolimnetic hypoxia from 1970–1991 and the effectiveness of the GLWQA in addressing the hypoxia problem and found that the reduction in phosphorus inputs coincided with reductions of total phosphorus in the water column with a subsequent reduction in hypolimnetic oxygen depletion rate (amount of oxygen lost in the hypolimnion per unit time) from the early 1970s until the early 1990s, though with large amounts of yearly varia-

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tion. The resurgence of mesotrophic species (Kane *et al.* 2004) and the shift from pelagic phytoplankton communities to benthic communities (Carrick 2004) indicated that Lake Erie was recovering from cultural eutrophication.

However, while eutrophication is a contributor to hypolimnetic hypoxia, physical forcers and oxygen transport may also be important. Rosa and Burns (1987) found that while there was an increase in oxygen depletion related to eutrophication from 1929 to 1980, the physics and shape of the lake influence hypoxia. Charlton (1980) looked at this relationship, and the relationship between hypolimnion thickness and oxygen depletion rate. As might be expected, decreased hypolimnion thickness increased the oxygen depletion rate. Further, this relationship held after the frequency of anoxia had decreased following the reductions in total phosphorus in the 1980s (Charlton 1987, Charlton *et al.* 1993). At the same time, the introduction of invasive benthic dreissenid mussels added another biological oxygen demand, further complicating the relationship between phosphorus controls and hypolimnetic hypoxia (Effler *et al.* 1998).

Oxygen budgets allow researchers to estimate effectiveness of management options and the relative importance of the various forcing functions. These oxygen models have recently been applied to study global hypoxia in aquatic ecosystems including rivers (Kirchesch *et al.* 1999), oceans (Sarma 2002), and small lakes (Joehnk and Umlauf 2001). Patterson *et al.* (1985) developed a comprehensive oxygen budget for the central basin of Lake Erie in the summer and observed that six factors influence the vertical oxygen budget in the central basin: (1) vertical mixing; (2) exchange across the air-water interface; (3) photosynthesis; (4) community respiration; (5) sediment oxygen demand including benthic respiration; and, (6) horizontal transport. Parameterizing these influences on the oxygen budget, Patterson *et al.* were able to predict changes in vertical oxygen profiles and to estimate the relative importance of each factor under various environmental conditions.

However, since this budget was tested in 1980, the trophic status of the Lake Erie has undergone profound changes, primarily due to the reduction in phosphorus loading into the lake and due to the introduction of the dreissenid mussels, both of which may have a strong influence on oxygen dynamics. Though external phosphorus loading was reduced to target levels since the mid 1980s (Dolan 1993, Dolan and McGunagle 2005), internal nutrient recycling may be increasing due to the exotic dreissenids (Conroy *et al.* 2005, James *et al.* 1997). Arnott and Vanni (1996) demonstrated that mussels excreted nitrogen and phosphorus at high rates and low N:P levels, which may shift the trophic status of the lake toward the conditions prevalent in the 1960s and 1970s. In addition to the predicted nutrient loading by mussels, other observations have indicated Lake Erie is returning to more eutrophic conditions. Planktonic communities have shown a resurgence of eutrophic taxa and increased biomass (Conroy *et al.* 2005) at the same time that total phosphorus concentrations in the water column are rebounding from lows in the early 1990s (Rockwell and Warren 2005).

In this manuscript, we apply a vertical oxygen budget model to the central basin of Lake Erie, and used measured and literature values for model parameterization. As mentioned above, the physical processes influencing hypolimnion hypoxia are important in the Lake Erie central basin. We therefore use a temperature gradient microprofiler to characterize the magnitude of mixing processes, incorporating this information into the oxygen budget. We use the budget to conduct a sensitivity analysis to determine the most important factors in the development of hypolimnetic hypoxia. We then test whether hypolimnetic mixing remains the most important factor (Patterson *et al.* 1985), and whether the parameters influenced by phosphorus loading are yet important to hypolimnetic hypoxia development, and thus may be influenced via control of external nutrient loading.

METHODS

Field Methods

Field methods for the initial parameterization of the model were conducted as part of the Lake Erie Trophic Status project aboard the USEPA *RV Lake Guardian*. A temperature gradient microprofiler (SCAMP, Precision Measurements Engineering) was used to sample temperature, temperature gradients, and oxygen at one millimeter resolution (SCAMP decent rate of 10 cm/s and sampling frequency 100 Hz), while fluorescence and Photosynthetically Active Radiation (PAR) profiles were sampled at 10 mm resolution. Two profiles of each parameter were sampled at each of the ten USEPA sampling sites in the Lake Erie central basin in August 2003 (Fig. 1). Corresponding wind surface speeds were obtained from NOAA (Cleveland) and averaged across the sampling period. Additional pa-