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Modeling as a Tool for Nutrient Management in Lake Erie: A Hydrodynamics Study

By: L.F. Leon, J. Imberger, R.E.H. Smith, R.E. Hecky, D.C.L. Lam and W.M. Schertzer

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In a Briefing Note

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Abstract

The introduction of the zebra mussel into Lake Erie has raised some concerns about their potential impact on water quality, particularly with respect to nutrients (phosphorus) dynamics. Coupled physical-biological numerical models are useful tools for understanding the relevant processes and the influence of biota and human activity on the ecological conditions in the lake and such a suite of models has been used to assess the impact of zebra mussels on the nutrient cycling in the lake.

This paper presents the hydrodynamic part of an integrated modelling study to understand these physical and ecological processes. Validation runs were performed with 1994 and 2001 data. Vertical thermistor chain data is compared against model calculations and mean circulation patterns are presented for the different runs. The validated model was then used to understand the flushing of the deep water, the internal wave weather and the residual circulation.

La modélisation comme outil de gestion des nutriments du lac Érié : une étude hydrodynamique

L. F. León, J. Imberger, R. E. H. Smith, R. E. Hecky, D. C. L. Lam et

W. M. Schertzer

Résumé

L'introduction de la moule zébrée dans le lac Érié a soulevé certaines préoccupations relatives à l'impact potentiel de l'espèce sur la qualité de l'eau, en particulier sur la dynamique des nutriments (phosphore). Les modèles numériques couplés physique-biologie sont des outils pratiques pour comprendre les processus pertinents ainsi que l'influence du biote et de l'activité humaine sur l'écologie du lac. Une suite de ces modèles a été utilisée pour évaluer l'impact des moules zébrées sur le cycle des nutriments du lac.

Les auteurs présentent la partie hydrodynamique d'une étude de modélisation intégrée visant à comprendre les processus physiques et écologiques. Les séries de validation ont été réalisées avec des données de 1994 et 2001. Les mesures sur la verticale fournies par les chaînes de thermistance sont comparées avec les calculs des modèles, et les régimes moyens de circulation sont établis pour les différentes séries. Le modèle validé est ensuite utilisé pour comprendre l'écoulement des eaux profondes, la température de l'onde interne et la circulation résiduelle.

NWRI RESEARCH SUMMARY

Plain language title

NWRI modeling study relates lake circulations and temperature distributions to Lake Erie water quality conditions

What is the problem and what do sicentists already know about it?

.Nutrient conditions in Lake Erie are affected by invading species. Scientists already know species such as zebra mussel can uptake nutrients and act as filter to these nutrients thereby affecting water quality conditions. The understanding of lake physics has also led scientists to develop simulation models for water movements and temperature in the lake. It is now possible to simulate the three-dimensional velocity components and thermal processes in the lake.

Why did NWRI do this study?

.To prove the hypothesis that the life cycles of the invading species such as zebra mussel are affected by water circulations and temperature, this study used a three-dimensional hydrodynamic model to simulate the water circulation and temperature over a period where zebra mussel measurements as well as water quality variables were observed. By comparing the physical model results with observed biological and chemical data, we gained important scientific insight on the life cycles and behaviour of zebra mussel and the water quality condition in Lake Erie.

What were the results?

.The results showed that persistent circulation gyres existed in Lake Erie during spring and summer periods where zebra mussels underwent important life cycle stages. The thermal stratification in Central and Eastern Basin of Lake Erie also affected the nutrient distribution. It was found that zebra mussels exert their greatest effects, in terms of re-directing nutrients and biomass from water column to the benthos, where water depths are shallow enough and mixing sufficiently vigorous that they can access a large fraction of the planktonic community from their benthic position. The magnitude of their effects will depend not only on water depth and mussel abundance, but also on the retention time of water masses in shallow and/or nearshore areas.

How will these results be used?

The results will contribute to better understanding of the interactions between physical, biological and chemical processes in Lake Erie. They can be used for consideration by the Lake Erie Lakewide Management Plan (LaMP). They can be also used to design an integrated set of observational programs to monitoring the water quality conditions in the lake.

Who were our main partners in the study?

University of Waterloo; University of Guelph, University of Western Australia

Sommaire des recherches de l'INRE

Titre en langage clair

Les études de modélisation de l'INRE relient les régimes de circulation et la répartition des températures du lac Érié aux conditions de qualité de l'eau.

Quel est le problème et que savent les chercheurs à ce sujet?

Les espèces envahissantes exercent une action sur les nutriments du lac Érié. Les scientifiques savent déjà que des espèces connues, comme la moule zébrée, captent et filtrent les nutriments, ce qui modifie la qualité de l'eau. La compréhension de la physique du milieu lacustre a également permis aux scientifiques de mettre au point des modèles de simulation pour les mouvements de l'eau et la température du lac. Il est désormais possible de simuler en trois dimensions les composantes de la vitesse de circulation et les processus thermiques dans le lac.

