

## Numerical study of dispersion and hydrodynamic connectivity of near-surface waters in Lake Huron

Jun Zhao, Yerubandi R. Rao and Jinyu Sheng

### ABSTRACT

A nested-grid hydrodynamic modeling system is used to examine the circulation and dispersion in Lake Huron and adjacent areas with specific attention to physical parameters pertinent to the estimation of hydrodynamic connectivity of near-surface waters. The nested system is forced by monthly mean surface heat flux and 12-hourly wind stress computed from wind speeds extracted from the National Centers for Environmental Prediction of the National Center for Atmospheric Research (NCEP/NCAR) 40-year reanalysis data. The three-dimensional model currents are used to calculate the retention and dispersion of conservative, near-surface particles carried by the currents. The near-surface dispersion is relatively low in Saginaw Bay, eastern Georgian Bay and the eastern North Channel; and relatively high over the western part of the main lake and the coastal region of south Lake Huron. The hydrodynamic connectivity in the surface water and connectivity matrices are calculated from particle movements carried passively by model currents superposed by a random walk process. The model results demonstrate that the hydrodynamic connectivity in the North Channel and Georgian Bay (ranging from 0.9 to 2.2%) is much weaker than those in the main lake (5.3 to 21.9%).

**Key words** | circulation, connectivity, dispersion, Lake Huron, model

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### INTRODUCTION

Lake Huron is the second largest Laurentian Great Lake and the fifth largest freshwater lake in the world. It contains a volume of 3,540 km<sup>3</sup>, and a shoreline of 6,157 km. It has horizontal dimensions of about 330 km east to west and 290 km north to south, with a maximum water depth of 230 m and an average water depth of about 60 m. Lake Huron is hydrologically inseparable from Lake Michigan, joined by the wide Straits of Mackinac (Saylor & Sloss 1976). Lake Superior drains into the St. Marys River which flows southward into Lake Huron. The water then flows south through the St. Clair River into Lake St. Clair, which in turn discharges through the Detroit River into Lake Erie.

Although Lake Huron retains much of its historic fish and wildlife habitats due to relatively low human population densities over the sides of the lake, the biological diversity in the region has been compromised by human influences ([http://binational.net/lakehuron\\_e.html](http://binational.net/lakehuron_e.html)). Fish and wildlife

in the region continue to be exposed to a multiplicity of physical, chemical, and biological stresses, such as degradation and loss of historical habitat in tributaries and near-shore habitat, eutrophication in localized areas, effects of harmful exotic species, effects of overfishing, and impact of persistent toxic contaminants. Contaminants in the near-shore are another concern for lake-wide management in the lake. Contaminants to Lake Huron originate from many sources, including industrial and municipal discharges, spills, landfills, storm sewers, and agricultural runoff. Furthermore, Lake Huron has a long retention time (more than 20 years) and large surface areas, which have resulted in the buildup of persistent substances that bioaccumulate in fish and wildlife.

Impairments of nearshore water quality along portions of southeastern Lake Huron have been a major public concern in recent years. In 2004, the Lake Huron Science

Committee (LHSC) led by the Ontario Ministry of the Environment (MOE) conducted a scientific examination of bacterial inputs to beaches of the Huron County Shoreline (LHSC 2005). Bacteria pollution data showed high frequencies and duration of exceedance above the standard level set for *Escherichia coli* (*E. coli*), resulting in frequent beach postings and/or closures set by the local authorities. Algal blooms occur in nutrient-enriched waters in some parts of Lake Huron, for example, Saginaw Bay. Although localized, elevated concentrations of nutrients in some watercourses along the eastern shoreline and Georgian Bay also resulted in algal blooms (LHSC 2005).

Physical processes in the Great Lakes occur over several temporal and spatial scales and influence the transport and deposition of nutrients and contaminants in the lakes (Rao & Schwab 2007). Compared to the lower Great Lakes (Ontario and Erie) and Lake Michigan, Lake Huron has received little attention in the studies of thermal structure and hydrodynamics. During the Upper Lakes Reference Study in 1974–1975, several current meters and temperature moorings were deployed in Lake Huron (Sloss & Saylor 1975). The current meter observations showed a basin-scale cyclonic gyre in the mean circulation, which is relatively weaker in summer compared with that in winter. On the other hand, circulation and thermal structure of Lake Huron have also been studied using numerical models developed for the Great Lakes. For example, Schwab & Bedford (1994) developed a real-time Great Lakes forecasting system using a three-dimensional (3D) terrain-following (or sigma-level) ocean circulation model known as the Princeton Ocean Model (POM, Mellor 2004). Currently the horizontal resolution of this system is coarse for using in the nearshore water quality assessments. Because of this reason, Sheng & Rao (2006) developed a nested-grid modeling system for Lake Huron and Georgian Bay based on a 3D primitive equation z-level ocean circulation model known as CANDIE (Canadian version of DieCAST, Sheng et al. 1998). That was the first attempt to apply a nested-grid modeling system to simulate the 3D circulation, thermal structure and associated seasonal variability in Lake Huron and adjacent Georgian Bay. Their model results were assessed using the currents and temperature observations made in the lake during the Upper Lake Reference Study. The model results showed a cyclonic coastal jet in both Lake Huron and

Georgian Bay. Further, the model reproduced the typical seasonal evolution of thermal structure in the upper 30 m in the lake reasonably well.

The physical transport processes are a dominant mechanism in mediating biological and geochemical processes in lakes. For example, the rate of horizontal mixing and dispersion of nutrients and contaminants determine the concentration gradients and their persistence to affect lake biology and chemistry. Several authors noted that retention time scales relative to reaction rates influences lake biology and in the formation of algal blooms (Imberger et al. 1983; Martin 2003). Hydrodynamic connectivity, or exchange, among marine populations has profound implications for population dynamics and genetics of marine organisms having a waterborne dispersive phase (Cowen et al. 2006). Comprehensive ecosystem models coupled with hydrodynamic models have been developed for the Great Lakes, for example, Lake Erie (Leon et al. 2006; Zhang et al. 2008) and Lake Michigan (Ji et al. 2002). However, such coupled models are relatively complex, and require large amounts of data and significant computational resource. On the other hand, particle transport models, which use output from circulation models, are computationally efficient and very useful in assessing the transport of both passive and active tracers for many applications. In one such example, Beletsky et al. (2007) developed a 3D physical-biological model of larval fish based on POM in Lake Michigan. They showed that physical processes play an important role in structuring the recruitment dynamics of Great Lakes fishes. More recently, several studies were carried out to assess geospatial and nearshore hydrodynamic characteristics in the Huron–Erie Corridor (<http://huron-erie.org/>) with a goal to provide natural habitat attributes including geomorphology, flow and thermal regimes for fish habitat restoration in the lake. These studies identified an urgent need to predict the circulation and associated hydrodynamics and ecological connectivity in these lakes.

