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Studies of Physical Processes in Lake Erie

BY:

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Abstract

Physical processes relevant to water quality in Lake Erie during summer stratified seasons are discussed in this paper. Currents, water temperature, winds, radiation and waves were recorded at fixed moorings in Lake Erie from April 2004 through October 2004. Surface winds and heat flux components are computed from the meteorological buoy observations in each of the three basins. Circulation within and between the basins are studied. The thermal structure and exchange processes during summer stratification in Lake Erie have also been examined using a time series data of horizontal velocity profiles from broadband ADCPs and temperature profiles from thermistor moorings.

Introduction

Lake Erie is located between the US and Canada. By volume it is the smallest, and by surface area it is the second smallest lake in the Great Lake system (Fig. 1). The physical characteristics of Lake Erie directly influence the functioning of the lake ecosystem to various stressors. As the shallowest of the Great Lakes, it warms quickly in the spring and summer and cools quickly in the fall. The shallowness of the basin and the warmer temperatures make it the most biologically productive of the Great Lakes.

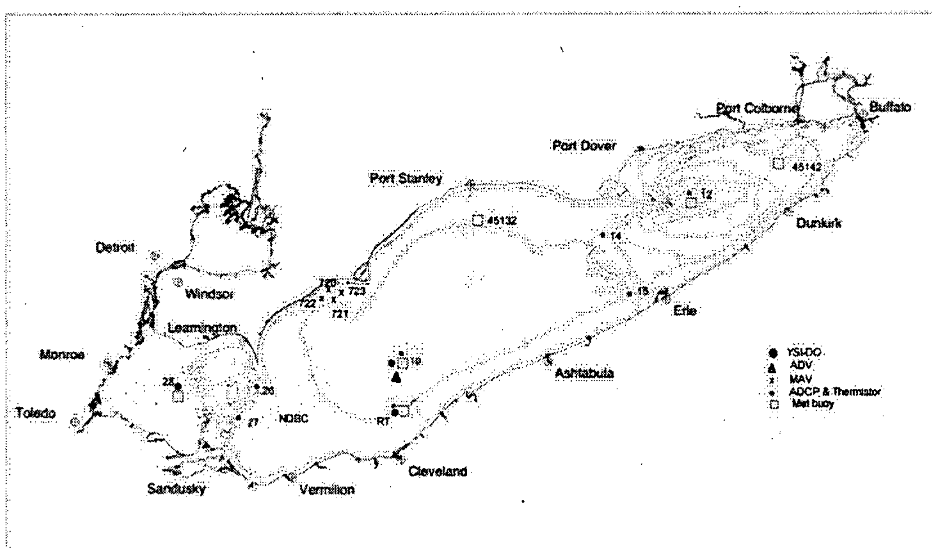

Fig 1: Map of Lake Erie with mooring details in 2004

The western basin is very shallow having an average depth of 7.4 m, the central basin is quite uniform in depth, with the average depth being 18.3 m and the maximum depth 25 m. The eastern basin is the deepest of the three with an average depth of 25 m and a maximum depth of 64 m. The central and eastern basins thermally stratify every year, but stratification in the shallow western basin is rare and very brief. Stratification impacts the internal dynamics of the lake, physically, biologically and chemically. These physical characteristics cause the lake to function as virtually three separate lakes. Eighty percent of Lake Erie's total inflow of water comes through the Detroit River. The remaining comes from precipitation and other tributaries flowing directly into the lake. The Niagara River is the main outflow from the lake.

Lake Erie is exposed to the greatest stress from urbanization, industrialization and agriculture from both the US and Canada. About one-third of the total population of the Great Lakes basin resides within the Lake Erie watershed. Eutrophication during 1950s to the 1970s caused anoxic conditions in the central basin. Phosphorus was deemed to be the main culprit. A comprehensive binational phosphorus reduction strategy was implemented to reduce phosphorus discharge from wastewater treatment plants, limit the use of phosphorus containing detergents in the watershed. The hoped-for elimination of low oxygen in the central basin hypolimnion has not occurred. Relatively large increases in nitrogen continue. Recently, a decrease in phosphorus concentrations around 1995 has been reversed as concentrations have rebounded through 2000-2001 (Charlton and Milne, 2004). The introduction of zebra mussels in the late 1980s triggered a tremendous ecological change in the lake. Zebra mussels have changed the habitat in the lake, altering the food web dynamic, energy transfer and how nutrients and contaminants are cycled within the lake ecosystem.