Pourquoi l'INRE a-t-il effectué cette étude?

.Afin de vérifier l'hypothèse que les cycles de vie des espèces envahissantes comme la moule zébrée sont modifiés par la circulation et la température de l'eau, les auteurs de l'étude ont utilisé un modèle hydrodynamique à trois dimensions pour simuler les conditions de circulation et de température sur une période de temps au cours de laquelle les mesures relatives à la moule zébrée ont été prises et les variables de la qualité de l'eau, observées. La comparaison des résultats des modèles physiques avec les observations biologiques et chimiques a fourni des indications scientifiques importantes sur les cycles de vie et le comportement de la moule zébrée ainsi que les conditions de la qualité de l'eau du lac Érié.

Quels sont les résultats?

.Les résultats ont montré qu'il y avait des mouvements giratoires persistants dans le lac Érié au printemps et à l'été au moment où les moules zébrées franchissent d'importantes étapes du cycle de vie. La stratification thermique des bassins du centre et de l'est du lac Érié influe aussi sur la distribution des nutriments. On a découvert que les moules zébrées produisaient le plus d'effets, en ce qui concerne la réorientation des nutriments et de la biomasse, des colonnes d'eau au benthos, dans des eaux suffisamment peu profondes et où le mélange était suffisamment vigoureux pour que les moules puissent accéder à une large fraction de la communauté planctonique de leur position benthique. L'ampleur de leurs effets dépend non seulement de la profondeur de l'eau et de l'abondance des moules, mais aussi du temps de rétention des masses d'eau dans les zones peu profondes ou à proximité des côtes.

Comment ces résultats seront-ils utilisés?

Les résultats vont aider à mieux comprendre les interactions des processus physiques, biologiques et chimiques du lac Érié. Ils peuvent être considérés aux fins du Plan d'aménagement panlacustre (PAP) du lac Érié, et aussi être utilisés pour créer une série intégrée de programmes d'observation pour contrôler les caractéristiques de la qualité de l'eau du lac.

Quels étaient nos principaux partenaires dans cette étude?

University of Waterloo, University of Guelph et University of Western Australia.

Modeling as a Tool for Nutrient Management in Lake Erie: A Hydrodynamics Study

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[1]University of Waterloo, Waterloo, Ontario, Canada.
[2]Centre for Water Research, University of Western Australia, Crawley, Western Australia, Australia.
[3]Environment Canada, National Water Research Institute, Burlington, Ontario, Canada.

Abstract

The introduction of the zebra mussel into Lake Erie has raised some concerns about their potential impact on water quality, particularly with respect to nutrients (phosphorus) dynamics. Coupled physical-biological numerical models are useful tools for understanding the relevant processes and the influence of biota and human activity on the ecological conditions in the lake and such a suite of models has been used to assess the impact of zebra mussels on the nutrient cycling in the lake.

This paper presents the hydrodynamic part of the modeling in the lake using the 3D ELCOM model. Validation runs were performed with 1994 and 2001 data. Vertical thermistor chain data is compared against model calculations and mean circulation patterns are presented for the different runs. The validated model was then used to understand the flushing of the deep water, the internal wave weather and the residual circulation.

Introduction

The introduction of the zebra mussel in Lake Erie has raised concerns on their potential impact on water quality, particularly in the nutrients (phosphorus) dynamics. Recent studies (Charlton, 2001; Boegman *et al.*, 2000; MacIsaac *et al.*, 1999; Charlton *et al.*, 1999) show, through the use of models, the potential impact of the arrival of the zebra mussel on the water quality of Lake Erie. Lam *et al.*, (2002), used a 9- compartment box water quality model (Lam *et al.*, 1987), to study the sensitivity of model parameters in order to assess the potential effect of zebra mussels on the total phosphorus concentration in Lake Erie since their arrival.

Such concern over water quality in the Great Lakes during recent years has given rise to the intention of applying coupled physical-biological numerical models as tools for understanding the relevant processes and the influence of biota and of human activity on the ecological conditions. The aim is to predict the effect of changing conditions and to simulate the input and dispersion of contaminants. During the last decades a series of

three-dimensional hydrodynamic models have been developed at different research institutes. An overview can be found in Lynch and Davies (1995) which includes the well known Princeton Ocean Model (Blumberg and Mellor, 1987). In recent years some of these models have been coupled with biological modules, sediment and contaminant transport models (Ahsan *et al.*, 1999; Imberger 1994; Dallimore *et al.*, 2001; Luyten *et al.*, 1999).

Schertzer (1999), provided a review of physical limnological characteristics on Lake Erie with emphasis on dynamical processes and currents. Water movements are complex in Lake Erie due to the fact that water exchange occurs between the three distinct basins of the lake and the mixing processes are affected by thermal stratification. Major water exchanges occur between the basins through hydraulic flow, flushing processes and horizontal mixing (Bartish, 1987). Intrusion of near anoxic central basin water into the shallower west basin can have biological implications. On the other hand, horizontal exchange of colder water from the east to central basins is one mechanism of oxygen renewal in the central basin (Boyce et al., 1980 and Chiocchio, 1981).