In this study the particle retention, dispersion, and hydrodynamic connectivity in near-surface waters in Lake Huron and Georgian Bay are calculated by using a particle transport model coupled to a nested-grid circulation model. The arrangement of this paper is as follows. The following section briefly describes the nested-grid modeling system, external forcing, and initial conditions used in the numerical

experiments. The section entitled Monthly mean circulation and model validation presents an example of the numerical simulations of circulation patterns during June 1974. This is followed by a section discussing the retention and dispersion of passive particles released at the near-surface in June of 1974. The penultimate section presents the hydrodynamic connectivity among nine sub-regions within the lake, followed by a summary of the results.

## THE NESTED-GRID CIRCULATION MODELING SYSTEM

The nested-grid modeling system used in this study is based on the 3D primitive equation z-level ocean circulation model known as CANDIE (Sheng *et al.* 1998), which has been successfully applied to various modeling problems in the coastal oceans and lakes (Davidson *et al.* 2001; Lu *et al.* 2001; Sheng & Rao 2006; Yang *et al.* 2008). The nested-grid modeling system has two sub-components: a coarse-resolution outer model covering Lake Huron (LH) and Georgian Bay (GB) between 79.4°W and 84.7°W and between 43°N and 46.3°N; and a fine-resolution inner model covering southeastern Lake Huron between 81.2°W and 82.2°W and between 43.1°N and 44.5°N (Figure 1). The outer model is adapted from Sheng & Rao (2006) with a horizontal resolution of about 2.5 km. The inner model covers the Lake Huron southeastern shores of Huron County with a horizontal resolution of about 0.9 km. The main reason for setting up the inner model over this region is to examine the dispersion and connectivity in the surface water in response to the increasing concern about the pollutant along the southeast shoreline. Both the inner and outer models have the same 30 unevenly spaced z-levels in the vertical. The conventional one-way nesting technique is used in this study, in which the currents and temperature field produced by the outer model are used to specify the flow and temperature distributions at the open boundaries of the inner model.

The nested-grid modeling system uses the hydrostatic and Boussinesq approximations in the model governing equations with the fourth-order numerics (Dietrich 1997) and a flux limiter (Thuburn 1996) to reduce numerical dispersion of the advection terms in the model. The model

uses the scheme of Large *et al.* (1994) for the vertical eddy mixing coefficient and the mixing scheme of Smagorinsky (1963) for the horizontal eddy viscosity coefficient  $A_m$  defined as:

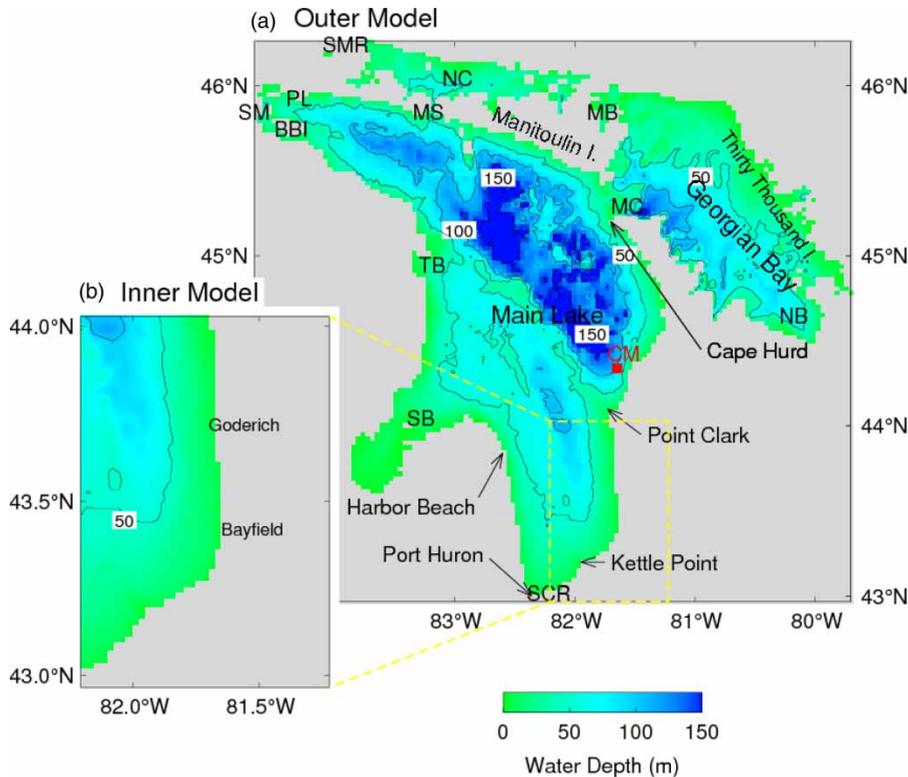
$$A_m = c\Delta x\Delta y\sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2} \quad (1)$$

where  $\Delta x$  and  $\Delta y$  are the grid spacing,  $u$  and  $v$  are the eastward and northward components of currents, and  $c$  is set to 0.1. The inverse horizontal turbulent Prandtl Number (the ratio of the eddy diffusivity  $A_h$  to the eddy viscosity  $A_m$ ) is set to 0.1. A quadratic bottom stress parameterization is used with a drag coefficient of  $2.5 \times 10^{-3}$  (Simons 1974).

The nested-grid modeling system is forced by the time-varying but spatially uniform wind stress and net heat flux at the lake surface. The wind stress used in this study is calculated using the bulk formula of Large & Pond (1981) from the wind speeds extracted from the National Centers for Environmental Prediction of the National Center for Atmospheric Research (NCEP/NCAR) 40-year reanalysis dataset (Kalnay *et al.* 1996). The amplitudes of the NCEP/NCAR wind fields were modified based on the observed wind speeds in Lake Huron (Sheng & Rao 2006). The net heat flux at the lake surface ( $Q_{\text{net}}$ ) is given by:

$$Q_{\text{net}} = Q_{\text{net}}^{\text{input}} + \gamma(LST^{\text{input}} - LST^{\text{model}}) \quad (2)$$

where  $Q_{\text{net}}^{\text{input}}$  is the input net heat flux (NHF),  $LST^{\text{input}}$  is the input lake surface temperature (LST),  $LST^{\text{model}}$  is the model-calculated LST, and  $\gamma$  is the coupling coefficient defined as  $\Delta z_1 \rho_o c_p / \tau$ , in which  $\Delta z_1$  is the thickness of the top z-level,  $c_p$  is the specific heat, and  $\tau$  is the restoring time scale set to 15 days. Because of the lack of reliable observations of the input net heat flux,  $Q_{\text{net}}^{\text{input}}$  is assumed to be horizontally uniform and equals to the climatological monthly mean NHF calculated from results produced by the Great Lakes Net Basin Supply Forecast (GLNBSF) Model (<http://mcc.sws.uiuc.edu/glakes/hur/nhu.html>).  $LST^{\text{input}}$  is also assumed to be horizontally uniform and equal to the linear combination of observed LST and the climatological monthly mean LST ( $LST^{\text{clim}}$ ) calculated from the GLNBSF model results during the



