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A model of the stratification and hypoxia in central Lake Erie

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Abstract

A two-dimensional reservoir model was applied to simulate the vertical-longitudinal hydrodynamics and water quality in Lake Erie during 1994. Central basin hypolimnetic anoxia was modelled to occur where the metalimnion intersected the sloping lake-bed, thus inhibiting diapycnal diffusion of dissolved oxygen (DO) through the water-column directly overlying the sediments. Using a sediment oxygen demand SOD $= 0.55$ gm^{2}d^{-1}, a threshold near bed buoyancy frequency criterion $N^2_{bed} > 10^{-3}$ s^{-2} was required for significant hypolimnetic DO depletion (DO $<$5 mgL^{-1}). Sensitivity analysis demonstrated that the pattern of near-bed depletion could be modelled to within ~ 2 mgL^{-1} by considering only surface and sediment DO fluxes; where nutrient loads and the remaining biogeochemistry were neglected within the model framework. Generalization to the SOD versus N^2_{bed} domain, suggests that for 1994 conditions SOD < 0.2 gm^{2}d^{-1} would ensure a near bed DO concentration greater than 5 mgL^{-1}; sufficient to support fish life.

1. Introduction

A significant decline in the water quality of Lake Erie (Fig. 1) occurred between the 1950s and 1970s due to the influx of phosphorus from agriculture, industrialization and urbanization. As the capacity of the lake to absorb waste was exceeded, western basin eutrophication and central basin hypolimnetic anoxia occurred. Billions of dollars have been spent on remedial programs aimed at improving water quality by controlling nutrient loads. Through the 1980s and 1990s these measures eliminated eutrophication, but persistent hypoxia remains in the central basin over a roughly 10,000 km^2 region.

An analysis of sediment cores (Delorme, 1982) concluded that periodic anoxia has occurred as a symptom of eutrophication for hundreds, maybe thousands, of years in the central basin of Lake Erie. However, the influence of cultural eutrophication in enhancing central

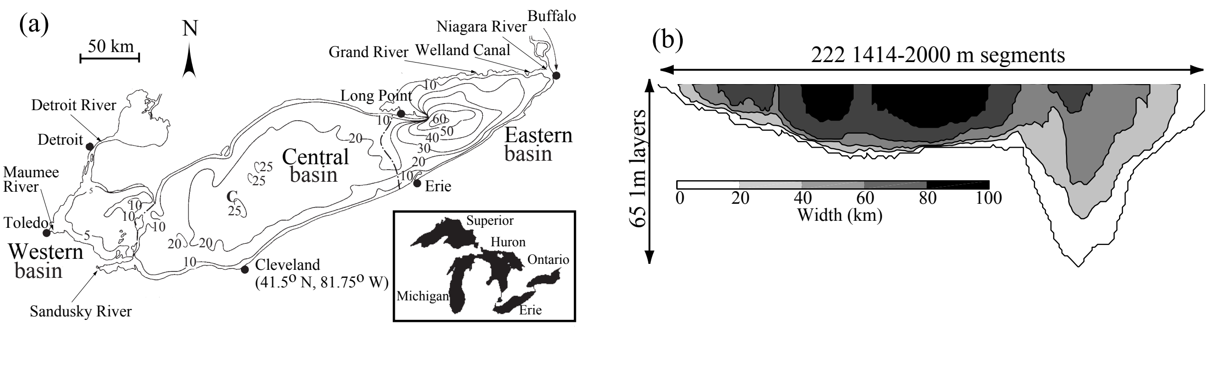

Figure 1: (a) Lake Erie bathymetric plan view (depths in m). (b) CE-QUAL-W2 solution plane (longitudinal cross-section) showing width contours.

basin anoxia remains unclear. Analysis of field data by Rosa and Burns (1987) suggests that hypolimnetic oxygen depletion rates have been steadily increasing during 1929-80. However, Charlton (1987) argues that an increasing trend in oxygen depletion is not apparent during this time and depletion rates fluctuate naturally with trophic conditions and physical factors such as the hypolimnion thickness and temperature. In Charlton's argument, the effects of phosphorus controls on oxygen depletion would be minimal.