Circulation patterns have been defined from observed and simulated values. Summer patterns had a consistent circulation scheme from east to west, including a main basin clockwise flow pattern in the middle of the central basin and a dominant anticlockwise current in the east basin (Saylor and Miller, 1987). Current measurements have identified such large scale circulation patterns, including gyres in the central and east basins and a narrow east current along the north shores of the lake. Many of the features suggested by Saylor and Miller (1987), including the clock and anticlockwise gyres, are simulated in the numerical model results presented in this study.

The 3D Model

Hydrodynamic modeling is the appropriate transport foundation for an accurate lake mass balance model, for two reasons. First, a hydrodynamic model offers a basis for simulating transport in response to meteorological forcing functions. Second, hydrodynamic model results are scaleable and provide transport magnitudes at the desired spatial and temporal resolution. This is useful when considering that the various processes incorporated in the mass balance are not necessarily modeled at the same scale or resolution, yet all depend upon a consistent transport simulation. In particular, the sediment and contaminant transport model requires high resolution simulations of current- and wave-induced shear stress to predict sediment transport.

The model used in this application is the Estuary and Lake Computer Model (ELCOM; Hodges *et al.*, 2000). It is a three-dimensional hydrodynamics model used for predicting the velocity, temperature and salinity distribution in natural water bodies subjected to external environmental forcing such as wind stress, surface heating or cooling and inflows and outflows. It is designed to facilitate modelling studies of aquatic systems over time scales extending to seasonal time scales, although the limit of computational feasibility depends on the size, the resolution requirements and computational resources.

The model solves the unsteady, viscous Navier-Stokes equations for incompressible flow using the hydrostatic assumption for pressure. Modeled and simulated processes include baroclinic and barotropic responses, rotational effects, tidal forcing, wind stresses, surface thermal forcing, inflows, outflows, and transport of salt, heat and passive scalars. The hydrodynamic algorithms in the model are based on the Euler-Lagrange method for advection of momentum with a conjugate-gradient solution for the free-surface height. It is unconditionally stable for purely barotropic flows; that is, they will produce stable numerical results for any time step. However, for stratified flows explicit discretization of the baroclinic terms in the momentum equation leades to a time step constraint based on the internal wave Courant-Friedrichs-Levy condition.

ELCOM reproduces internal wave motions extremely well, especially when the spatial variability of the wind field is taken into consideration (Laval *et al.*, 2003). Internal waves are an important component of the circulation in any stratified lake (Imberger, 1998). ELCOM's success at modeling internal wave fields is due to its use of a mixing layer model, improving estimation of stratification in a highly stratified lake, combined with a conservative flux-limiting scalar advection scheme (Hodges *et al.*, 2000). The model can be run either in isolation for hydrodynamic studies, or coupled with CAEDYM (Computational Aquatic Ecosystem Dynamics Model) for simulation of biological and chemical processes.

Long-term preservation of lake stratification is ensured using a potential energy conserving filtering technique to counteract the accumulation of numerical error. ELCOM's success at reproducing lake circulation when the spatially variability of the wind field is considered, is expected to be critical to reproducing the circulation of Lake Erie where wind variability has been shown to be important to wind induced setup (Schwab, 1978).

Simulations

The hydrodynamic 3D simulation on lake Erie requires physical and meteorological input data, together with vertical thermistor chain measurements to validate the output from the model. With respect to the physical data, the depth values were extracted for a 2km grid from a very detailed bathymetric map in a CD distribution by the National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/greatlakes). The meteorological data (wind speed and direction, air temperatures, incident solar radiation, relative humidity and cloud cover) were supplied by the National Water Research Institute (NWRI), Boegman et. al., (2000) and Schertzer, (2004).

For the 1994 simulation, data was available at 3 vertical thermistor chain buoys (one in each of the west, central and east basins) for a five month period (May to September). In 2001, the only site with vertical measurements of temperature was located in the East basin of Lake Erie. Both data sets, meteorological and vertical temperatures were processed into hourly values. Inflow and outflow for the main rivers included in the simulation (Detroit and Niagara rivers) were also obtained from NWRI. Figure 1 shows the plan view of Lake Erie and the locations of the monitoring buoys.