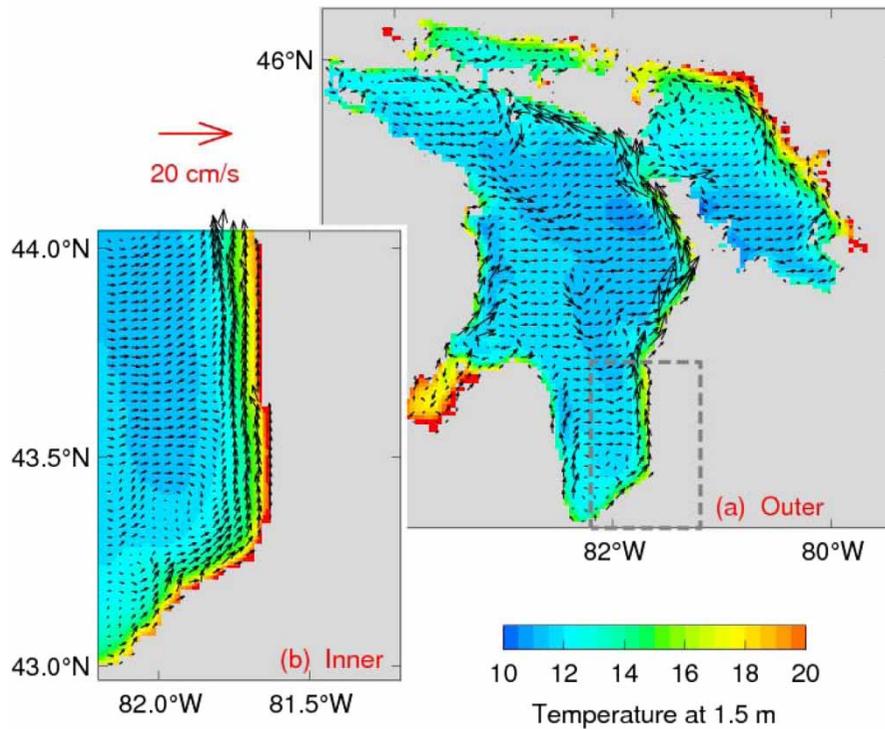
**Figure 1** | Selected bathymetric features for the nested-grid modeling system, which consists of (a) the coarse-resolution outer model covering Lake Huron and Georgian Bay, and (b) the fine-resolution inner model covering the southeast shoreline of Lake Huron. Abbreviations are used for St Mary's River (SMR), St Clair River (SCR), straits of Macinac (SM), Patrick Landing (PL), Bois Blanc Island (BBI), Mississagi Strait (MS), Main Channel (MC), North Channel (NC), Thunder Bay (TB), Saginaw Bay (SB), Nottawasaga Bay (NB), and Manitowaning Bay (MB). Current meter site is marked by a solid square.

observation period, and equals to  $LST^{clim}$  at other times (see Sheng & Rao (2006) for details).

The model is integrated from the rest, with the model time step of 15 minutes for the outer model and 4.5 minutes for the inner model. Previous observations in Lake Huron demonstrate that, during early April, water temperatures in the lake are close to  $4^{\circ}\text{C}$  with small vertical gradients due to the convective overturns during this period. Therefore, the nested modeling system is integrated from April to October in 1974, and initialized with a spatially uniform temperature of  $4^{\circ}\text{C}$  and salinity of 0.2 psu at every grid point. It should be noted that, due to the strong wind-driven character of the lake hydrodynamics, the spin-up time of the lake circulation is relatively short (Beletsky & Schwab 2001). Therefore the effect of the initial conditions on the long-term model simulations should be negligible after a few weeks.

## MONTHLY MEAN CIRCULATION AND MODEL VALIDATION

Figure 2 shows the monthly mean near-surface (1.5 m) circulation and temperature produced by the nested-grid modeling system in June 1974. The June mean currents produced by the outer model feature southeastward/eastward currents in the Main Lake basin, and a cyclonic coastal jet flowing first northward along the east coast from Kettle Point to Cape Hurd and then veering northwestward along the southwestern shoreline of Manitoulin Island to Patrick Landing, with a small branch turning eastward to flow into Georgian Bay. There are two less intense anti-cyclonic coastal jets flowing northward along the west coast, one from Port Huron to Harbor Beach, the other between Saginaw Bay and Thunder Bay. The June mean near-surface currents are approximately eastward in central Georgian Bay. A strong northwestward coastal current was running over eastern Georgian Bay



**Figure 2** | Monthly mean near-surface (1.5 m) currents and temperature distribution in June 1974. Velocity vectors are plotted at every third model grid point for (a) outer model results, and at every fourth grid point for (b) inner model results.

from Nottawasaga Bay to Manitowaning Bay. **Figure 2** also demonstrates that the near surface water in June is warmer over the narrow coastal regions close to the shore in Lake Huron and Georgian Bay, with the warmest temperature being about 20 °C in Saginaw Bay and along coastal regions of Thirty Thousand Islands. In the central regions of Lake Huron and Georgian Bay, the near-surface temperature in June is relatively colder and about 11 °C.

