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Development of a Three-Dimensional Hydrodynamic Circulation Model for Lake Huron and Georgian Bay

Jinyu Sheng and Yerubandi R. Rao

NWRI Contribution No. 04-176

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Development of a Three-Dimensional Hydrodynamic Circulation Model for Lake Huron and Georgian Bay

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Development of a Three-Dimensional Hydrodynamic Circulation Model for Lake Huron and Georgian Bay

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Abstract:

A primitive equation z-level ocean circulation model known as CANDIE (Canadian Version of Diecast, Sheng et al., 1998) is used in the development of a three-dimensional circulation model for Lake Huron and Georgian Bay. The lake circulation model domain covers the region between 275.3°E (84.7°E) and 280.6°E (79.4°W) and between 43°N and 46.3°N, with a horizontal resolution of roughly 2.5 km and 30 z-levels in the vertical. The model is used to simulate the large-scale circulation, temperature distribution and their seasonal variability in 1974-75, during which a field program was conducted in Lake Huron. The model is forced by monthly mean surface heat flux and 12-hourly wind stress computed from wind speeds extracted from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) 40-year reanalysis data. The model reproduces reasonably well the general circulation and annual cycle of the thermal stratification in the region. The model results presented in this report demonstrate the suitability of the z-level CANDIE model in simulating the large-scale hydrodynamics in lakes.

Élaboration d'un modèle tridimensionnel de la circulation hydrodynamique pour le lac Huron et la baie Georgienne

Jinyu Sheng et Yerubandi R. Rao

Résumé :

Un modèle aux équations primitives de la circulation océanique de niveau z connu sous le nom de CANDIE (version canadienne de Diecast, Sheng *et al.*, 1998) sert à la mise au point d'un modèle tridimensionnel de la circulation dans le lac Huron et la baie Georgienne. Le domaine du modèle du régime de circulation du lac couvre la région située entre 275,3 °E (84,7 °E) et 280,6 °E (79,4 °W) et entre 43 °N et 46.3 °N, avec une résolution horizontale d'environ 2,5 km et de 30 niveaux z à la verticale. Le modèle sert à simuler la circulation à grande échelle, la distribution de température et la variabilité saisonnière en 1974-1975, période durant laquelle un programme de terrain a été réalisé dans le lac Huron. Le modèle est forcé par des flux de chaleur en surface mensuels moyens et une tension du vent de 12 heures, calculée à partir des vitesses du vent extraites des données d'une nouvelle analyse sur 40 ans des NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research). Le modèle reproduit raisonnablement bien la circulation générale et le cycle annuel de la stratification thermique de la région. Les résultats obtenus présentés dans ce rapport démontre l'adaptation du modèle CANDIE de niveau z pour simuler les caractéristiques hydrodynamiques à grande échelle dans les lacs.

NWRI RESEARCH SUMMARY

Plain language title

Development of a three-dimensional hydrodynamic circulation model for Lake Huron and Georgian Bay.

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

The Lake Huron ecosystem has been affected by natural and anthropogenic activities such as degradation and loss of historical habitat in tributaries, invasion of non-native nuisance species such as zebra mussel, over-fishing and reproduction failure, degradation and loss of near-shore habitat including coastal wetlands, toxic contaminants and eutrophication in some localized areas. Lake Huron, unlike the other Great Lakes does not have a lakewide management planning process to drive future efforts. As a result, Environment Canada with partners from the U.S. has undertaken an effort to initiate action on Lake Huron. One of the purposes of the Lake Huron Initiative is to develop an action-oriented process for addressing Lake Huron and to help identify priority issues and future efforts needed to ensure a sustainable Lake Huron watershed.

Why did NWRI do this study?

Despite a few field investigations in 1974-75, much remains unknown about the circulation and thermal regime in Lake Huron. The previous studies using very limited observations have indicated that the circulation and thermal regime will have impact on the distribution of dissolved and suspended materials within the nearshore zone. Water use and related water quality problems, particularly from nutrient releases from fish farming could have impact on Lake Huron as the water drains into the North Channel and Georgian Bay system. NWRI has been actively involved in circulation and water quality issues due to the operations of these fish farms in the North Channel and Georgian Bay.

What were the results?

A three-dimensional hydrodynamic model for Lake Huron and Georgian Bay has been developed based on the primitive equation z-level circulation model. The preliminary model results show a cyclonic coastal jet in both Lake Huron and Georgian Bay, which is relatively stronger in summer and fall than those in other seasons. The model also predicted reasonably well the seasonal evolution of thermal stratification in the upper 50 m in the lake.

How will these results be used?

The results will be used to improve the environmental monitoring/modeling and assessment of the Great Lakes. This extensive set of results will be useful for providing the most needed boundary forcing for small-scale circulation and water quality models that are being developed for aquaculture studies in Georgian Bay and the North Channel.

Who were our main partners in the study?

Dr. Jinyu Sheng, University of Dalhousie, Halifax, NS.

Sommaire des recherches de l'INRE

Titre en langage clair

Élaboration d'un modèle tridimensionnel de circulation hydrodynamique pour le lac Huron et la baie Georgienne.

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

L'écosystème du lac Huron a été affecté par les activités naturelles et anthropiques comme la dégradation et la perte de l'habitat historique dans les affluents, l'invasion par des espèces nuisibles non indigènes (comme la moule zébrée), la surpêche et l'échec de la reproduction, la dégradation et la perte de l'habitat côtier (notamment les milieux humides), les contamination par les toxiques et l'eutrophisation de certains secteurs localisés. Contrairement aux autres Grands Lacs, le lac Huron ne fait l'objet d'aucun processus de planification de gestion panlacustre permettant d'orienter les efforts futurs. C'est pourquoi Environnement Canada, avec divers partenaires des États-Unis, a mis sur pied un projet visant à mettre en œuvre diverses mesures dans le lac Huron. L'un des objectif de la Lake Huron Initiative est d'élaborer un processus proactif qui se penche sur la situation du lac et aide à cerner les grands enjeux et les futurs efforts nécessaires pour assurer la viabilité du bassin hydrographique du lac.

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

Malgré de nouvelles études réalisées sur le terrain en 1974-1975, bien des choses demeurent inconnues au sujet de la circulation et du régime thermique du lac Huron. Les études antérieures qui utilisaient des observations très limitées ont révélé que ces deux paramètres avaient une incidence sur la distribution des matières dissoutes et en suspension dans la zone littorale. L'utilisation de l'eau et les problèmes connexes de qualité de l'eau découlant notamment des rejets d'éléments nutritifs des piscicultures, pourraient avoir eu une incidence sur le lac étant donné que les eaux se jettent dans le bassin du chenal du Nord et de la baie Georgienne. L'INRE a participé activement à l'étude de la circulation et des problèmes de qualité de l'eau attribuables à l'exploitation de ces piscicultures dans le bassin.

Quels sont les résultats?