Central basin oxygen dynamics have been investigated using one-dimensional (vertical) oxygen/temperature models. Patterson et al. (1985) found that production and respiration dominated the water-column oxygen budget during low wind speeds, while surface fluxes dominated during periods of high wind. Bottom mixing was found to delay the onset of anoxia by distributing the sediment oxygen demand (SOD) through the hypolimnion. Lam and Schertzer (1987) also found physical factors important in regulating hypolimnetic anoxia. A hypolimnion thickness of less than 4 m and a turbulent diffusivity less than 1 cm^2s^{-1} increased the likelihood of anoxia development in the central basin. More recently, Edwards et al. (2005) found hypolimnetic oxygen depletion to be sensitive to SOD, hypolimnetic respiration and hypolimnetic mixing. All of these studies demonstrate that, while primary production in the epilimnion is the ultimate driver of hypolimnetic anoxia through establishment of the SOD, hypolimnetic mixing and hence stratification are key factors influencing the frequency of occurrence.

The objective of this study is to isolate the effects of stratification on the formation of hypolimnetic anoxia. This is accomplished by applying a computational hydrodynamic and water quality model to Lake Erie that is validated against field data from 1994 and data characteristic to the late 1960s. The effects of stratification on DO are isolated by switching off components of the biogeochemistry within the model framework.

2. Methods

The two-dimensional hydrodynamic and water-quality reservoir model, CE-QUAL-W2 version 2.11 was applied to model the hydrodynamics and nutrient, algae and dissolved oxygen (DO) dynamics in Lake Erie. The model has been extended to include a multi-parameter zebra mussel and zooplankton module (Boegman et al., 2006). CE-QUAL-W2 resolves the longitudinal and vertical reservoir axes, and is well suited for application to relatively long, narrow water bodies such as Lake Erie, which has a 6:1 aspect ratio (Fig. 1). The longitudinal coordinate direction was aligned with the lake's longitudinal axis, corresponding to the direction of hydraulic flow, the strongest seiche and storm surge movements, and gradients in temperature, nutrient concentration and plankton biomass. The vertical coordinate direction resolves the vertical thermal structure, which supports internal waves, regulates the rate of vertical mixing and hence the vertical distribution of oxygen. The model has been shown to provide an accurate simulation of the May through October 1994 vertical-longitudinal hydrodynamics, temperature field and water-quality structure (Boegman et al., 2001, 2006). In all simulations, unless otherwise noted, the DO field was initialized at 12 mgL^{-1} and SOD = 0.55 gm^2d^{-1}.

3. Results

3.1. Temperature field

The vertical variations in water temperature predicted by the model at station C (Fig. 1) are very similar to those found in the observed data for this location during 1994 (Fig. 2). The degree of stratification increased through June, culminating with a firmly established thermocline at a depth of approximately 20 m by 15 July (day 196). The distinct near-bed thermocline persisted through the end of the simulation on Sept. 26 (day 269). These observations are typical for central Lake Erie.

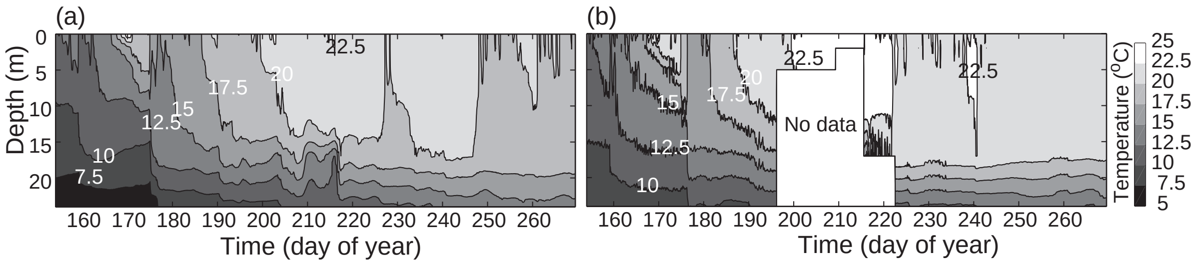

Figure 2: Depth versus time isotherms comparing the (a) modelled and (b) observed temperature profile at central basin station C. The isotherm contour interval is 2.5^{o}C.

3.2. Dissolved oxygen

The simulated 1994 summer DO (laterally averaged) was compared to three sets of mid-lake vertical profiles at 13 stations distributed along the longitudinal axis of the lake (Fig. 3). In general, the field observations and model compare favourably. The model does not reproduce the higher observed DO in the central basin epilimnion (segments 85 to 125 during Aug.) and the western basin (segments 1 to 20 during Jun. through Aug.). Prior to seasonal stratification, both the observed and modelled DO were relatively constant with depth throughout the lake. The DO was lowest in the warm, shallow western basin and highest in the deep, cold eastern basin. With the progression of summer, the characteristic deoxygenation of the central basin hypolimnion was both modelled and observed.