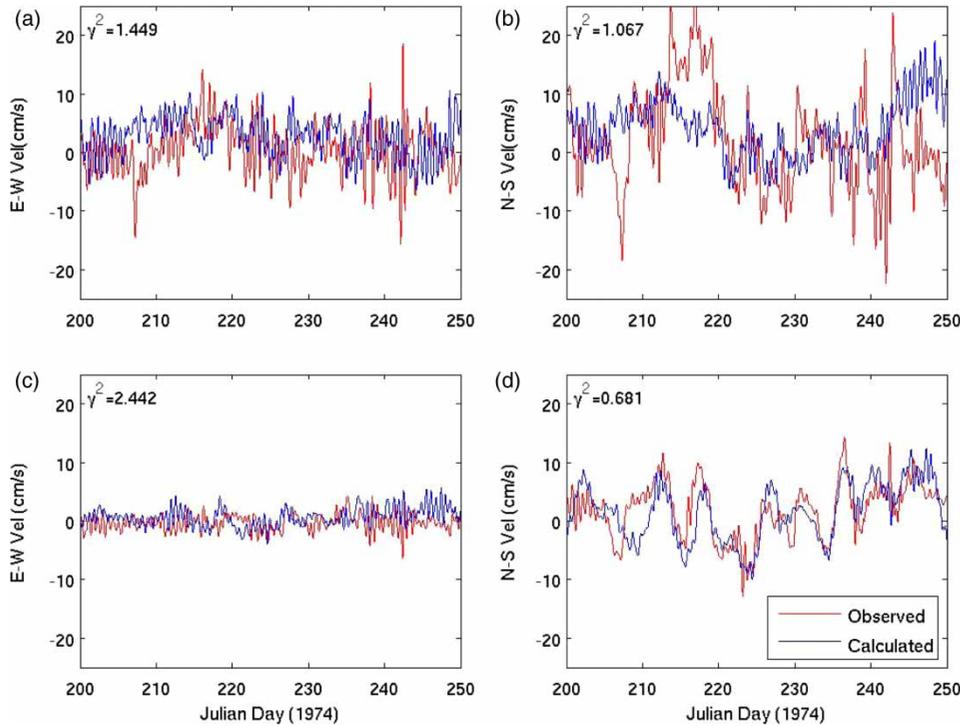
The monthly mean near-surface currents produced by the nested-grid modeling system in other months have similar large-scale circulation features as in June, with a strong cyclonic coastal jet along the shoreline and relatively weak southeastward currents over the central region of the Main Lake. The thermal structure in the lake produced by the model has significant seasonal variations in the lake, which changes from vertically well mixed in late fall and early spring to strongly stratified in summer.

To examine the model performance in simulating hydrodynamics in Lake Huron, the model results are compared with the observed currents at site CM from Julian day 200 (18 July) to 250 (6 September) 1974 in **Figure 3**. The model

skill is quantified in terms of the  $\gamma^2$  value, which is defined as the variance of the model errors (differences between the observations and model results) normalized by the observed variance. The  $\gamma^2$  value is zero if the model results fit the observations perfectly. Otherwise, a larger  $\gamma^2$  value indicates that the model produces less well the observations. The  $\gamma^2$  values of northern and southern components of the currents (alongshore currents) are 1.07 at 10 m and 0.68 at 40 m. By comparison, the eastern and western components of the currents (cross-shore currents) are not simulated well with higher  $\gamma^2$  values of 1.45 at 10 m and 2.44 at 40 m. More discussion of seasonal variations of the circulation and thermal structure and validation of the lake-wide model results can be found in [Sheng & Rao \(2006\)](#).

## RETENTION AND DISPERSION OF NEAR-SURFACE PARTICLES

The dispersion and retention in Lake Huron and Georgian Bay are examined based on horizontal movements



**Figure 3** | Comparison of time series of observed and modeled velocity components at 10 m (a) and (b); 40 m (c) and (d) at site CM.

of conservative particles carried passively by model currents. The horizontal movements of passive particles are calculated numerically using the fourth-order Runge-Kutta scheme (Press *et al.* 1989) based on

$$\vec{x}(t_0 + \Delta t) = \vec{x}(t_0) + \int_{t_0}^{t_0 + \Delta t} \vec{u}(\vec{x}, t) dt + \vec{\delta} \quad (3)$$

where  $\vec{x}(t_0 + \Delta t)$  and  $\vec{x}(t_0)$  are horizontal position vectors of a passive particle at time  $t_0 + \Delta t$  and initial time  $t_0$  respectively;  $\vec{u}(\vec{x}, t)$  is the horizontal velocity vector of model currents;  $\Delta t$  (1 hour) is the time step used in the numerical integration, which is much greater than the time steps used in the numerical simulation of the nested-grid modeling system; and  $\vec{\delta}$  is additional random horizontal displacements used to represent the influence of physical processes that are not modeled explicitly in this study (such as displacements associated with turbulent flow or currents driven by high-frequency wind forcing, both of which are not simulated by the nested-grid modeling system). We follow Hannah *et al.* (1997)

and express  $\vec{\delta}$  as

$$\vec{\delta} = (\xi\sqrt{2\kappa\Delta t}, \zeta\sqrt{2\kappa\Delta t}) \quad (4)$$

where  $\xi$  and  $\zeta$  are random deviates from a Gaussian distribution of zero mean and unit variance respectively, and  $\kappa$  is an additional horizontal eddy diffusivity for the random displacements which is set to  $2 \text{ m}^2 \text{ s}^{-1}$  (Rao & Murthy 2001).

To quantify retention and dispersion of passive particles, we follow Cong *et al.* (1996) and Sheng *et al.* (2009), and define the retention index as

$$R(\vec{x}, t) = \frac{N(\vec{x}, t)}{N(\vec{x}, t_0)} \quad (5)$$

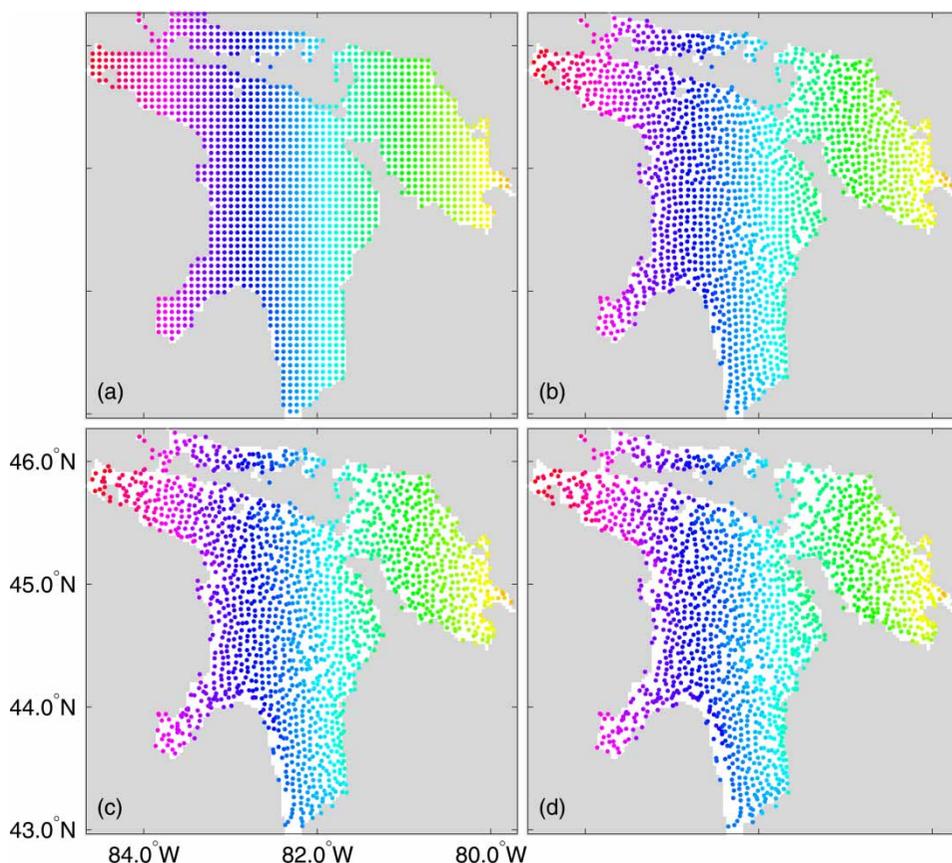
where  $N(\vec{x}, t_0)$  is the number of particles released initially in a sub-area of a given size centered at  $\vec{x}$  at initial time  $t_0$ , and  $N(\vec{x}, t)$  is the number of original particles remaining within the sub-area at some later time  $t$ . The retention index defined above represents the proportion of particles released in a