On a mis au point un modèle tridimensionnel de la circulation hydrodynamique pour le lac Huron et la baie Georgienne en se basant sur le modèle aux équations primitives de circulation de niveau z. Les résultats préliminaires du modèle mettent en évidence un jet côtier cyclonique dans le lac et dans la baie, relativement plus fort en été et à l'automne que pendant les autres saisons. Le modèle prévoit aussi raisonnablement bien l'évolution saisonnière de la stratification thermique dans les 50 premiers mètres du lac.

Comment ces résultats seront-ils utilisés?

Ces résultats serviront à améliorer la surveillance et la modélisation de l'environnement et l'évaluation des Grands Lacs. La série complète des résultats sera utile pour obtenir le forçage tant recherché pour les modèles de circulation et de qualité de l'eau à petite échelle qui sont mis au point pour les études de l'aquaculture dans la baie Georgienne et le chenal du Nord.

Quels étaient nos principaux partenaires dans cette étude?

Dr Jinyu Sheng, Université Dalhousie, Halifax (N.-É.)

Development of a Three-Dimensional Hydrodynamic Circulation Model for Lake Huron and Georgian Bay

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1. Introduction

Bordered by the province of Ontario and the state of Michigan, Lake Huron is the second largest great lake and the fifth largest freshwater lake in the world. Lake Huron comprises four interconnected water bodies: the Main Lake, Saginaw Bay, North Channel and Georgian Bay (Figure 1), and has a horizontal dimension of about 330 km east to west and 295 km north to south. At low water datum, Lake Huron contains 3540 km^3 of water, has a maximum water depth of about 230 m and an average water depth of about 60 m. Lake Huron is connected to Lake Michigan via narrow straits of Mackinac (SM) to the northwest, Lake Superior via St. Mary's River (SMR) to the north, and Lake St. Clair via St. Clair River (SCR) to the south (Figure 1). Major inflows to Lake Huron come from Lakes Superior via SMR (about 2100 $m^3\,s^{-1}$) and Michigan via SM (about 1400 $m^3\,s^{-1}$). Lake Huron discharges at its southern end through the SCR into Lake St. Clair, which in turn discharges through the Detroit River into Lake Erie.

The Lake Huron ecosystem, which consists of fresh water fisheries, wildlife, shoreline marshes and wetlands, had been significantly affected by natural and anthropogenic activities such as degradation and loss of historical habitat in tributaries, invasion of non-native nuisance species such as zebra mussel, over-fishing and reproduction failure, degradation and loss of near-shore habitat including coastal wetlands, toxic contaminants and eutrophication in some localized areas. Water use and related water quality problems, particularly from nutrient releases from fish farming could also have impact on Lake Huron as the water ultimately drains into the North Channel and Georgian Bay system. Lake Huron is recovering from decades of environmental contamination, but still faces significant threats from shoreline development and invasive species. Therefore, knowledge of water movements in the lake and the interconnected channels and bays will be particularly useful to improve the current understanding of the chemical and biological processes that occur simultaneously in the lake.

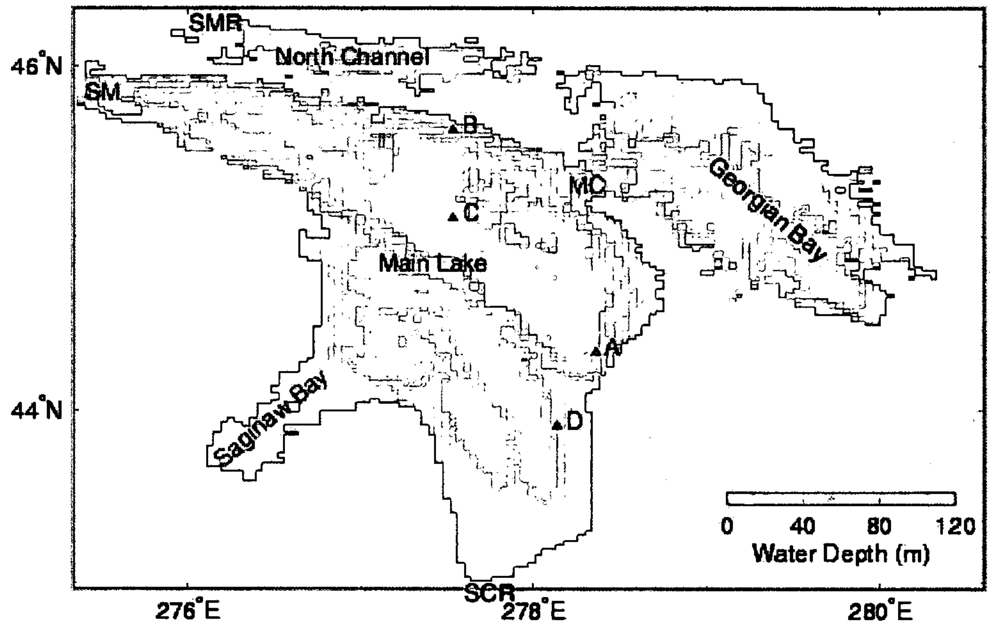

Figure 1: Selected bathymetric features within the Lake Huron model domain. Abbreviations are used for Main Channel (MC), straits of Macinac (SM), St. Mary's River (SMR) and St. Clair River (SCR). Four sites marked by solid triangles are chosen to present model results.

Early studies on the Lake Huron circulation were made using drift bottles by Harrington (1894), who observed a prevailing cyclonic surface circulation in the main basin. Sloss and Saylor (1975) analysed the current meter records from 1966 summer moorings and confirmed the general cyclonic circulation during the summer season. As part of the Upper Lakes Reference Study, several current meter and temperature moorings were deployed by the Canada Centre for Inland Waters and the Great Lakes Environmental Research Laboratory in Lake Huron during 1974-75 (IJC, 1977). It was showed that the winter mean circulation in the lake is characterized as a southward flow along the Michigan coast and a return northward flow along the east coast. It was also showed that the summer mean circulation in the region is relatively weaker than the winter mean circulation. Another notable feature of the Lake Huron summer circulation is a surface flow into the Georgian Bay that implies a return flow at deeper depths to the main lake. Except for these large scale hydrodynamic studies, Lake Huron has not received much attention to describe the lake's thermal structure and circulation. Accurate simulation of water movements in Lake Huron is crucial for development of water quality models for small embayments of North Channel and Georgian Bay. This model will provide the much needed large scale circulations, seasonal distributions and boundary conditions to develop water quality models.

A collaborative project between the Great Lakes Environmental Laboratory and Ohio State University an experimental Great Lakes Forecasting system was developed recently (Schwab, personal comm., 2004) using a three-dimensional (3D) terrain-following (or sigma-level) ocean circulation model known as the Princeton Ocean Model (POM). This report deals with an application of a 3D primitive-equation z-level ocean circulation model known as CANDIE in developing a hydrodynamic model for Lake Huron, North Channel and Georgian Bay. The main objective of this study is to demonstrate the suitability of a 3D z-level circulation model in simulating the large-scale circulation, thermal structure and associated seasonal distributions in Lake Huron which affect significantly the distribution of water quality (biochemical) components of the lake system.