3.3. Coupling between stratification and dissolved oxygen

The two-dimensional model formulation employed in this study allowed investigation of the spatial correlations between stratification and DO. During June and July, differential heating between the western and central basins caused the thermocline to intersect the lake-bed along the sloping transition between these basins, near segment 50 (Fig. 4a,b). At this location, oxygen depletion was modelled to occur directly above the sediments (Fig. 4e,f). The deeper mid-central basin hypolimnion, near segment 100, remained weakly stratified with DO $>$ 6 mgL^{-1}. The characteristic deepening and sharpening of the central basin seasonal thermocline from summer heat input (Fig. 3c,d) caused the intersection zone of the metalimnion with the lake-bed to move eastward into the deeper mid-central basin. The anoxic zone followed this migration (Fig. 3g,h). These results are in agreement with those of the one-dimensional studies described above, in which local stratification has a strong influence upon the temporal occurrence of central basin anoxia.

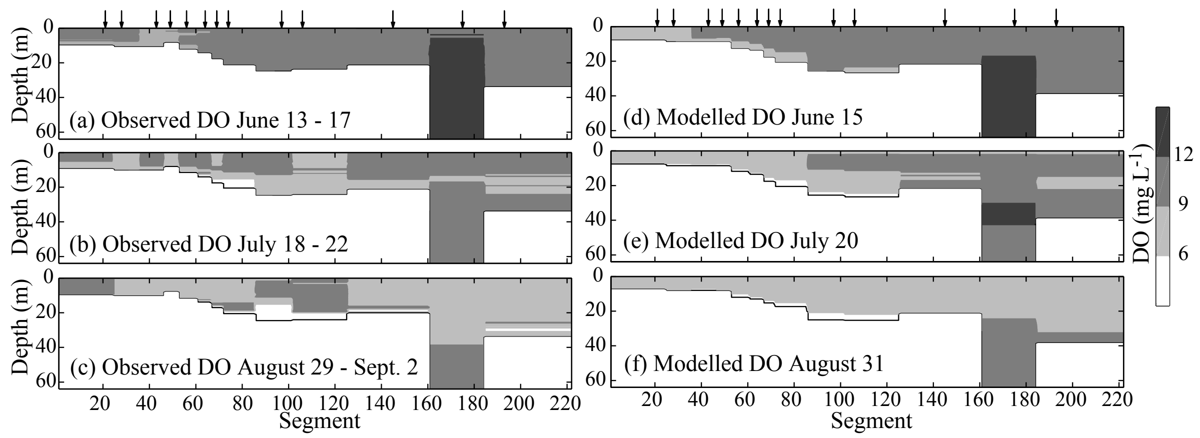

Figure 3: Modelled and observed (mid-lake) DO profiles. Both the modelled and the field data are longitudinal interpolations from profiles at the locations indicated by the arrows.

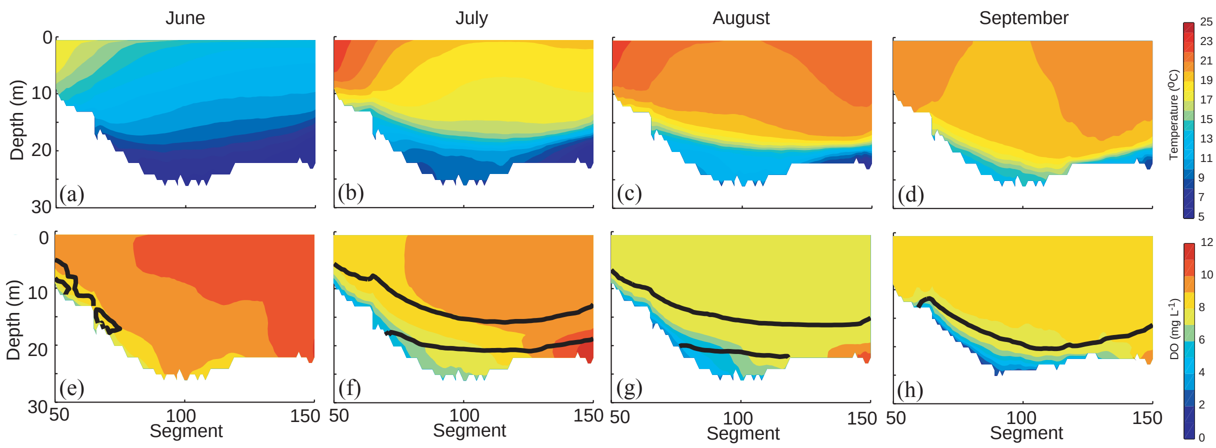

Figure 4: Contours of modelled 1994 water temperature (1^oC) and DO concentration (1 mgL^{-1}) in the central basin. Data are monthly averages of daily output. The thick black line denotes the $N^2 = 10^{-3}$ s^{-2} contour. Between these lines $N^2 > 10^{-3}$ s^{-2}.