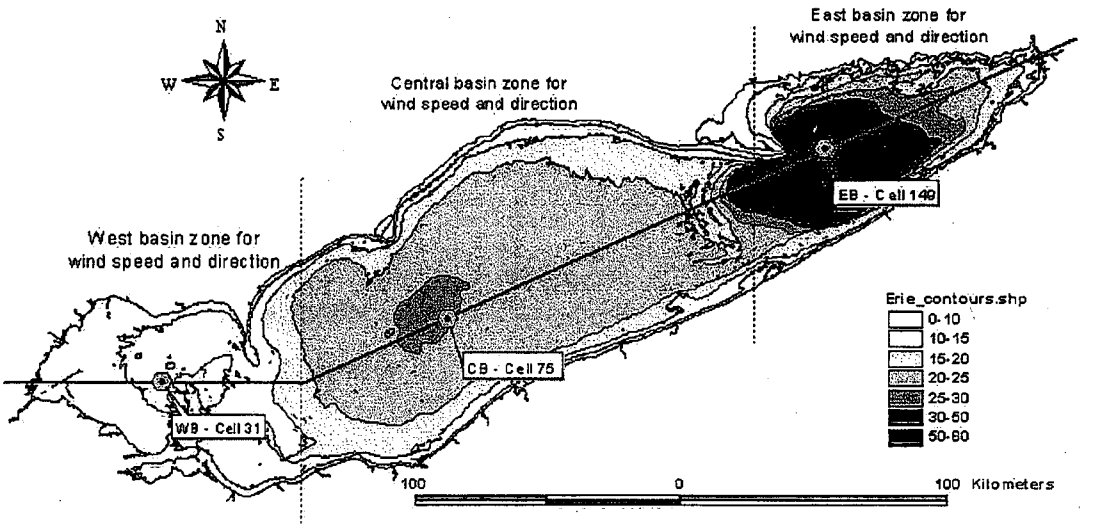

Figure 1. Bathimetry of Lake Erie, showing zones for wind forcing and location of buoys (thermistor chains) and cell numbers on longitudinal cross section.

Different values for the forcing data were used to take into account the spatial variability of meteorological conditions across the lake. As noted in Fig. 1, the lake was divided in three sections (west, central and east basins) where hourly input was provided. The following meteorological data is required to run the model: air temperature, wind speed and direction, incident short wave solar radiation and cloud cover factors. As an example, Fig. 2 shows the windroses for the three different basins and Fig. 3 presents the hourly meteorological data used for the 1994 simulation.

The model results compared well with observed temperature profile data at the sampling locations. Fig. 4 shows the measured and calculated profiles at the three different sites for the 1994 simulation. Similarly, Fig. 5 shows the profile comparison for the only vertical thermistor chain available for 2001. As can be seen from the profile plots, the thermal structure starts with a shallow unstratified west basin, progressing towards a deeper stratified central and eastern basins. In general terms, comparison of modelled and observed vertical thermal profiles showed a very good agreement.

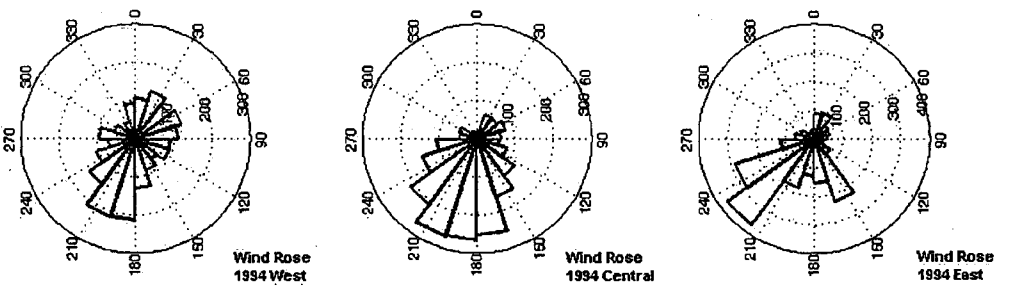

Figure 2. 1994 windroses for the west, central and east basins in Lake Erie.