The last major physical experiments conducted in Lake Erie were Project Hypo in 1970 (Burns and Rosa, 1972) and the Lake Erie Bi-National Investigation in 1979/80 (Boyce et al. 1987). These were intensive investigations that resulted in better understanding of the dynamics of the lake thermal regime, circulation and inter-basin transports applied to water quality problems in the lake. Application of water quality models suggest that simulations of nutrients and dissolved oxygen are diverging from the observations (Lam et al. 2002). This suggests that there may be very real effects that can be attributable to the influence of invasive species like zebra mussels and climate change. To resolve these pressing issues there is a critical need for better estimates of lake circulation, thermal structure and mixing to support further development of lake hydrodynamic, water quality and ecosystem models. Because of these concerns a multi-disciplinary team has been formed in the National Water Research Institute to address these issues. In the present paper we will discuss observations of key physical processes during the ice-free period from early spring to late fall of 2004.

The Experiment

The measurements for obtaining currents, winds, and temperatures consisted of Eulerian measurements during the spring and summer of 2004. As part of the field program, current meter and thermistor moorings were deployed at several locations in the lake

(Fig. 1). Five broadband and one narrowband RDI Acoustic Doppler Current Profilers (ADCP) provided vertical profiles of horizontal currents during this period. The ADCP located in the east basin (station 12) was mounted 20 m below the surface on stable sub-surface floats facing up and the rest are installed at the bottom facing up. The ADCP deployed at station 14 also measured the wave conditions. In addition to ADCPs, single point current meters (Nobska-MAVS) at sub-surface (10 m) were deployed at four locations. The accuracy of all these measurements is of considerable significance in the analysis. The current speed measurements are accurate to the order of 0.3 cm s^{-1} for MAVS, 0.25 cm s^{-1} for ADCPs, whereas directions are accurate to $\pm 2^o$ for both types of instruments. The data return of currents from ADCPs was excellent; however, the data from one point current meters is not complete because of the directional problems encountered in the deployment. In the central basin at 23-m depth a current measuring system, Sontek-Acoustic Doppler Velocimeter (ADV) was deployed. This instrument provided high frequency current information every three hours during the deployment. It has been used to estimate the wave conditions in the central basin.

Water temperature data were obtained from six moorings with thermistors deployed at 1-3 m intervals in the epilimnion, and at a lesser frequency (5 m) in the bottom waters. Apart from this water temperature was also obtained from the current meters and the ADCP instrument location at the bottom. The different temperature sensors used in the experiment yielded an accuracy of temperature from ±0.002°C to ±0.2°C. Three meteorological buoys, one in each basin of the lake provided the wind and radiation data. The incoming and net radiations were measured with Eppley pyranometers and radiometers. Apart from these meteorological data were also obtained from NDBC and Environment Canada (EC) real-time buoy network. The experiment also consisted of several joint EC and USEPA surveillance cruises measuring the water quality parameters from research vessels during the whole season.

Meteorological observations

The variability of currents is determined by prevailing winds over the lake. As an example the wind measurements at station 19 have been presented as approximate meteorological forcing during this period. The wind stress was obtained from the quadratic law given as $\tau = \rho_a C_d |W| W$, where ρ_a = 1.2 kg m^{-3} is the air density, W is wind velocity. In general, drag coefficient C_d increases with the wind speed and estimated as $C_d = (0.8 + 0.065\ W)X10^{-3}$ for W >1 m s^{-1} . A low-pass filter, using a 24 h period for the cut-off, was used to remove the high frequency information in the wind stress (Fig. 2a). The filtered time series has peaks of over 0.2 N m^{-2} during some episodes, usually associated with easterly storms towards the end of the summer. The winds were moderate during the rest of the experimental period, except on day 252. On this day, strong easterlies blew over the entire lake. The surface heat flux is calculated as a balance between the heat sources and sinks. Figure 2b shows the hourly (thin curve) and daily averaged (thick curve) surface heat flux during the experimental period. The daily averaged heat flux ranged from – 258 W m^{-2} to 191 W m^{-2} during this deployment period.