The arrangement of this report is as follows. The next section introduces the 3D hydrodynamic circulation model of Lake Huron and the model external forcing. Section 3 presents the model results. Section 4 is a summary and conclusion.

2. The hydrodynamic model and external forcing

The hydrodynamic circulation model used in this study is a three-dimensional primitive equation z-level ocean circulation model known as CANDIE (Canadian version of DieCAST, Sheng et al., 1998). It is an outgrowth of the DieCAST model developed by Dietrich et al. (1987). CANDIE has been successfully applied to various modelling problems on the shelf, including wind-driven circulation over an idealized coastal canyon (Sheng et al. 1998), a density-driven coastal current (Sheng, 2001), tidal circulation in the Gulf of St. Lawrence (Lu et al., 2001), wind-driven circulation over a stratified coastal embayment (Davidson et al., 2001), and seasonal circulation in the northwestern Atlantic Ocean (Sheng et al., 2001). Most recently CANDIE has been applied to the western Caribbean Sea by Sheng and Tang (2003, 2004) and Lunenburg Bay of Nova Scotia by Sheng and Wang (2004). The reader is referred to the Appendix for governing equations and sub-grid scale mixing parameterizations used in CANDIE.

The Lake Huron circulation model covers the region between 275.3°E (84.7°W) and 280.6°E (79.4°W) and between 43°N and 46.3°N (Figure 1), using the 2 km by 2 km bathymetry developed by Schwab (personal comm., 2004). The model horizontal resolution is about 2.5 km. There are 30 unevenly spaced z-levels with the centers of each z-level located at 1.5, 4.5, 7.5, 10.5, 13.5, 16.5, 19.5, 22.5, 25.5, 28.5, 31.5, 34.5, 37.5, 40.5, 43.5, 50.8, 62.5, 74.2, 85.8, 97.5, 109.2, 120.8, 132.5, 144.2, 155.8, 167.5, 179.2, 190.8, 202.5 and 214.2 m respectively.

The present setup of the Lake Huron model has four closed model boundaries. Effects of inflows from Lakes Superior and Michigan and outflows to Lake St. Clair on the lake hydrodynamics will be examined in the future study. At the model lateral closed boundaries, the normal flow, tangential stress of the currents and horizontal fluxes of temperature and salinity are set to zero (freeslip conditions). The model uses the sub-grid scale mixing parameterization scheme of Smagorinsky (1963) for the horizontal eddy viscosity and the schemes proposed by Large et al. (1994) for the vertical mixing coefficients. The turbulent Prandtl Number is set to 0.1. The model also uses the fourth-order numerics (Dietrich 1997) and Thuburn's (1996) flux limiter to better represent the nonlinear advection terms in the model.

Two types of external forcings are used to drive the model in this report. The first type is the net heat flux at the sea surface (Q_{net}) parameterized as:

$$Q_{net} = Q_{net}^{clim} + \beta\,(SST^{clim} - SST^{model}) \qquad (1)$$

where Q_{net}^{clim} is the monthly mean net heat flux and SST^{clim} is the monthly mean sea surface temperature interpolated onto the model grid and taken from the monthly mean results produced by the Great Lakes Net Basin Supply Forecast Model (Figure 2), and β is the coupling coefficient defined as $\Delta z_1 \rho_o c_p / \tau$, where Δz_1 is the thickness of the top z-level, c_p is the specific heat, and τ is the restoring time scale which is set to 15 days.

The second type of the model forcing is the 12 hourly wind stress calculated from the wind speeds interpolated onto the model grid from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) 40-year reanalysis data (Kalnay et al., 1996). The horizontal resolution of the NCEP/NCAR reanalysis data is 15/8 degree, which is about 147 km and 208 km in the eastward and northward directions respectively in the study region. To examine the seasonal and spatial variabilities of the wind forcing used to drive the model, we calculate the seasonal mean wind stress in each season. The seasonal mean wind stress in 1974 (Figure 3) is roughly eastward in winter and fall, and northeastward in spring and summer. In comparison, the seasonal mean wind stress in 1975 (Figure 4) is relatively weak and roughly eastward in spring and relatively strong and roughly northeastward in the other three seasons. The seasonal mean wind stress is spatially uniform, which is expected since the horizontal resolution of the NCEP/NCAR reanalysis data is very coarse.

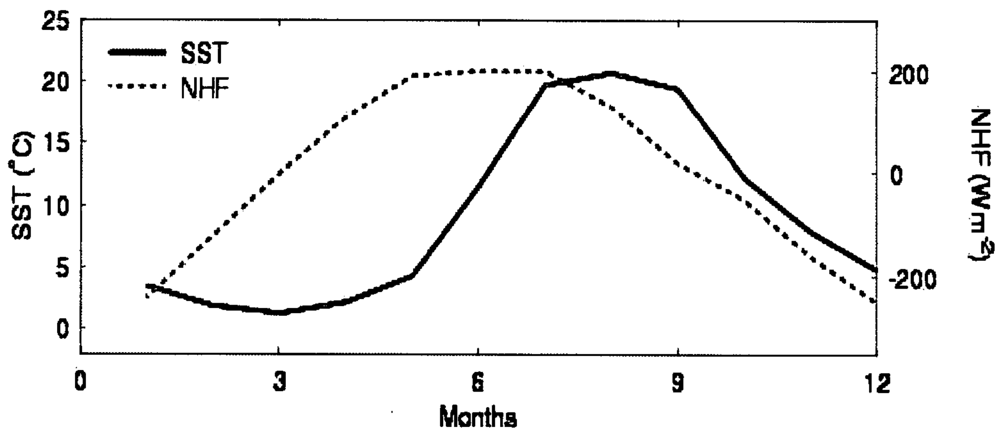

Figure 2: Monthly mean sea surface temperature (SST) and net heat flux (NHF) taken from the model results computed by the Great Lakes Net Basin Supply Forecast Model (http: mcc.sws.uiuc.edu/glakes/hur/nhu.html).