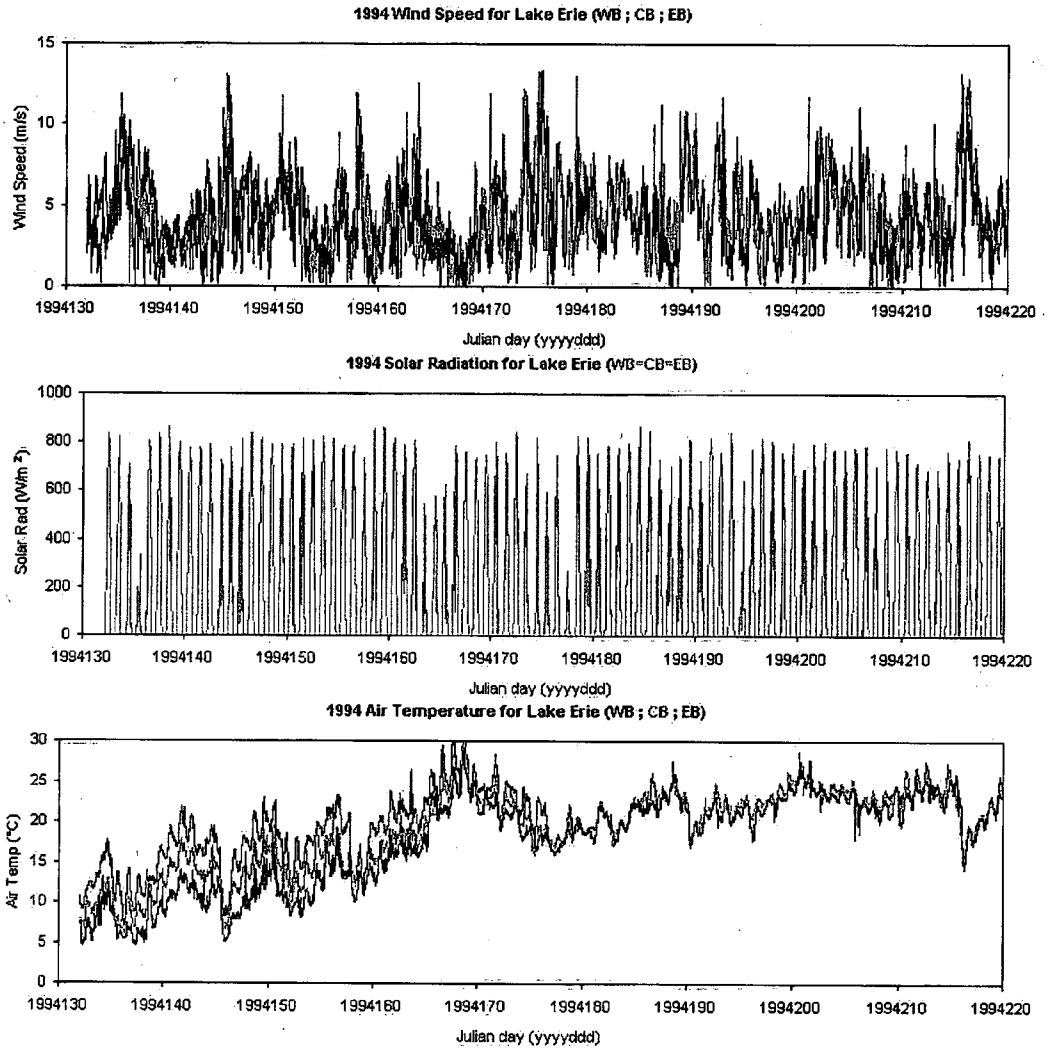

Figure 3. Forcing data (wind, solar radiation and air temperature) at the three different basins for the 1994 model simulation.

Figures 6 and 7 present mean circulation patterns for 1994 and 2001 respectivelly. It is worth noticing the intense west-central circulation interactions in contrast with the low exchange presented in the central-east basins. More on the dynamics of the motions is presented in the discussion section.

Hydrodynamic simulations performed with ELCOM and shore-based meteorological data predict significant internal wave activity during summer stratification in the central basin. Interaction of internal waves with bottom topography appears to lead to breaking and turbulence at both west and east ends of the central basin when meteorological forcing and density fields are appropriate. At the eastern end of central basin, there is potential for exchange of metalimnetic water across the ridge separating central basin from east basin. At the western end of the central basin, exchange occurs with the west basin.