given sub-area at  $t_0$  remaining inside the sub-area at a later time  $t$ . The value of  $R$  is between 0 and 1, with higher values corresponding to higher retention of particles. In the case of  $R=0$ , all the particles are flushed from the given sub-area between time  $t_0$  and  $t$ . Once the retention index  $R$  is known, the dispersion rate can readily be calculated from  $(1 - R(\bar{x}, t))$ . Therefore only the calculation and discussion of the retention index are discussed in this study.

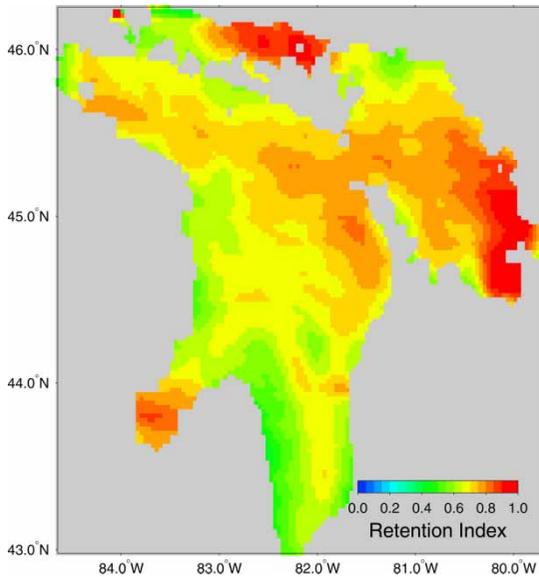
The velocity field used to calculate the particle trajectories is the monthly mean currents produced by the nested-grid modeling system. The passive particles are released in the surface layer of the lake, and are assumed to be non-reactive and neutrally buoyant. Each particle can be considered as a small parcel of water and do not affect the density of water. The movement of each particle is the combination of movements carried passively by the

mean velocity field produced by the model and a stochastic component (random walk) described in Equation (4). The passive particles are released uniformly in the surface water of Lake Huron and Georgian Bay on June 1 (Julian day 152, Figure 4(a)). Figure 4(b)–(d) shows the positions of the particles after 3, 6, 9 days of continuous advection and diffusion. The latter is mainly associated with the random walk process described in Equation (4). During the 9 days of movements, the near-surface particles are carried by the June mean currents away from their original positions. Particle movements are large along the south-eastern coastline, resulting from the intense coastal jet in this area.

Based on the horizontal movements of particles, the retention index for surface waters in Lake Huron can be calculated using Equation (5). The sub-area used in the calculation of the retention index is a square box with the



**Figure 4** | Horizontal positions of near-surface particles (1.5 m) that are advected passively by June mean near-surface currents produced by nested-grid outer model at day (a) 152.0, (b) 155.0, (c) 158.0, and (d) 161.0 in 1974. Particles are color-coded to indicate the starting positions at day 152.0. The full color version of this figure is available online at <http://www.iwaponline.com/wqjrc/toc.htm>.



**Figure 5** | Distribution of retention indices in Lake Huron in June 1974 based on the horizontal movements of near-surface particles advected by June mean near-surface currents produced by the nested-grid outer model.