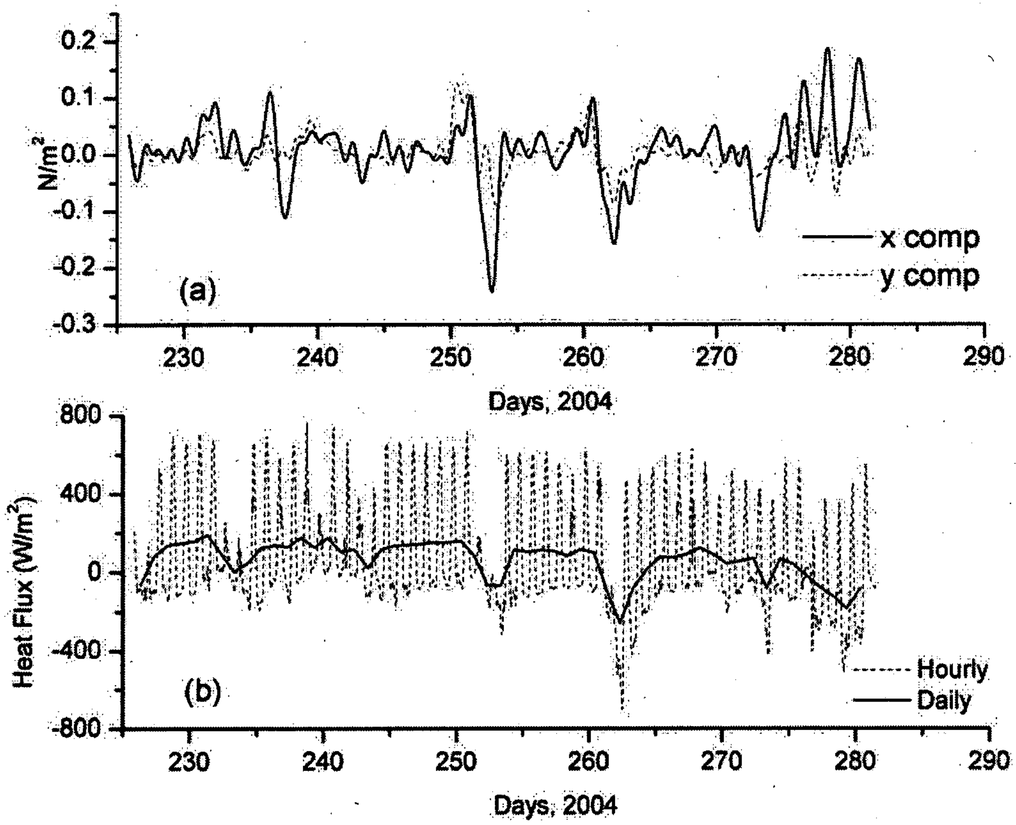

Fig 2: The time series of wind stress and surface heat flux at station 12 during summer.

Currents and Thermal Structure

Mean circulation in Lake Erie during summer were discussed in earlier contributions (Saylor and Miller, 1987). These investigations revealed large scale lake respone to prevailing meteorological forcings. However, these studies were based on data with coarse vertical resolution. In this section, by using a time series of horizontal velocity and temperature profiles, we provide some examples of the variability of circulation and thermal structure during the summer at selected stations in the east basin and in the Pennslvania channel in Lake Erie. Figures 3a &3b show temperature (^{0}C) obtained in the east basin at station 12. The mean temperature decreases as we go to deeper layers. In 2004 stratification was established by the middle of June (Day 165) and persisted till the middle of September (Day 262). During the early stratification the thermocline was located at 10-12 m below the surface. Once the full stratification was established in the summer, the thermocline migrated to 20 m or so. Comparison of temperature (Fig 3b) and wind stress (Fig 2a) time series reveals that upwelling and downwelling of the thermocline correspond to north-eastward and westward winds (Days 230 to 238).