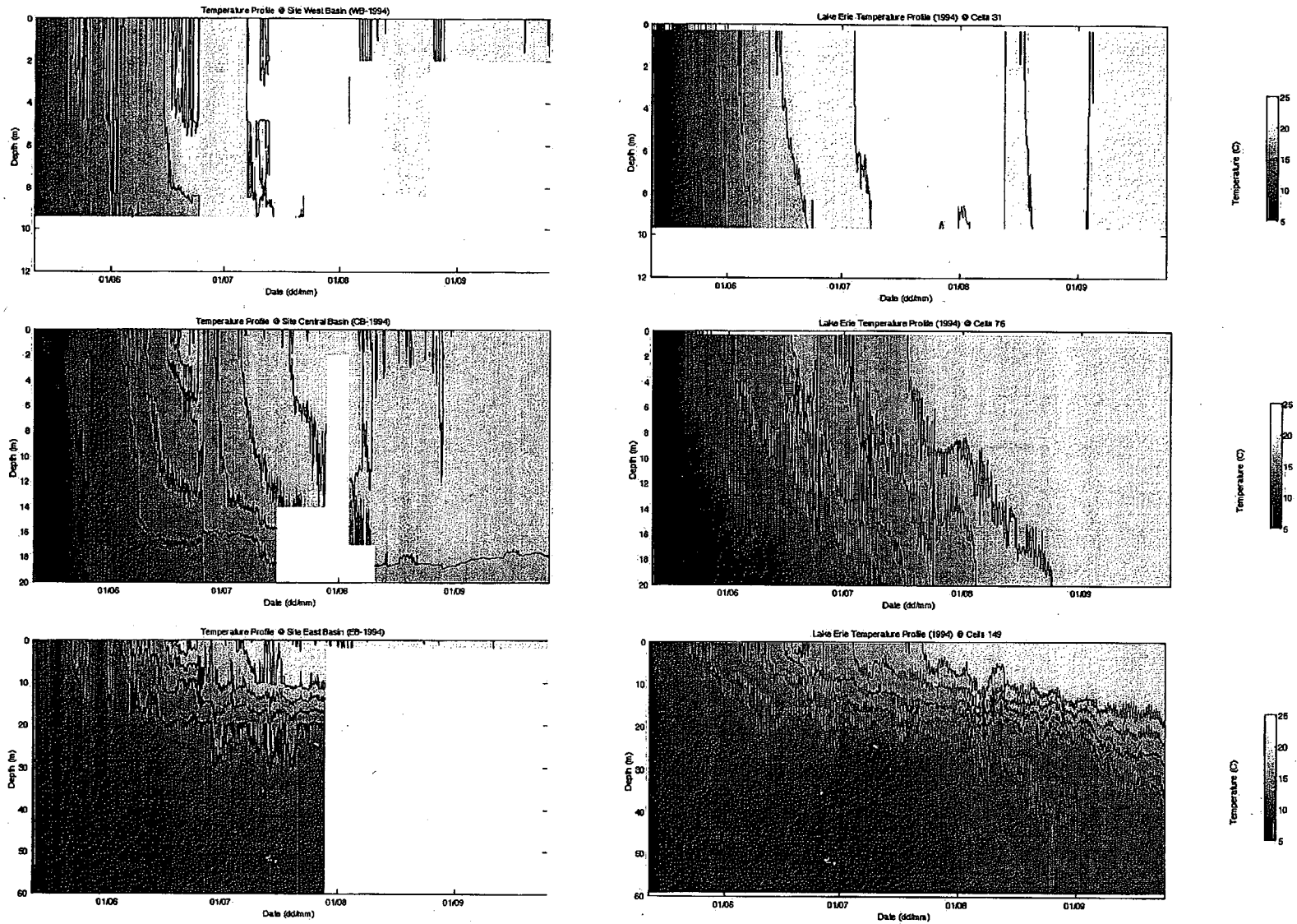

Figure 4. Measured (left) and calculated (right) profiles at different sites (west-top, central-middle, east-bottom) for the 1994 simulation

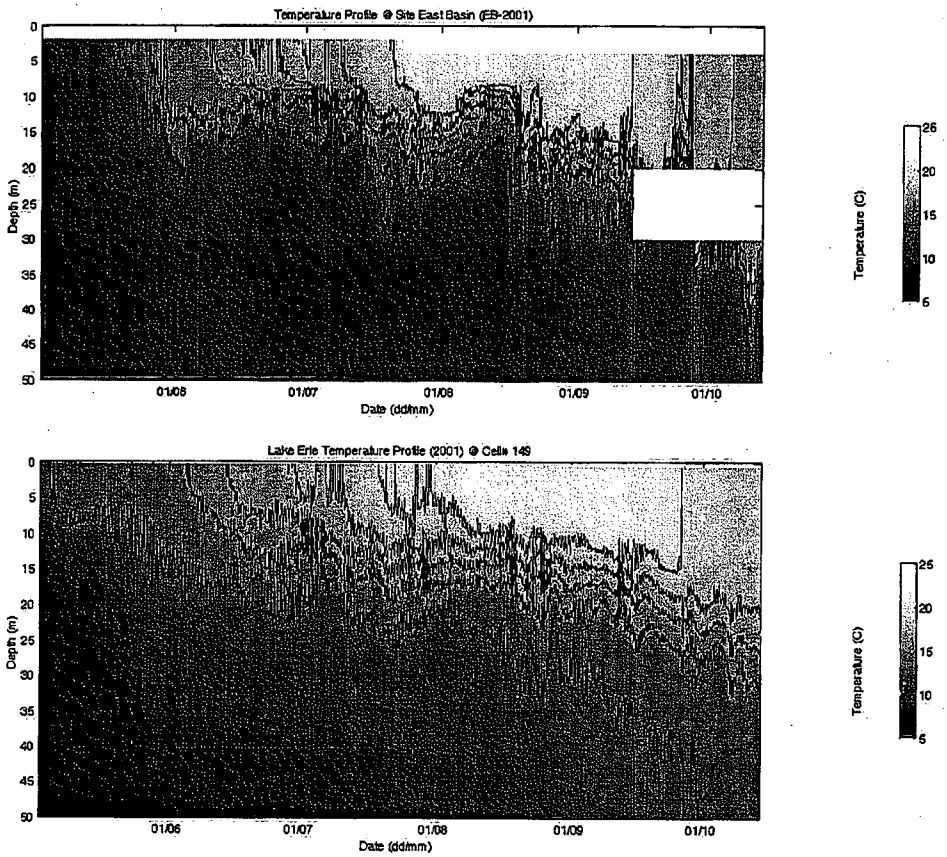

Figure 5. Measured and calculated profiles at the east basin for the 2001 simulation

In the central basin, there is internal wave activity but amplitudes are less, breaking less frequent. The thermocline, and the boundary between hypolimnion and metalimnion, is more dynamic in depth and steepness at the western and eastern ends of the central basin than in the central part. We hypothesize that these general predictions can be verified if good meteorological forcing data are collected and the model output compared against temperature profiles and current velocities measured at selected points in the central basin. The hydrodynamic features predicted by ELCOM have significant implications for mechanistic modelling of the hypolimnetic oxygen regime. The lateral margins of the east basin are also predicted to be sites of high internal wave energy and turbulence, and will be modelled and compared against observed temperature profiles for additional nearshore sites deployed in 2003.