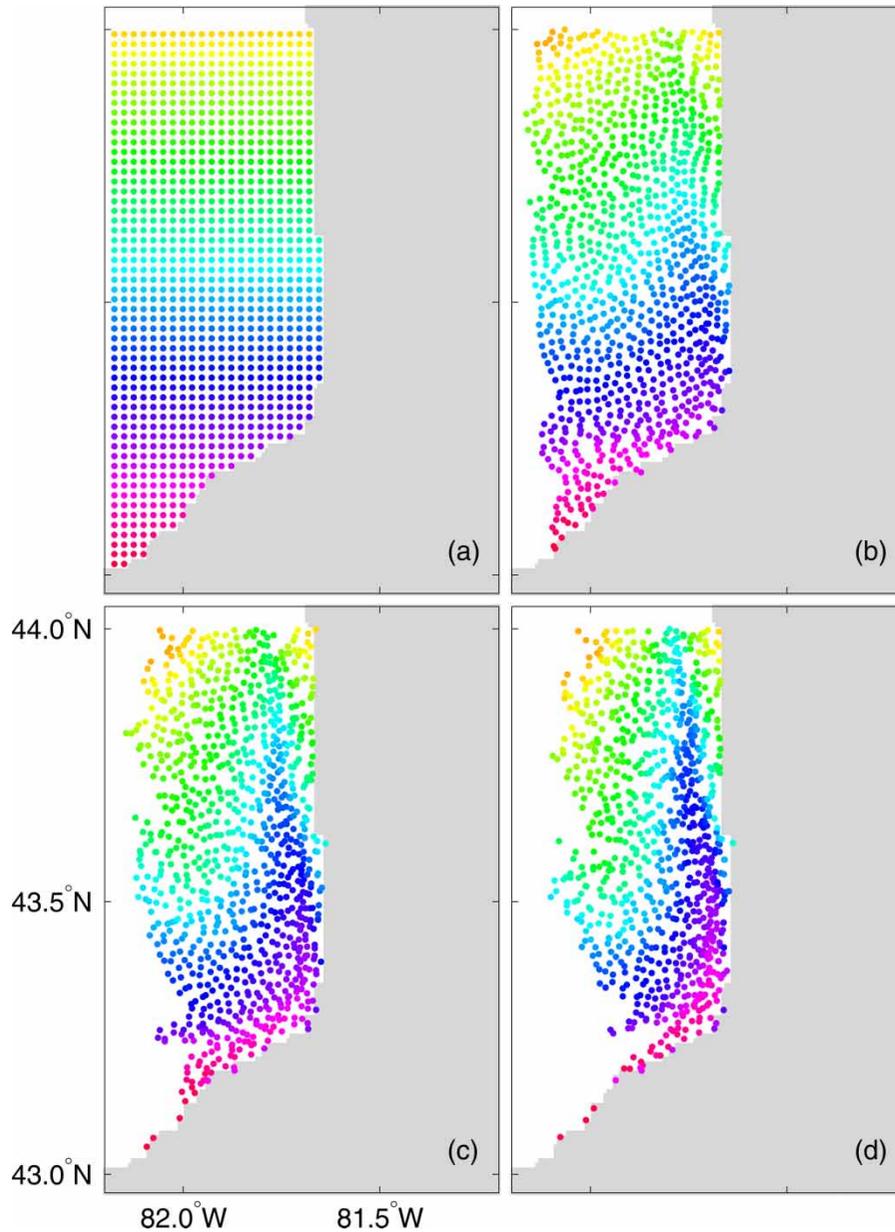
horizontal dimensions of  $50 \times 50$  km. Within each box, near-surface passive particles are released uniformly with 80 particles per  $\text{km}^2$ . Figure 5 presents the retention indices of near-surface waters for a 9-day period from day 152 to 161 calculated from the monthly mean current in June 1974. The 9-day retention is small and about 0.4 near the coastal region in south Lake Huron due to the strong coastal jet. The high retention indices of greater than 0.8 occur in Saginaw Bay, the eastern North Channel, and eastern Georgian Bay, resulting from relatively weak currents over these regions. It should be noted that the computed retention indices shown in Figure 5 are not very sensitive to the choice of the dimensions of the box (or sub-area) used in the calculation. Nevertheless, the computed indices will be too noisy if the area of the box is too small and too smooth if the area of the box is too large.

We next examine the horizontal movements of passive particles in southeastern Lake Huron calculated from the near-surface (1.5 m) currents produced by the fine-resolution inner model. Figure 6(a)–(d) shows the original positions of near-surface particles and positions of particles after 3, 6, and 9 days of advection and diffusion, respectively. The near-surface particles have significant northeastward movements along the coast associated with relatively strong coastal currents. The particles near

Kettle point area are carried to Bayfield beach area by day 9. In comparison with the particle movements over southeastern Lake Huron calculated from the outer model currents shown in Figure 4, the particle movements shown in Figure 6 demonstrate a clear pathway for near-surface particles of moving from the area close to Kettle Point to the coastal waters of southeastern Lake Huron, indicating the advantage of the fine-resolution inner model over the coarse-resolution outer model in simulating circulation and particle movements over the region.

Figure 7 presents retention indices of near-surface water computed from the monthly mean near-surface currents produced by the fine-resolution inner model, at day 3, day 6 and day 9, for a 9-day period from the first day of June, July, and August, respectively. The sub-area used in the calculation of the retention index is a square box with the horizontal dimensions of  $20 \times 20$  km. (The dimensions of the square box used here are about 2.5 times smaller than the dimensions used in Figure 5, which is consistent with the fact that the grid spacing of the inner model is about 2.5 times finer than the outer model.) Within each box, near-surface passive particles are released uniformly with 100 particles per  $\text{km}^2$ . The horizontal distribution of retention indices for near-surface particles advected by inner model currents for 3 days in each of the 3 months have similar large-scale features, characterized by relatively high retention indices of about 0.6–0.8 over the deep area, and lower retention indices of about 0.4 over the coastal region. The retention indices for 6 and 9 days have similar pattern as those for 3 days, but with reduced magnitude. The retention indices also exhibit month-to-month variability. The retention indices for 9 days of particle movements near Goderich Beach and Bayfield Beach are about 0.3 in June, and near zero in July, due to the month-to-month variability of the currents field.

To examine the role of the high-frequency variability in the flow field in generating the horizontal dispersion of near surface particles in the study region, we calculated the retention indices (Figure 8) based on the particle movements carried by hourly currents produced by the fine-resolution inner model. The retention indices associated with hourly currents show larger month-to-month