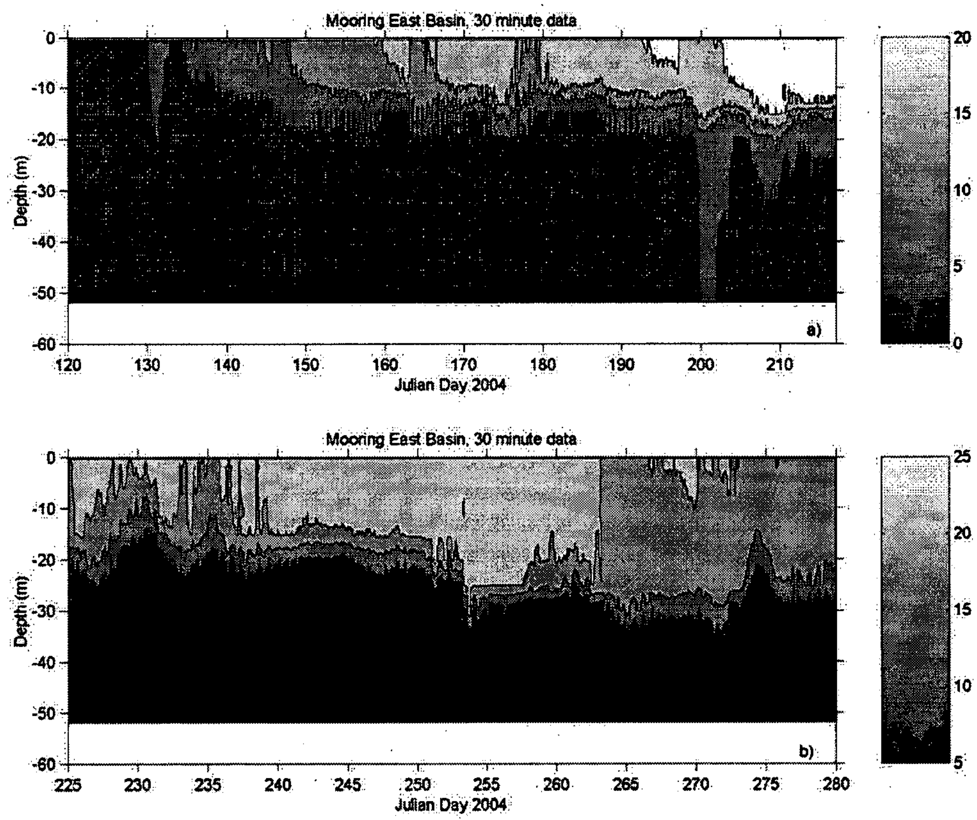

Fig 3: Time series of vertical thermal structure in the east basin during spring and summer seasons.

Typical plots of clock-wise and anti-clockwise rotary spectra of currents at all ADCP bins are plotted in Figures 2a and 2b, respectively. In general the spectra are characterized by a flat peak around 4-6 days (0.01 cph) and a spectral minimum around 24-30 hours. The dominant peak near 17-18 hr corresponds to the near-inertial period of Lake Erie. The near-inertial oscillations are characteristic feature of summer stratification and are observed to be intermittent. The spectral minimum at 24 to 30 hours is a characteristic feature of energy transfer from large scale lake wide circulation to small scale oscillations.

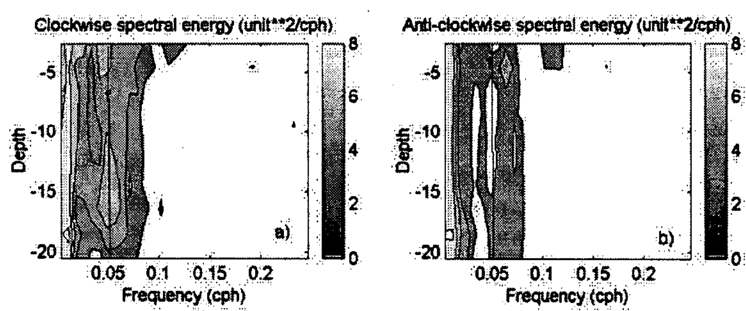

Fig 4: Rotary spectra of currents at station 15.

The transport of cold, oxygenated hypolimnion water from the eastern to the central basin has been considered as a possible oxygen renewal mechanism for the central basin bottom waters (Burns and Rosa, 1972; Boyce et al., 1987). Figures 5a to 5c show the variations of low-pass filtered currents and temperature at a station in the Pennslvania channel. The two-layer structure of along-channel currents can be seen on a few occasions supporting the earlier observations that mesolimnion and hypolimnion transport is towards the central basin. However, the mean transport appears more or less unidirectional and follows along-the-lake winds (Fig 2a). The current reversals associated with winds were common during the summer regime, with each episode on average lasting for 4-6 days.