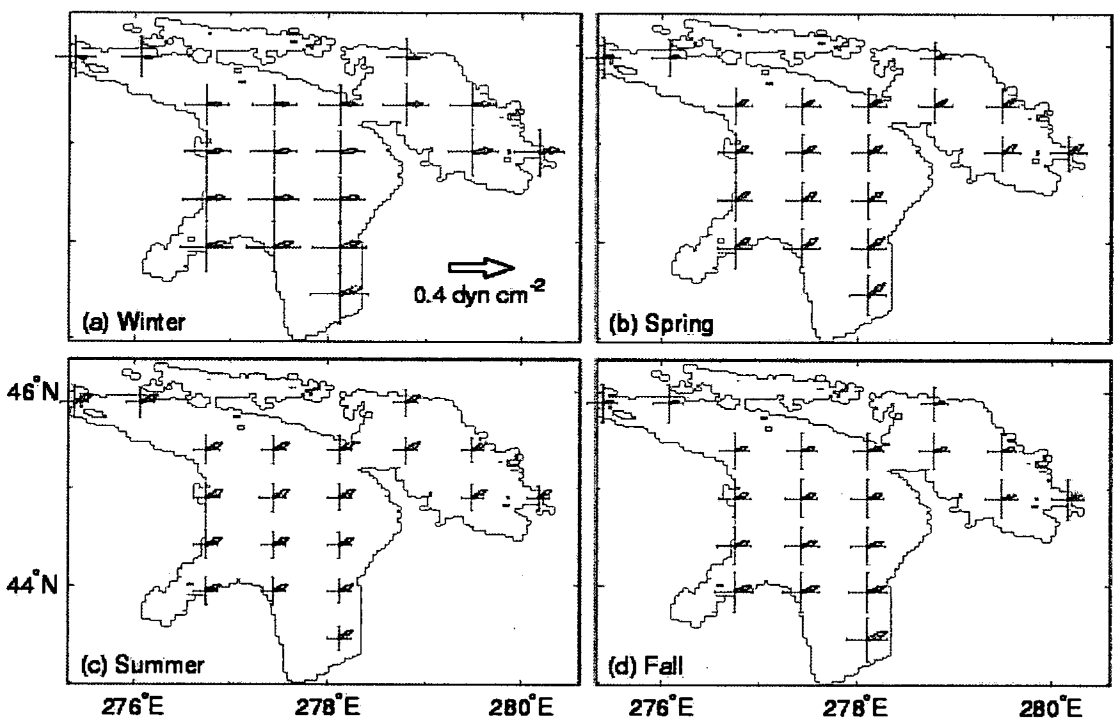

Figure 3: Seasonal mean wind stress (arrows) in 1974 calculated from 12 hourly wind speeds interpolated onto the model grid from the NCEP/NCAR reanalysis. The length of the error bar represents one standard deviation of the eastward and northward components of the wind stress, respectively.

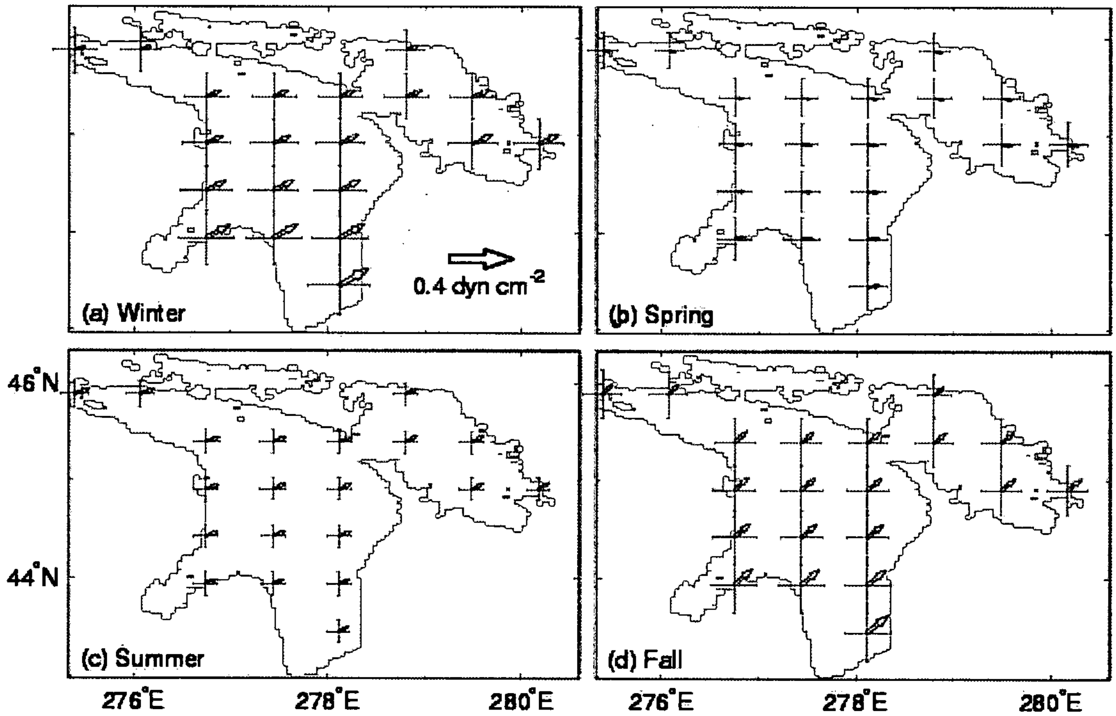

Figure 4: Seasonal mean wind stress (arrows) in 1975 calculated from 12 hourly wind speeds interpolated onto the model grid from the NCEP/NCAR reanalysis. The length of the error bar represents one standard deviation of the eastward and northward components of the wind stress, respectively.

The wind forcing also has large temporal variability at the synoptic scale. To demonstrate this, we calculate the standard deviation of the wind forcing with respect to the season mean in each season (Figures 3 and 4). The temporal variability of the wind stress at the synoptic scale is relatively weaker in summer and stronger in other three seasons in 1974-75. It is interesting to note that the seasonal mean wind stress in spring of 1975 is the weakest, but has large temporal variability that is highly comparable to those in other three seasons of the year.

3. Model results

We initialize the Lake Huron model with spatially uniform temperature of 4°C and salinity of 0.2 ppt at every model grid point, and force the model with 12 hourly wind stress and monthly mean surface heat flux. We integrate the lake model for two years from January 1, 1974 to the end of 1995. As pointed out by Beletsky and Schwab (2001), the typical spin-up time of the lake circulation is relatively short, due mainly to the strong wind-driven character of the lake hydrodynamics. Therefore, the effect of the initial condition on the long-term model simulation should be very small after a few weeks.

3.1 seasonal mean circulation

To demonstrate the model performance in simulating seasonal variability of the lake circulation in the study region, we calculate the seasonal mean currents and temperature distributions in 1974-75 (Figures 5-8). The seasonal mean near-surface (at 1.5 m) circulation in 1974 is characterized by a narrow coastal jet that flows cyclonically along the coast of the Main Lake and Georgian Bay (Figure 5). This cyclonic coastal jet is relatively stronger in summer and fall and relatively weaker in winter and spring. The seasonal mean near-surface circulation in the North Channel and the northern part of Lake Huron is very complex and highly variable with season. Over the central region of the Main Lake, the seasonal mean near-surface circulation in 1974 is relatively weak and roughly southeastward. Over the southern portion of the Main Channel between Lake Huron and Georgian Bay, there is a strong eastward flow that enters Georgian Bay from the southeastern Lake Huron (Figure 5), which is consistent with previous studies.