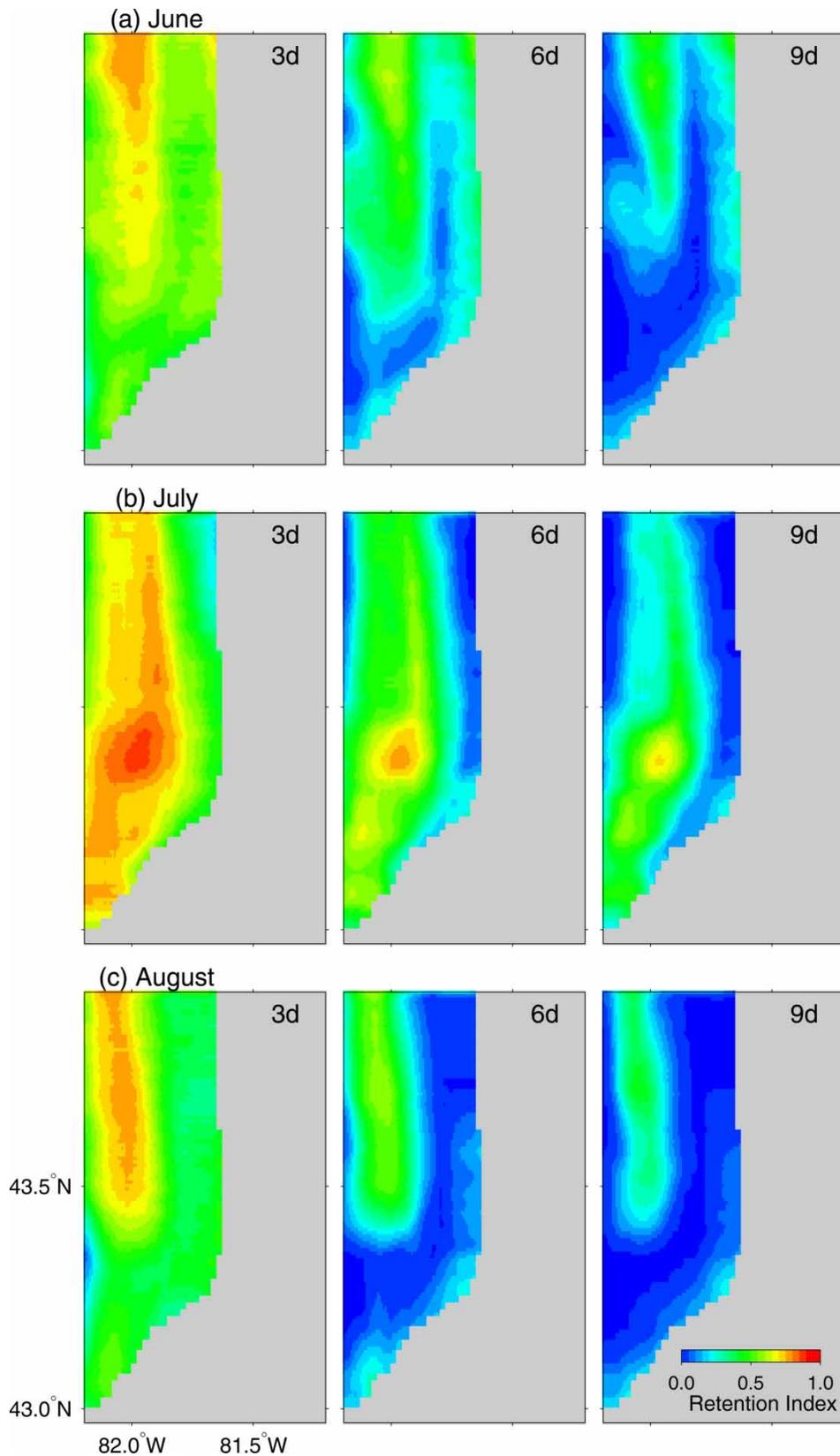


**Figure 6** | Horizontal positions of near-surface particles (1.5 m) that are advected passively by June mean near-surface currents produced by nested-grid inner model at day (a) 152.0, (b) 155.0, (c) 158.0, and (d) 161.0 in 1974. Particles are color-coded to indicate the starting positions at day 152.0. The full color version of this figure is available online at <http://www.iwaponline.com/wqjrc/toc.htm>.

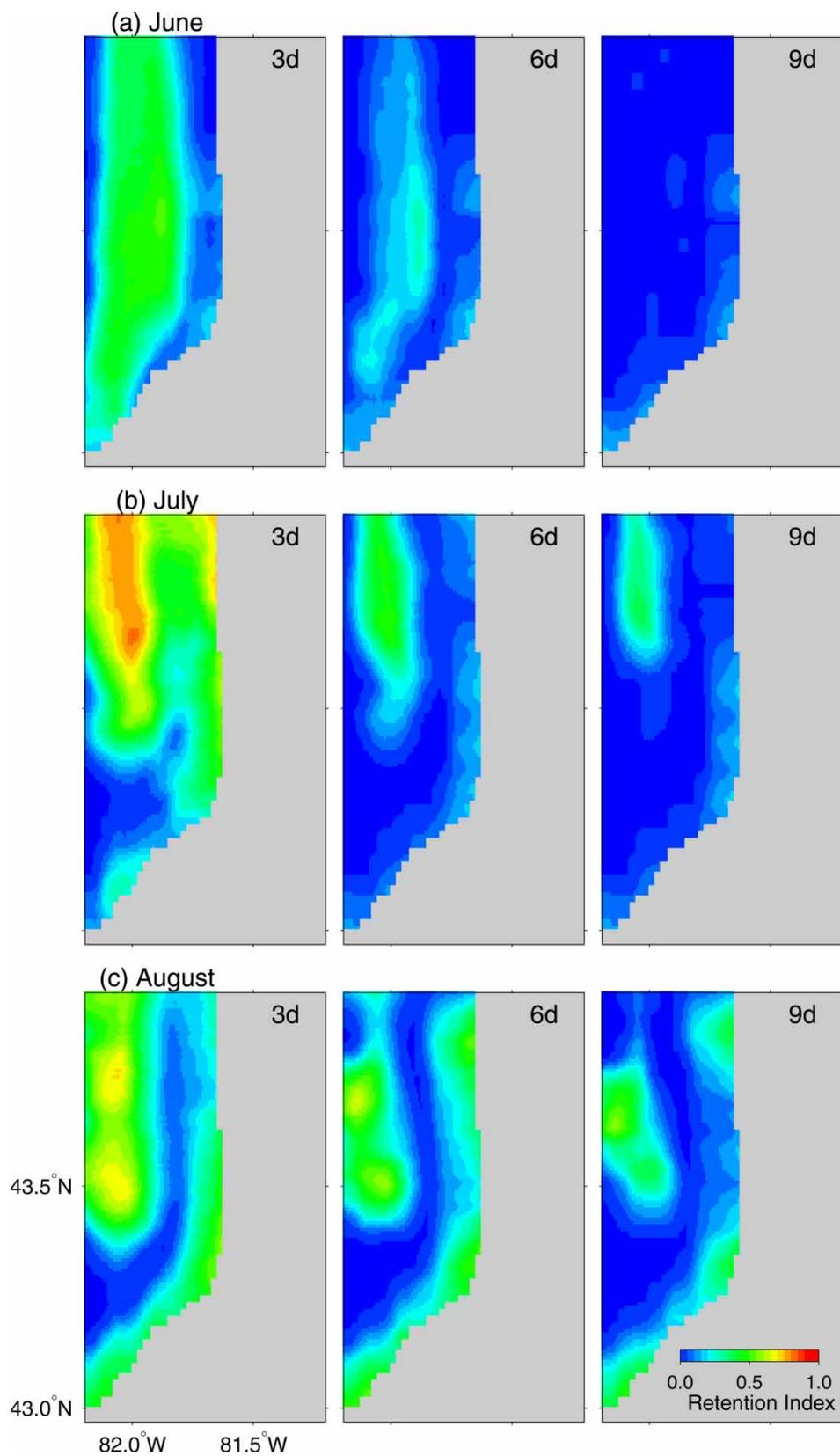
variability than those for monthly mean currents during the study period. The 9-day retention indices of particle movements over the deep area are near 0 in June, but about 0.5 in July and August. In the coastal region near Goderich Beach and Bayfield Beach, the retention indices for 9 days are about 0.5 in August and 0.1 in June and July.