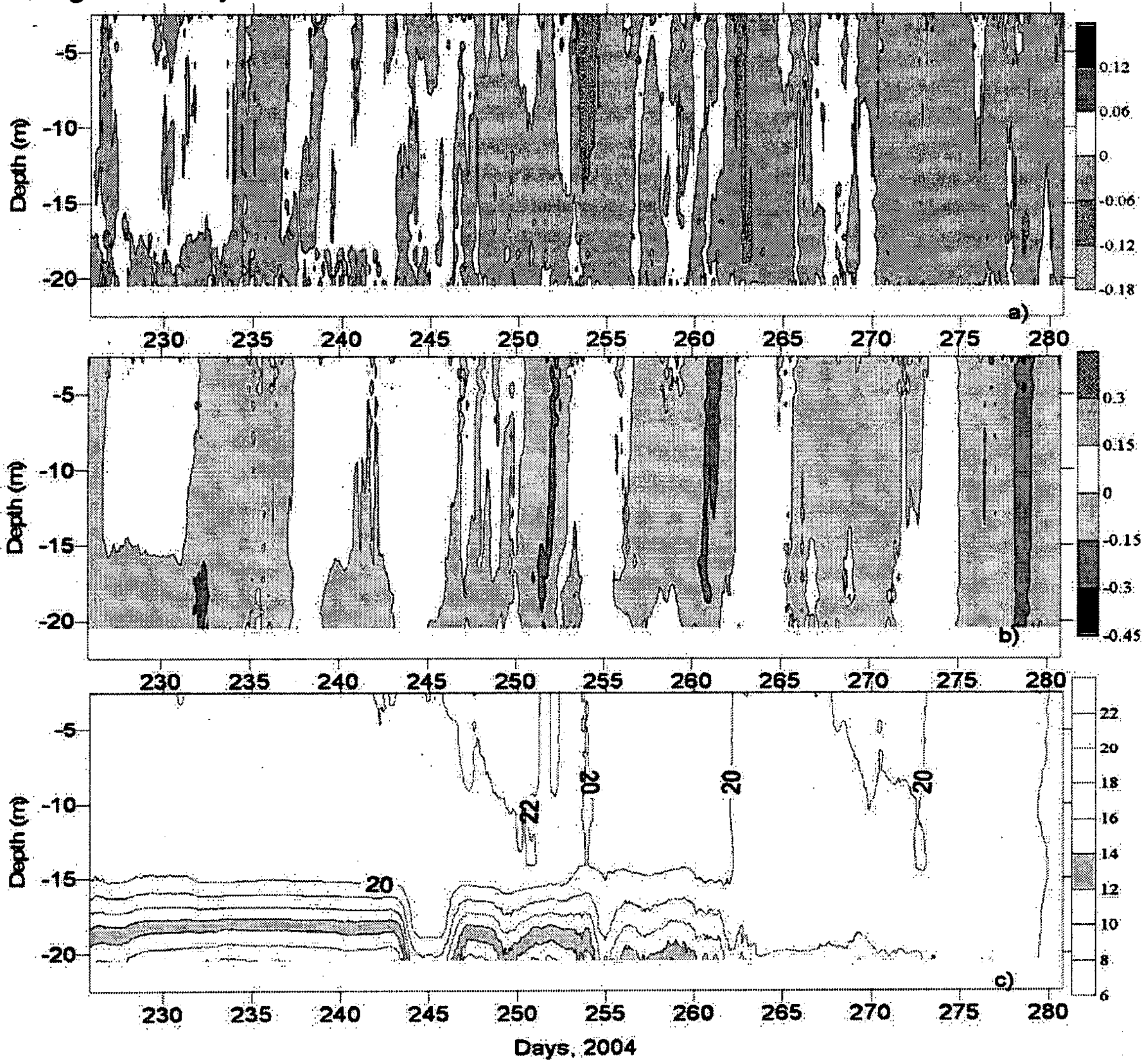

Fig 5: Vertical structure low-pass filtered currents (a) cross-channel b) along channel) and thermal structure at station 15.

Conclusions

This study presents some examples of physical limnology observations from a large experiment in Lake Erie. Flow and thermal structure in the lake presents a complex scenario during certain episodes and also under mean summer stratified conditions. The time series of vertical structure of along-channel currents and temperature in the Pennslvania channel showed strong influence of along-the-lake winds, and two-layer structure probably associated with return currents due to surface and internal pressure gradients. Further studies using the complete data base and non-linear numerical models to investigate the circulation and mixing are in progress.