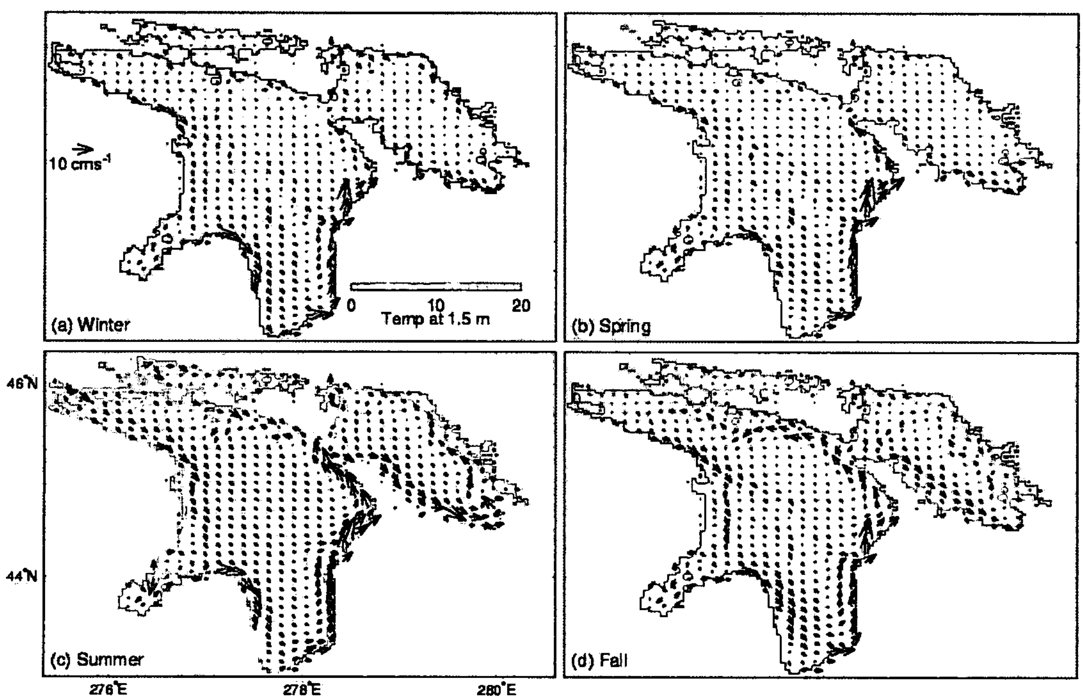

Figure 5: Seasonal mean near-surface (1.5 m) currents and temperature distributions in 1974. Velocity vectors are plotted at every fourth model grid point.

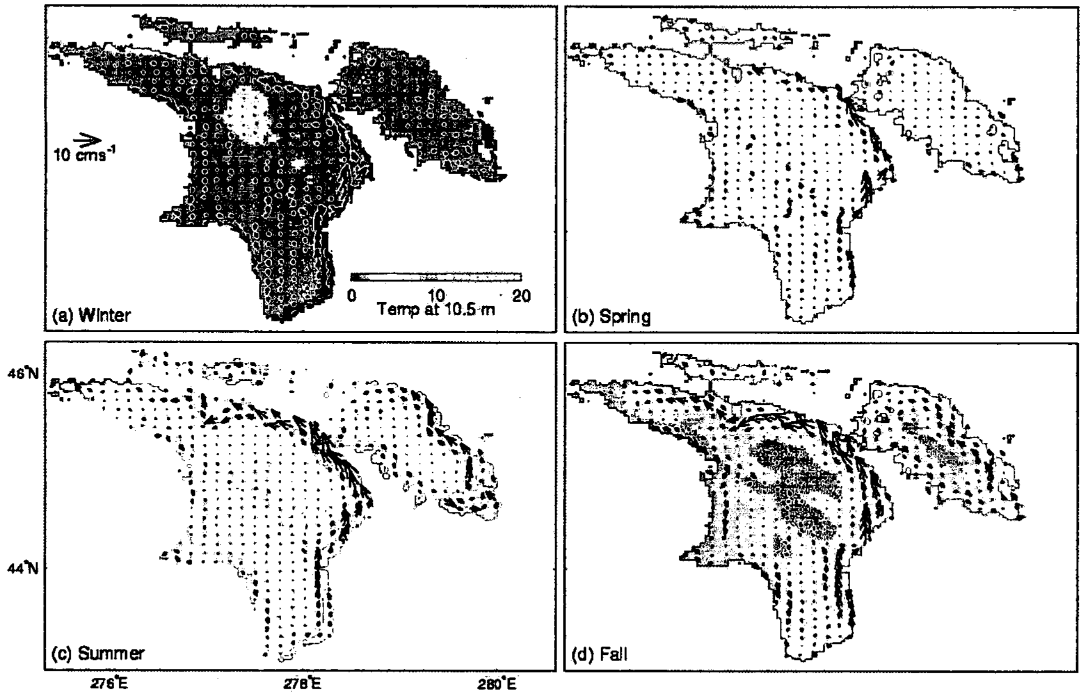

Figure 6: Seasonal mean sub-surface (10.5 m) currents and temperature distributions in 1974. Velocity vectors are plotted at every fourth model grid point.

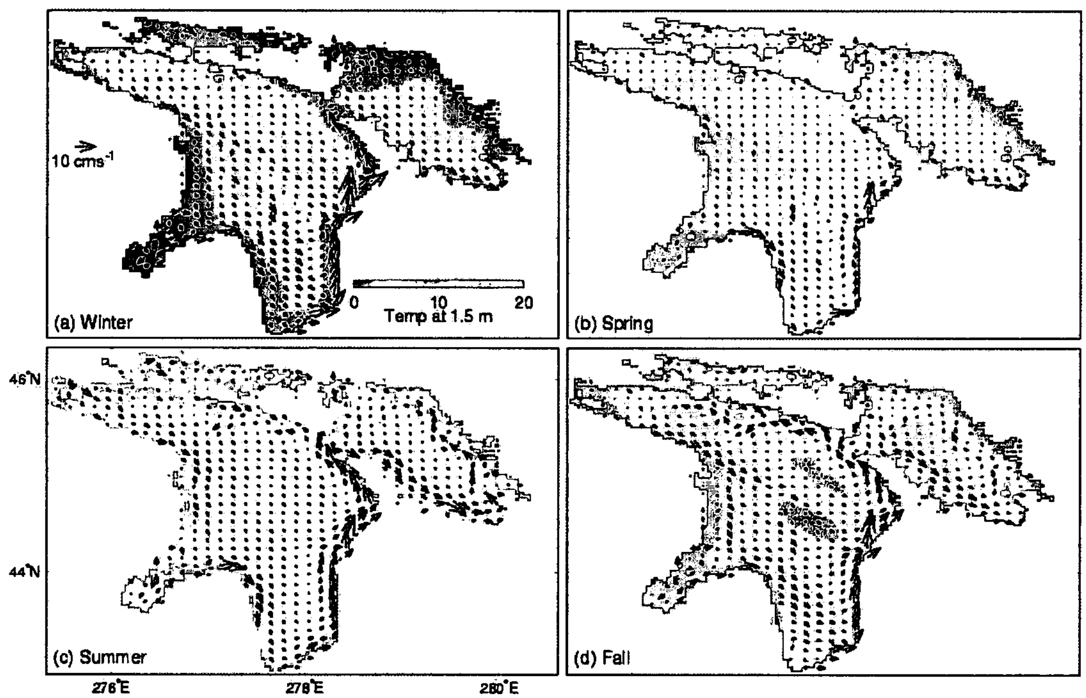

Figure 7: Seasonal mean near-surface (1.5 m) currents and temperature distributions in 1975. Velocity vectors are plotted at every fourth model grid point.