If available and to further validate model results, other comparisons are desirable, e.g. with observed satellite plume data, water level data, current meter measurements. In the web page for the Lake Erie project, the reader can find a section with an attempt to use some satellite images to compare against surface temperature modeled in the lake. Presenting such comparisons exceeds the space and scope of the present paper. The URL reference is: http://sciborg.uwaterloo.ca/~lfleonvi/eriemodel/satellite_page.html.

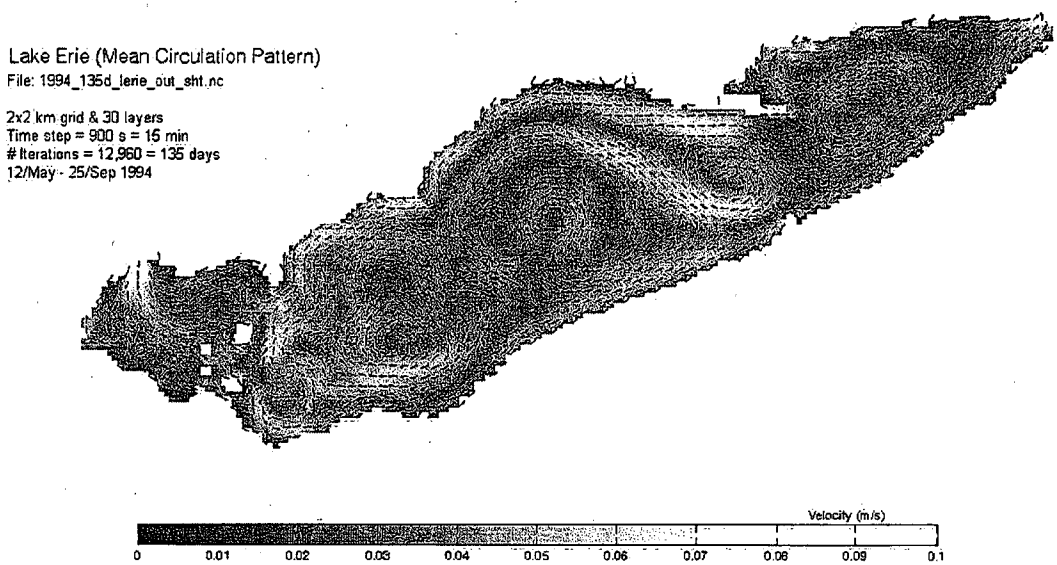

Figure 6. Mean circulation patterns for the 1994 run and zoom in the East basin.

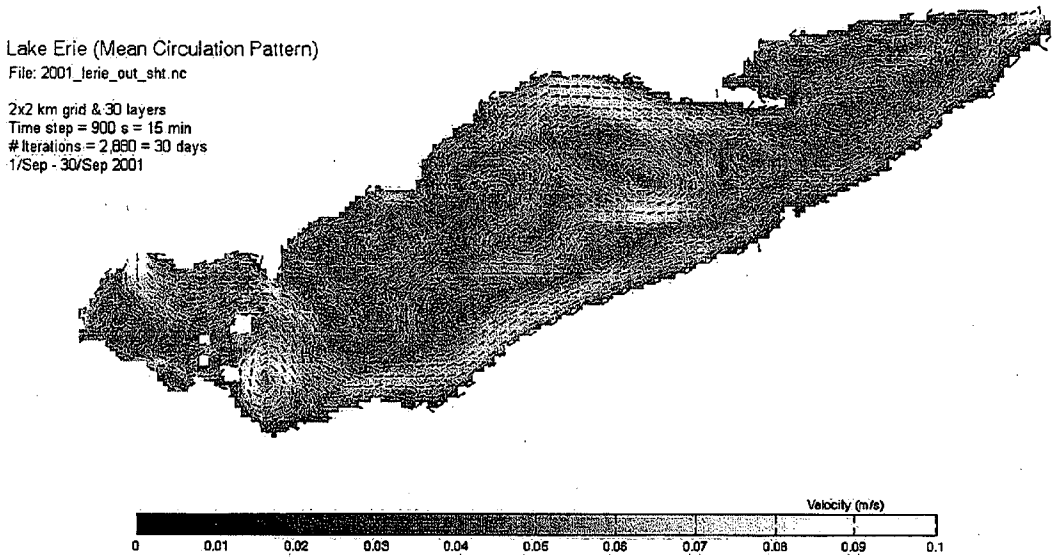

Figure 7. Mean circulation patterns for the 2001 partial 30 day late summer run.