It is proposed that the coupling between hypolimnetic oxygen depletion and near-bed stratification results from oxygen being depleted directly above the sediments while stratification inhibits replenishment via vertical transport of oxygenated near-surface water. In central Lake Erie, the degree of stratification is controlled by surface thermodynamics and vertical turbulent mixing. The degree of stratification in the water-column can be quantified according to the buoyancy frequency $N^2 = -(g/\rho_o)(\partial\rho/\partial z)$, where g is the gravitational constant, ρ_o=1000 kgm^{-3} is the characteristic water density, $\rho(z)$ is the water-column density profile and z is the vertical coordinate (positive upwards). Typically in lakes 10^{-10}s^{-2} $< N^2 < 10^{-1}$ s^{-2}. In Fig. 4e-h, a threshold criterion of $N^2 > 10^{-3}$ s^{-2} at the sediment-water interface is shown to be sufficient to induce localized near-bed oxygen depletion.

Correlations between N^2, DO and SOD were further examined by plotting DO as a function of N^2 and the height above bottom, H (Fig. 5a). For $N^2 >\sim 10^{-4}$ s^{-2}, DO depletion increases toward the lake-bed where the SOD is applied. The DO depletion at

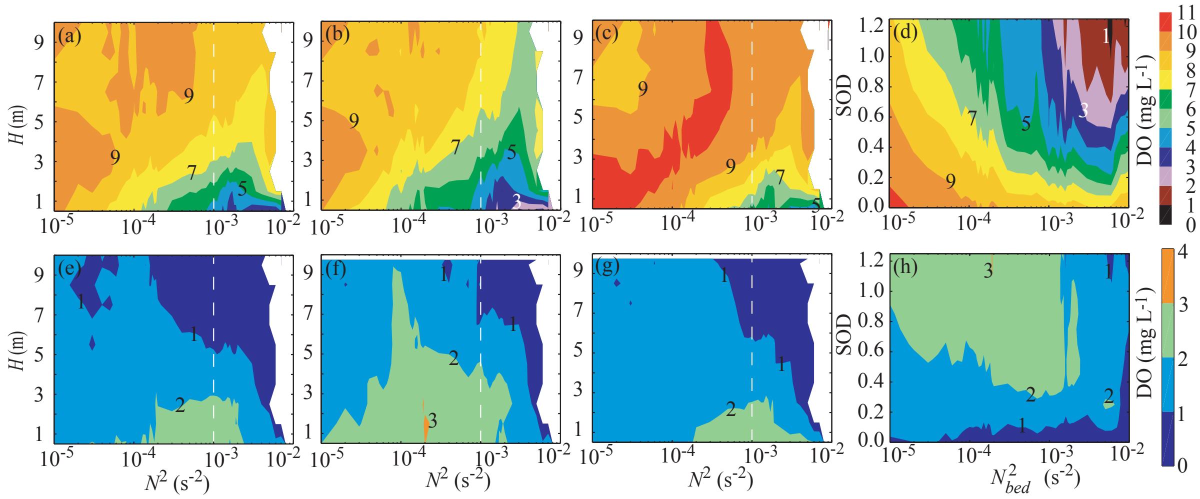

Figure 5: Contour plot of mean DO concentration in the H versus N^2 domain for (a) 1994 loads, (b) late 1960s loads and (c) surface DO flux and SOD only. Dashed white line denotes $N^2 = 10^{-3}$ s^{-2}, as indicated in Fig. 4. Data are monthly averages of daily output that have been bin-averaged with corresponding standard deviations in panels (e) to (h). The closest computational point to the lake-bed is $H = 0.5$ m; here $N^2 = N^2_{bed}$.

the bed increases in proportion to N^2; demonstrating the significance of the local degree of stratification. These data have been bin-averaged from Fig. 4 and have a standard deviation less than 3 mgL^{-1} (Fig. 5e).