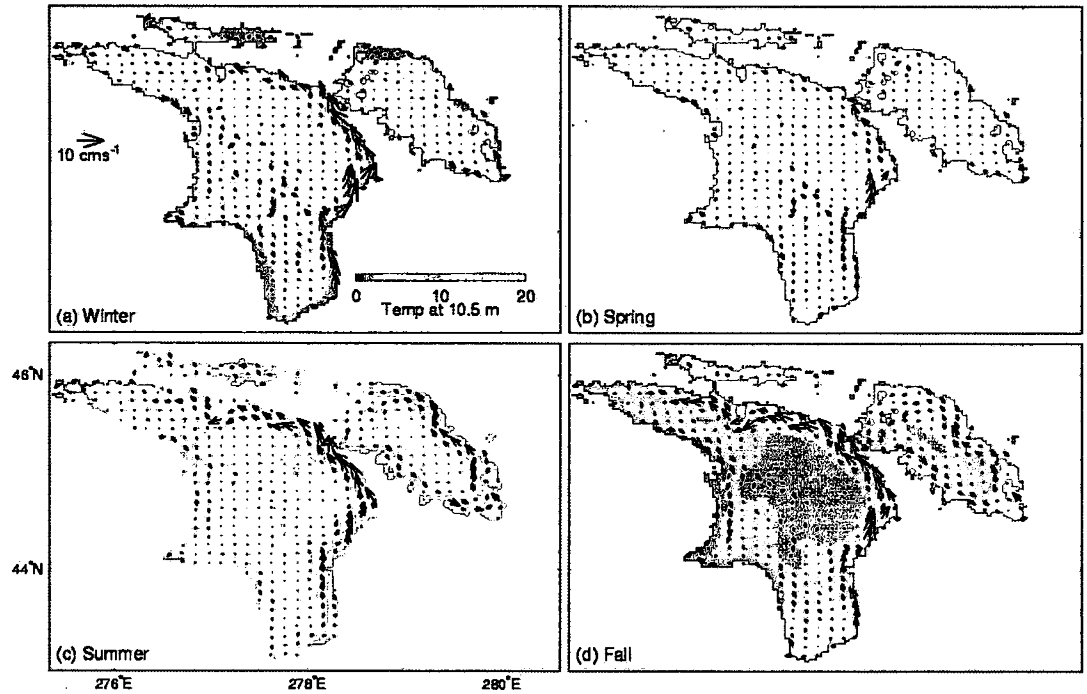

Figure 8: Seasonal mean sub-surface (10.5 m) currents and temperature distributions in 1975. Velocity vectors are plotted at every fourth model grid point.

The seasonal mean near-surface temperature distribution produced by the model is spatially uniform in winter and spring of 1974, which is about 1°C in winter and 4°C in spring. The summer and fall mean near-surface temperatures are also relatively uniform in the interior of the Main Lake and Georgian Bay, and reach about 18°C in summer and 10°C in fall (Figure 5c and d). Over the coastal regions of the Main Lake and Georgian Bay and over the southern North Channel and Saginaw Bay, the near-surface temperatures in summer and fall are about a few degrees warmer than those in the interior.

The seasonal mean sub-surface (10.5 m) currents and temperature distributions are very similar to the near-surface fields in winter and spring of 1974, which are characterized by a strong northward jet along the east coast of the Main Lake and spatially uniform temperature distributions of about 2°C in winter and 4°C in spring in the whole study region (Figures 6a and b). The seasonal mean sub-surface circulation in summer and fall of 1974 consists of an intense coastal jet flowing northward along the east coast and a weak return flow running southward along the west coast of the Main Lake. In Georgian Bay, there is a persistent cyclonic coastal jet at 10.5 m depth in both summer and fall of 1974 (Figures 6c and d). Over the central regions of the Main Lake and Georgian Bay, the seasonal mean sub-surface temperature is about 12°C in summer and 10°C in fall. In comparison with the seasonal mean temperature at 1.5 m (Figure 5), the seasonal mean sub-surface temperature at 10.5 m is about 4°C colder in summer, but almost same as the near-surface temperature in the other three seasons of 1974, indicating that the vertical stratification of temperature is established in summer but reduced or completely eliminated in other seasons. Over the coastal regions of the Main Lake and Georgian Bay, the summer and fall mean sub-surface temperatures are about a few degrees warmer than those in the interior.

The seasonal mean currents and temperature distributions in 1975 (Figures 7 and 8) are highly comparable to those in 1974, except that the winter circulation is relatively stronger and the summer circulation is relatively weaker in 1975 than those in 1974. Beletsky et al. (1999) constructed the seasonal mean circulation in the Great Lakes based on the long-term current observations made during the 1960s and 1980s. They showed that the observed seasonal mean circulation in Lake Huron is cyclonic near the coastal region in both winter and summer. Our model results presented in Figures 6a,c and 7a,c are in general agreement with the observations.

3.2 Annual thermal cycle

One of the most important hydrodynamic features in the Great Lakes is a profound annual cycle of the thermal structure that changes from entirely mixed vertically in later fall and winter to strongly stratified in summer (Boyce et al., 1989). To demonstrate the performance of the z-level CANDIE model in simulating the seasonal cycle of the thermal structure in Lake Huron, we examine the time-depth distributions of simulated temperature fields at four selected sites in Figures 9 and 10. The main reason for choosing these four sites is that current-meter moorings were deployed in 1974-75 and direct comparison of the model results with the observations can be made in the future study.

Due to continuous cooling at the lake surface in winter, strong convection occurs in winter and early spring of 1974, led to vertically uniform temperatures of about 2^{o}C at all the four sites (Figures 9 and 10). The thermal stratification is gradually established in the top 50 m in later spring and summer, but reduced significantly in later fall of 1974 and in winter of 1975 due to surface cooling. The thermal stratification in the upper lake is reestablished in summer 1975, but erased again in later fall of the year. It should be note that the simulated thermal structures presented in Figures 9 and 10 are highly comparable to those produced by the sigma-level model in Lake Michigan made by Beletsky and Schwab (2001).

3.3 Synoptic variability of simulated lake currents

Figures 11-14 present time series of simulated horizontal currents at three depths of 1.5 m, 10.5 m and 19.5 m at the four sittes. The near-surface currents have large synoptic variability, particularly at site C, which is located at the central region of the Main Lake. The synoptic variability decreases significantly with depth.