## HYDRODYNAMIC CONNECTIVITY

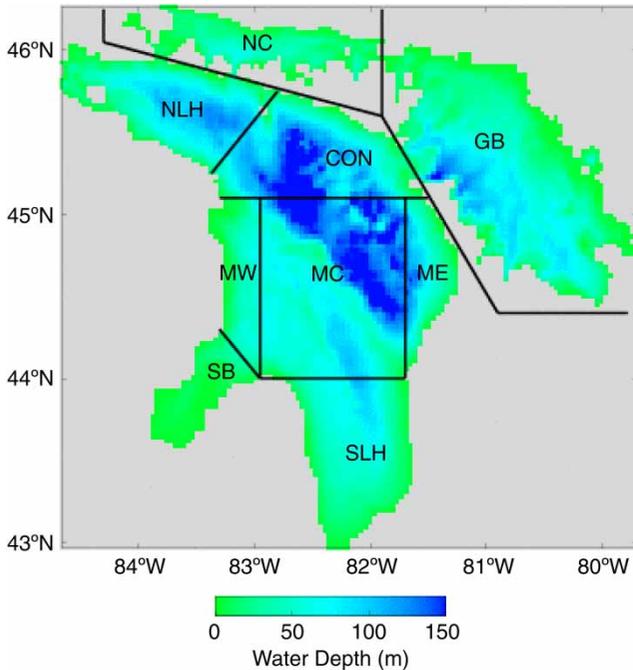
To investigate the dynamic connectivity of surface waters in the lake, we divide the outer model domain into nine sub-regions (with names and boundaries of the regions indicated in Figure 9), and estimate the exchanges of near-surface particles between different regions based on particle



**Figure 7** | Distribution of retention indices over southeast Lake Huron based on the horizontal movements of near-surface particles advected by monthly mean near-surface currents produced by nested-grid inner model in (a) June, (b) July, and (c) August in 1974.



**Figure 8** | Distribution of retention indices over southeast Lake Huron based on the horizontal movements of near-surface particles advected by hourly near-surface currents produced by nested-grid inner model in (a) June, (b) July, and (c) August in 1974.



**Figure 9** | Names and boundaries of nine regions in the model domain used in the calculation of transition matrix of passive particles in the surface waters. Abbreviations are used for North Channel (NC), Georgian Bay (GB), Northern Lake Huron (NLH), connected area (CON), west of Middle Lake (MW), center of middle lake (MC), east of Middle Lake (ME), Saginaw Bay (SB), and Southern Lake Huron (SLH).

movements discussed above under Retention and dispersion of near-surface particles.

We follow Thompson *et al.* (2002) and Sheng *et al.* (2009) and express the percentages of passive particles originating from a specific sub-region  $S_i$  to make transitions to other sub-regions over a fixed time interval in terms of a transition matrix. Table 1 presents the

transition (or connectivity) matrix for the nine sub-regions of the outer model domain based on the horizontal movements of near-surface particles advected passively by the outer model monthly mean currents in June during the 9-day period. Each area in the vertical direction of Table 1 represents a sub-region of release and each area in the horizontal direction of the table represents where the particles are found at the end of the time period. The diagonal elements of the transition matrix from bottom-left to top-right in Table 1 represent percentages of near-surface particles released in a specific sub-region remaining (or retaining) in the same sub-region (i.e. the retention index during the 9-day model time period). The horizontal elements with respect to each diagonal element in the transition matrix represent the percentages of the near-surface particles released in  $S_i$  reaching to other sub-regions (sink or downstream areas, see also Tang *et al.* (2006)), and vertical elements represent the percentages of the near-surface particles released in other sub-regions (source or upstream areas) moving to  $S_i$  during the 9-day period. It should be noted that the sum of horizontal elements in each row of transition matrix is equal to unity (Thompson *et al.* 2002).

The hydrodynamic connectivity between the sub-regions of the outer model domain can be analyzed based on Table 1. For an example, the transition of the ninth element from left in the first row (i.e. the diagonal element) is about 0.91, indicating that about 91% of near-surface particles released in Southern Lake Huron (SLH) are retained in SLH during the 9-day period.

**Table 1** | Connectivity (transition) matrix of near-surface waters over nine sub-areas of the outer model domain during a 9-day period calculated from outer model currents. All the values are multiplied by 100 and those less than 0.005 are not shown

	NC	GB	NLH	CON	MW	MC	ME	SB	SLH
SLH	–	–	–	–	–	5.3	2.8	–	91.4
SB	–	–	–	–	7.1	2.4	–	87.8	2.7
ME	–	–	–	7.5	–	2.6	89.8	–	–
MC	–	–	–	–	–	79.8	11.6	–	8.6
MW	–	–	–	–	68.7	21.9	–	2.9	6.5
CON	–	3.7	–	80.0	5.0	11.2	–	–	–
NLH	–	–	83.7	15.3	–	–	–	–	–
GB	–	99.0	–	0.9	–	–	–	–	–
NC	97.0	2.2	0.7	–	–	–	–	–	–

SLH receives about 3% of near-surface particles released in Saginaw Bay (SB, the ninth element from left in the second row), and about 9% of near-surface particles released in the center of Middle Lake (MC, the eighth element from left in the fourth row) and 7% of near-surface particles released over the west of Middle Lake (MW, the eighth element from left in the fifth row) during the period.

## SUMMARY

A 3D nested-grid circulation modeling system was applied to simulate the circulation, thermal structure and associated seasonal variability in Lake Huron and Georgian Bay, with a special emphasis of circulation over southeastern Lake Huron.

The model-calculated currents produced by the nested-grid modeling system were used to track the horizontal movements of near-surface particles in the lake. A random walk process was added to represent influence of physical processes that are not modeled explicitly in this study such as turbulent motions and currents driven by high-frequency wind forcing. Based on the particle movements, the retention, dispersion and hydrodynamic connectivity of surface waters in Lake Huron and Georgian Bay were calculated in terms of the retention index and connectivity (transition) matrix. Distributions of retention indices over the whole lake using short model runs indicates that horizontal dispersion of near-surface particles is relatively small in Saginaw Bay, eastern North Channel, and eastern Georgian Bay. A connectivity matrix calculated from the particle trajectories quantified the exchange of passive particles among nine sub-regions within the lake. Particle exchanges from Georgian Bay and North Channel are much weaker than those sub-regions in the main lake due to the restriction of narrow passages isolating these areas.

This study provides a basis to begin comprehending connectivity within the lake and to allow the development of more complex models. Combined with ecological and epidemiological models, the hydrodynamic model developed here will serve to evaluate the ecological connectivity among population and communities within the lake, and to predict

the spread of contaminants, water borne diseases and invasive species through the lake.

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