3.4. Sensitivity analysis

A sensitivity analysis was performed to investigate the roles of nutrient loads, biogeochemistry and SOD on the near-bed DO concentration. The first simulation applied 1994 conditions without nutrient loads, resulting in a negligible change in DO concentration relative to Fig. 5a (not shown). The second simulation examined the impacts of cultural eutrophication by applying increased phosphorus and decreased nitrogen loads characteristic to the late 1960s (Boegman et al., 2006); 1994 meteorological forcing was applied. For this simulation, enhanced primary production occurred causing a near uniform ~ 1 mgL^{-1} decrease in DO concentration throughout the domain (Fig. 5b). The third simulation isolated the effects of stratification from production and respiration by switching off all biogeochemistry except for the free-surface oxygen flux and the SOD within the model framework. For this simulation, a near uniform 2 mgL^{-1} increase in DO concentration occurred throughout the domain (Fig. 5c).

These simulations demonstrate that nutrient loads and respiration/production have a relatively uniform effect on the modelled DO concentration in H versus N^2 space, where $H < 10$ m. That these factors do not significantly influence the spatial pattern of DO depletion suggests that nutrient loads and respiration/production are important in regulating the ambient DO levels throughout this portion of the water-column, but do not specifically control the formation of near-bed DO depletion. This is modelled to be a function of N^2 and the proximity of a water parcel to the SOD as given by the height above the sediments, H.

The sensitivity of the 1994 simulations to SOD were also investigated. At $H = 0.5$ m in the central basin (Fig. 5d), the DO concentration is modelled to decrease with increasing SOD and increasing N^2_{bed}. For 1994 conditions, SOD < 0.2 gm^{2}d^{-1} would ensure a near-bed DO concentration greater than 5 ± 3 mgL^{-1} (mean $\pm$ standard deviation); sufficient for the support of fishlife, as mandated by the Great Lakes Water Quality Agreement.

4. Conclusions

The occurrence of near-bed oxygen depletion in central Lake Erie was modelled as a function of N^2_{bed} and SOD. As mixing erodes stratification, this model is consistent with the inverse correlation between hypolimnetic mixing and anoxia (Patterson et al., 1985; Lam and Schertzer, 1987). Variation of nutrient loads and respiration/production modulated the severity of depletion by ~ 2 mgL^{-1}. These findings suggest that the shallow basin morphology causes a natural regime atypical to the Great Lakes Region, where the metalimnion intersects the sediments over a large off-shore area; thus favouring oxygen depletion. This conjecture is supported by the findings of Delorme (1982). To fully utilize N^2_{bed} and SOD as predictors for anoxic events, the variability in these functions must be related to external forcing such as climate and nutrient loads.

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References

Boegman, L., Loewen, M. R., Culver, D. A., Hamblin, P. F., and Charlton, M. (2006). Spatial-dynamic modelling of algal biomass in Lake Erie: Relative impacts of zebra mussels and nutrient loads. *J. Water Resour. Plng. and Mgmt. - ASCE*, (Submitted).

Boegman, L., Loewen, M. R., Hamblin, P. F., and Culver, D. A. (2001). Application of a two-dimensional hydrodynamic reservoir model to Lake Erie. *Can. J. Fish. Aquat. Sci.*, 58:859–869.

Charlton, M. N. (1987). Lake Erie oxygen revisited. *J. Great Lakes Res.*, 13(4):697–708.

Delorme, L. D. (1982). Lake Erie oxygen: the prehistoric record. *Can. J. Fish. Aquat. Sci.*, 39:1021–1029.

Edwards, W. J., Conroy, J. D., and Culver, D. A. (2005). Hypolimnetic oxygen depletion dynamics in the central basin of Lake Erie. *J. Great Lakes Res.*, 31 (Sup. 2):262–271.

Lam, D. C. and Schertzer, W. M. (1987). Lake Erie thermocline model results: comparison with 1967-1982 data and relation to anoxic occurrences. *J. Great Lakes Res.*, 13(4):757–769.

Patterson, J. C., Allanson, B. R., and Ivey, G. N. (1985). A dissolved oxygen budget for Lake Erie in summer. *Freshwater Biology*, 15:683–694.

Rosa, F. and Burns, N. M. (1987). Lake Erie central basin oxygen depletion changes from 1929-1980. *J. Great Lakes Res.*, 13(4):684–696.