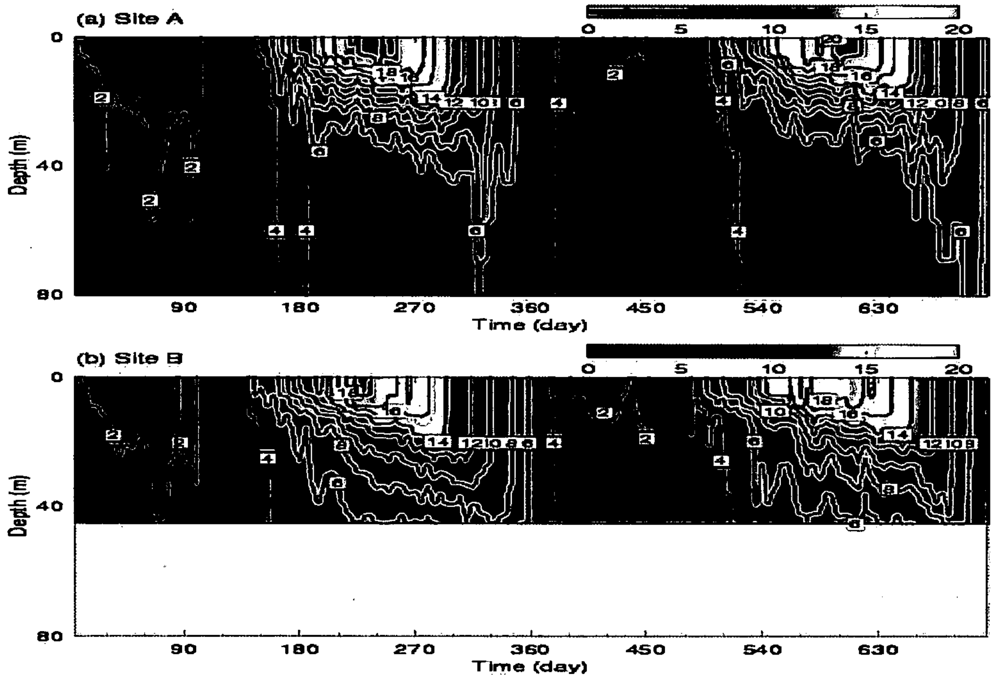

Figure 9: Time-depth distributions of model calculated temperature for the two-year period starting from January 1, 1974 to the end of 1975 at sites A and B.

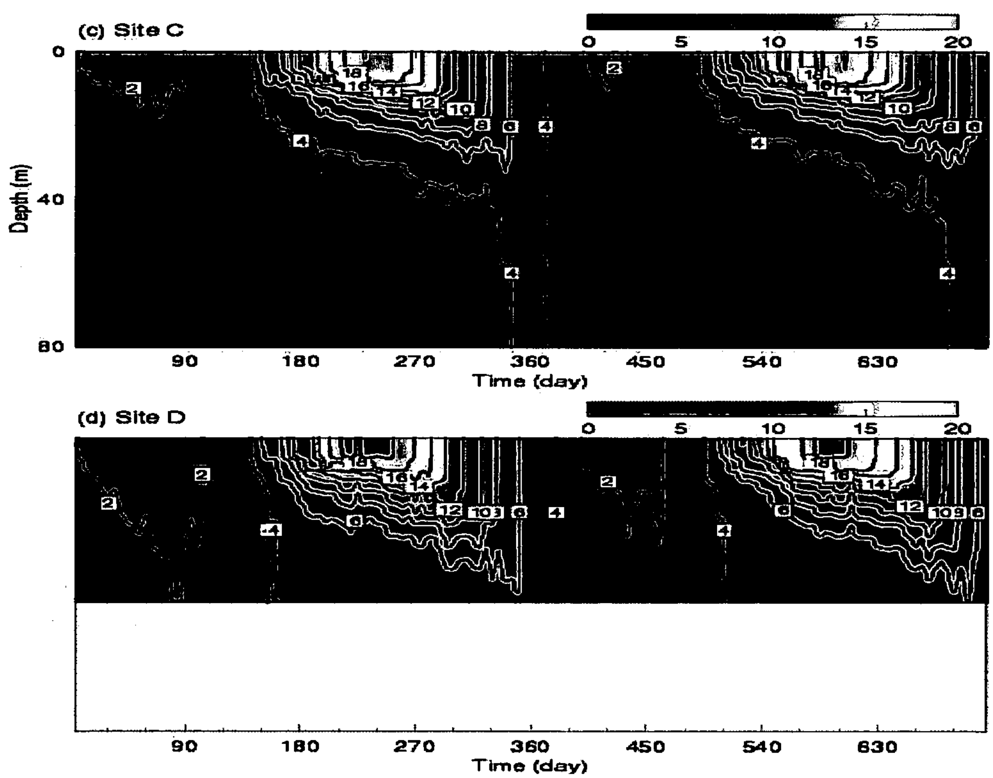

Figure 10: Time-depth distributions of model calculated temperature for the two-year period starting from January 1, 1974 to the end of 1975 at sites C and D.

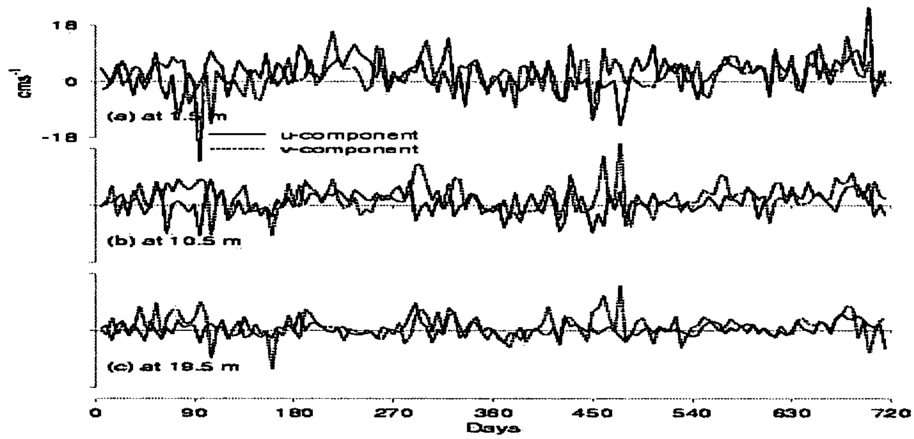

Figure 11: Timeseries of eastward (red) and northward (blue) components of simulated currents at three depths of 1.5 m, 10.5 m and 19.5 m at site A.

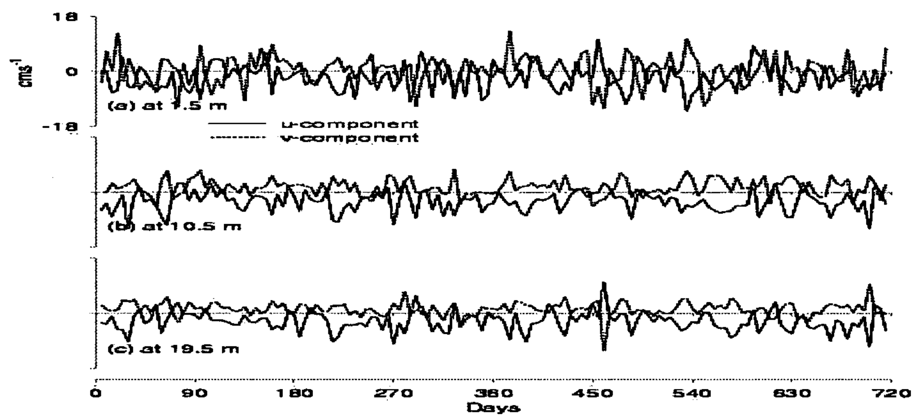

Figure 12: Timeseries of eastward (red) and northward (blue) components of simulated currents at three depths of 1.5 m, 10.5 m and 19.5 m at site B.