Discussion

The summer mean circulation for 1994 depicted two gyres, one anticlockwise and one clockwise, in the west-central basin. The gyres entrained water from the western basin and the Sandusky Bay area that would be expected to carry much, if not most, of the external phosphorus load to the central basin (Dolan 2004 and Lesht *et al.* 1991 pers. comm.). The west central basin also has typically higher water clarity than the west basin (e.g. Charlton *et al.* 1999), probably because its greater depth allows for more effective sedimentation of particles contributing to turbidity. This may set the stage for potentially large rates of phytoplankton production in the west central basin.

The west central part has been the most productive one of Lake Erie in the 1990's in terms of areal primary production (Millard *et al.* 1999, Smith *et al.* 2004); a gyre like circulation is probably a key mechanism for retaining externally supplied nutrients in the west central region. It may thus be expected that variations of the circulation patterns will contribute to variability of primary production and its spatial distribution in the central basin. For instance, the late summer circulation pattern in 2001 (fig 7), featured a clockwise gyre in the west central region similar to that in the average summer circulation of 1994 (fig 6), but it was not tightly coupled to a strong anticlockwise gyre.

External nutrient loads would then be transported eastward more quickly and would support less extensive phytoplankton development in the west central basin. The transport and/or dispersion of blooms of phytoplankton generated or already underway in the west basin and/or Sandusky area, which have included outbreaks of the potentially-toxic Microcystis (e.g. Budd *et al.* 2001), will also be dependent on the prevailing circulation. The clockwise gyre depicted by the model for both periods of simulation may help explain why such blooms have so far not been clearly documented to spread further into the central basin than the south-western part included in the gyre.

The model depicted, as might be expected, predominantly along-shore average circulation in the nearshore (coastal) zone of both central and east basins. Since the largest part of the external phosphorus load is from diffuse sources in the nearshore (e.g. small tributaries, Dolan 2004) processes in the nearshore can have a major impact on the fate of external nutrients and other materials. Such processes may include filtering and particle deposition by dreissenid mussels, which have been associated with significant decreases of total phosphorus and chlorophyll in nearshore zones where mussels have become abundant (e.g. Nicholls and Hopkins 1993, Nicholls *et al.* 1999) but much less so, or not at all, in offshore waters (e.g. Charlton *et al.* 1999, Makarewicz *et al.*1999).

Dreissenids exert their greatest effects, in terms of re-directing nutrients and biomass from water column to the benthos, where water depths are shallow enough and mixing sufficiently vigorous that they can access a large fraction of the planktonic community from their benthic position (e.g. Fahnenstiel *et al.* 1995, MacIssac *et al.* 1999). The magnitude of their effects will depend not only on water depth and mussel abundance, however, but also on the retention time of water masses in shallow and/or nearshore areas.

The model average circulation did show areas of exchange between nearshore and offshore, associated with gyre-like features in both central and eastern basins. In particular, the clockwise gyres in the Eastern Basin and the anti-clockwise gyres (Fig. 6) were consistent with the computed and observed hydrodynamic results reported by Simons (1976) for the stratified period during 1970 with similar wind conditions. Although it requires more calculations and data than could be incorporated in the present paper, it is possible to quantify such exchanges with the help of the model. Quantification of exchanges and of along-shore transport is essential if we are to understand the fate of the materials re-directed by dreissenids in the nearshore, and the consequences for the lake as a whole.

Conclusion

Hydrodynamic model results were used to explain the dynamic water movements in the three basins of Lake Erie. The model results compared well with observed temperature profile data at a few sampling locations and thus offers the potential of exploring the three-dimensional effects of nutrient transports in these basins. These preliminary results indicated the strong influence of meteorology on the thermal stratification of the lake and should be explored further for studying the effects of possible climatic changes on lake hydrodynamics, and vice versa.

Acknowledgements

We acknowledge the receipt of data for this analysis from several sources. All of the 1994 datasets were provided by Leon Boegman. Meteorological data for the west, central and east basins of Lake Erie were provided by Paul Hamblin (NWRI). Detroit River inflow data were received courtesy of the National Oceanic and Atmospheric Administration (NOAA), contact Cynthia Sellinger. Niagara River outflows at Buffalo, NY was received courtesy of the Unites States Geologic Survey (USGS). Water profile data from thermistor chain moorings were supplied by Paul Hamblin (NWRI) based on data collected by Farrell Boyce (NWRI). Temperature data for 2001 are based on the mooring 01-01T-034A052 from the deep thermistor mooring in the east basin supplied by W.M. Schertzer (NWRI). The authors (L.Leon, D.C.Lam and W.M.Schertzer) were supported in part by a grant from the CFCAS (Canadian Foundation for Climatic and Atmospheric Sciences)

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