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NWRI RESEARCH SUMMARY

Plain language title

Physical processes in Lake Erie

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

Water quality in Lake Erie is controlled by nutrient reductions. Since the arrival of alien mussels to the lake the results are confusing. Scientists and program managers have known that zebra mussels would cause changes in plankton production and nutrients, which are the main factors for lake-wide management of Lake Erie.

Why did NWRI do this study?

In 2002, NWRI published sensitivity results based on a nine-box water quality model. This study identified several knowledge and data gaps, particularly about the lake thermal structure, mixing and circulation in post-zebra mussel period.

What were the results?

This is a preliminary data analysis, further studies using the complete data base and non-linear numerical models to investigate the circulation and mixing are in progress. We have observed an array of complexities in lake currents that vary in magnitude, time and space. Circulation in Lake Erie shows large scale features due to the meteorological forcing, and meso-scale circulations due to earth's rotation, topography, etc.

How will these results be used?

This study is the first major study after the Bi-National study carried out in early eighties. It has been supported and partially funded by Ontario Region, Lake Erie LaMP and Great Lakes 2020 program in Environment Canada. The results will be used to improve Lake Erie hydrodynamic and water quality models.

Who were our main partners in the study?

Several organizatons were involved in the planning and executing of the program such as Lake Erie LaMP, Ontario Region were the main partners while the University of Waterloo and University of Windsor, NOAA-GLERL were collaborating partners.

Étude de processus physiques dans le lac Érié

Yerubandi R. Rao

Résumé

Cet article discute certains processus physiques liés à la qualité de l'eau du lac Érié durant la stratification estivale. Les courants, la température de l'eau, les vents, le rayonnement et les vagues ont été observés à l'aide de bouées captives dans le lac Érié d'avril à octobre 2004. Les des vents de surface et les composantes de flux de chaleur sont calculés à partir d'observations effectuées à l'aide de bouées météorologiques placées dans chacun des trois bassins. La circulation à l'intérieur des bassins et entre les bassins est étudiée. La structure thermique et les processus d'échange durant la stratification estivale dans le lac Érié ont également été examinés à l'aide de séries chronologiques de profils de la vitesse horizontale obtenus d'ADCP à large bande et de profils de la température obtenus de bouées à thermistance.

Sommaire des recherches de l'INRE

Titre en langage clair

Processus physiques dans le lac Érié

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

La qualité de l'eau du lac Érié est déterminée par la baisse des nutriants. Les résultats sont déroutants depuis l'arrivée de moules étrangères dans le lac. Les scientifiques et les gestionnaires de programme savaient que la moule zébrée amènerait des changements dans la production du plancton et les nutriants, qui sont les principaux facteurs nécessitant une gestion panlacustre du lac Érié.

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

En 2002, l'INRE a publié des résultats de sensibilité basés sur un modèle de la qualité de l'eau à neuf boîtes. Cette étude a décelé plusieurs lacunes dans les connaissances et les données, en particulier quant à la structure thermique du lac, au mélange et à la circulation dans la période qui suit celle des moules zébrées.

Quels sont les résultats?

Cette analyse des données est préliminaire; d'autres études utilisant toute la base de données et des modèles numériques non linéaires pour étudier la circulation et le mélange sont en cours. Nous avons observé une série de complexités dans les courants lacustres, qui varient en magnitude ainsi que dans le temps et dans l'espace. La circulation dans le lac Érié révèle des caractéristiques à grande échelle résultant du forçage météorologique, ainsi que des effets de circulation à mésoéchelle dus à la rotation de la Terre, à la topographie, etc.

Comment ces résultats seront-ils utilisés?

Cette étude est la première étude importante après l'étude binationale du début des années 1980. Elle a été appuyée et partiellement financée par la Région de l'Ontario, le PAP du lac Érié et le programme Grands Lacs 2020 d'Environnement Canada. Les résultats seront utilisés pour améliorer les modèles de l'hydrodynamique et de la qualité de l'eau du lac Érié.

Quels étaient nos principaux partenaires dans cette étude?

Plusieurs organisations ont participé à la planification et à l'exécution du programme; le PAP du lac Érié et la Région de l'Ontario ont été les principaux partenaires, tandis que l'université de Waterloo, l'université de Windsor et le GLERL de la NOAA ont été des collaborateurs.

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