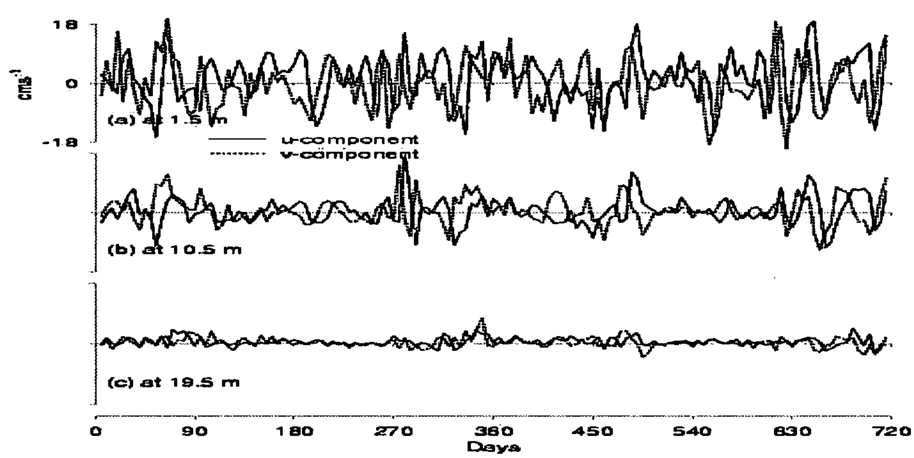

Figure 13: Timeseries of eastward (red) and northward (blue) components of simulated currents at three depths of 1.5 m, 10.5 m and 19.5 m at site C.

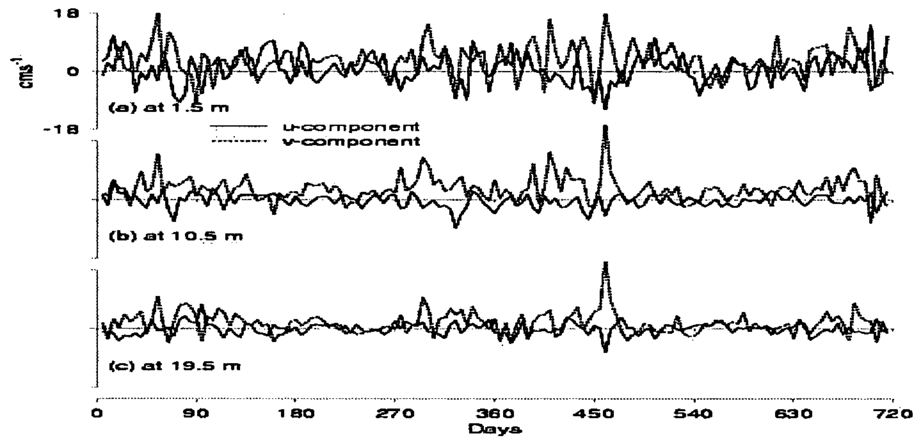

Figure 14: Timeseries of eastward (red) and northward (blue) components of simulated currents at three depths of 1.5 m, 10.5 m and 19.5 m at site D.

4. Summary and future work

We developed a three-dimensional hydrodynamic model for Lake Huron and Georgian Bay based on the primitive equation z-level ocean circulation model known as CANDIE. We used this lake circulation model in the numerical studies of large-scale circulation and temperature distributions in 1974-75. During this period an extensive field program was conducted in Lake Huron. We forced the model with monthly mean net heat flux and 12 hourly wind stress calculated from the wind speeds extracted from the coarse-resolution NCEP/NCAR reanalysis data. The model results generate a cyclonic coastal jet in both Lake Huron and Georgian Bay, which is relatively stronger in summer and fall than those in other seasons. The model also generates reasonably well the seasonal evolution of thermal stratifications in the upper 50 m in the lake. The model results presented in this report demonstrated clearly the suitability of the z-level CANDIE model in simulating the large-scale hydrodynamics in lakes. Our future work will include (1) investigation of the effect of inflows and outflows through the model open boundaries on the general circulation in the lake; (2) sensitivity studies of model results to the surface heat flux boundary condition and the sub-grid scale vertical and horizontal mixing parameterizations; (3) assessment of the model performance by comparing the model results with the current and temperature measurements in 1974-75; and (4) simulations of the general circulation, thermal structures and associated seasonal variability in later 1990s.

Appendix: Basic Equations of the Ocean Circulation Model

The three-dimensional primitive equation ocean circulation model known as CANDIE (http://www.phys.ocean.dal.ca/programs/CANDIE, or see Sheng et al. 1998; Sheng et al. 2001) is used in this study. The governing equations of the model can be written in spherical coordinates as

Governing Equations

$$\frac{\partial u}{\partial t} + \mathcal{L}u - fv = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \mathcal{F}_m u$$
$$\frac{\partial v}{\partial t} + \mathcal{L}v + fu = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} + \mathcal{F}_m v$$
$$\frac{\partial p}{\partial z} = -\hat{\rho} g$$
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$
$$\frac{\partial (T,S)}{\partial t} + \mathcal{L}(T,S) = \mathcal{F}_h(T,S)$$

$$\mathcal{L}Q = u\frac{\partial Q}{\partial x} + v\frac{\partial Q}{\partial y} + w\frac{\partial Q}{\partial z}$$
$$\mathcal{F}_{(m,h)}Q = \mathcal{D}_{(m,h)}Q + \frac{\partial}{\partial z}\left(K_{(m,h)}\frac{\partial Q}{\partial z}\right)$$
$$\mathcal{D}_{(m,h)}Q = \frac{\partial}{\partial x}\left(A_{(m,h)}\frac{\partial Q}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_{(m,h)}\frac{\partial Q}{\partial y}\right)$$

where *u, v* and *w* are the east, north and vertical components of the flow, p is pressure, and ρ is the density calculated from the model potential temperature *T* and salinity *S* which, in turn, are updated using the conservation equations. Here K_m and K_h are vertical eddy viscosity and diffusivity coefficients, *f* is the Coriolis parameter, *L* is an advection operator, D_m and D_h are diffusion operators, and A_m and A_h are horizontal eddy viscosity and diffusivity coefficients, respectively.

The model uses the subgrid-scale mixing parameterization scheme of Smagorinsky (1963) for the horizontal eddy viscosity A_m and the schemes proposed by Large et al. (1994) for the vertical mixing coefficients K_m and K_h. The turbulent Prandtl Number $A_h/A_m$is set to 0.1. The model uses the fourth-order numerics (Dietrich 1997) and Thuburn's (1996) flux limiter to discretize the nonlinear advection terms.

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