

**Provided for non-commercial research and educational use only.
Not for reproduction or distribution or commercial use.**



This article was originally published by IWA Publishing. IWA Publishing recognizes the retention of the right by the author(s) to photocopy or make single electronic copies of the paper for their own personal use, including for their own classroom use, or the personal use of colleagues, provided the copies are not offered for sale and are not distributed in a systematic way outside of their employing institution.

Please note that you are not permitted to post the IWA Publishing PDF version of your paper on your own website or your institution's website or repository.

Please direct any queries regarding use or permissions to wqjrc@iwap.co.uk

Assessment of a NEMO-based hydrodynamic modelling system for the Great Lakes

Frederic Dupont, Padala Chittibabu, Vincent Fortin, Yerubandi R. Rao and Youyu Lu

ABSTRACT

Environment Canada recently developed a coupled lake–atmosphere–hydrological modelling system for the Laurentian Great Lakes. This modelling system consists of the Canadian Regional Deterministic Prediction System (RDPS), which is based on the Global Environmental Multiscale model (GEM), the MESH (*Modélisation Environnementale Surface et Hydrologie*) surface and river routing model, and a hydrodynamic model based on the three-dimensional global ocean model Nucleus for European Modelling of the Ocean (NEMO). This paper describes the performance of the NEMO model in the Great Lakes. The model was run from 2004 to 2009 with atmospheric forcing from GEM and river forcing from the MESH modelling system for the Great Lakes region and compared with available observations in selected lakes. The NEMO model is able to produce observed variations of lake levels, ice concentrations, lake surface temperatures, surface currents and vertical thermal structure reasonably well in most of the Great Lakes. However, the model produced a diffused thermocline in the central basin of Lake Erie. The model predicted evaporation is relatively strong in the upper lakes. Preliminary results of the modelling system indicate that the model needs further improvements in atmospheric–lake exchange bulk formulae and surface mixed layer physics.

Key words | Great Lakes, hydrodynamic modelling, hydrology, Lake Ontario, model intercomparison

Frederic Dupont (corresponding author)
Canadian Meteorological Centre (CMC),
Environment Canada,
Dorval, QC,
Canada
E-mail: Frederic.Dupont@ec.gc.ca

Vincent Fortin
Recherche en prévision numérique
environnementale,
Environnement Canada,
Dorval, QC,
Canada

Padala Chittibabu
Yerubandi R. Rao
National Water Research Institute (CCIW),
Environment Canada,
Burlington, ON,
Canada

Youyu Lu
Bedford Institute of Oceanography,
Fisheries and Oceans Canada,
Dartmouth, NS,
Canada

INTRODUCTION

The Laurentian Great Lakes in North America have a combined surface area of 246,000 km² within a basin of 774,000 km². The Great Lakes are the largest fresh surface water source in the world, and provide drinking water to 40 million US and Canadian citizens. Economic activities such as commercial and sport fishing, recreation and shipping are worth billions of dollars. Understanding the processes governing this complex ecosystem and developing operational forecasting capabilities of the lake state are very crucial to safe economic and recreational activities around the coasts of the Great Lakes. Man-made developments such as urbanization, industrialization and agricultural activities from both the United States and Canada continue to increase the pressure on these water bodies and their management.

With horizontal scales of hundreds of kilometres, depth scales of hundreds of metres, and a well-developed seasonal thermal stratification in the summer and partial-to-full winter ice coverage, the Great Lakes' basins exhibit the same physical phenomena observed in the coastal ocean or inland seas. The thermal structure and circulation in the Great Lakes vary seasonally, along with surface fluxes (Boyce *et al.* 1989). During the winter and spring the lakes are generally isothermal and the wind forcing can penetrate deep into the water column. In summer, thermal stratification forms in most of the lakes. Because of the large horizontal scale, the Laurentian Great Lakes have significant impacts on the local weather and climate (Anyah & Semazzi 2004; Obolkinm & Potemkin 2006). In turn,

atmospheric conditions, such as surface winds and heat flux, precipitation and evaporation, also have significant influences on the thermal structure (King *et al.* 1997) and water level in lakes (Hanrahan *et al.* 2010).

Hydrodynamic modelling of lakes in three dimensions gives a thorough understanding of various physical processes that influence transport and distribution of chemical and biological elements in the lakes. Real-time forecasts of temperature, water levels, ice conditions, surface waves and currents are useful for commercial (shipping, fishing) and recreational activities (boaters, swimmers, divers, shoreline anglers). Water safety is one of the major concerns of the users of the lakes and Search and Rescue (SAR) activities are challenging for both the Canadian and American authorities. For effective SAR and many other operations it is vital to accurately forecast the hydrodynamical processes and weather conditions in the lakes.

For these reasons, various attempts have been made over the years to develop three-dimensional (3D) hydrodynamic models for the Great Lakes (e.g., Bennett 1977; Simons 1980); and during the last 2 decades 3D coastal ocean models have been adapted to the Great Lakes. In one such example, the Princeton Ocean Model (POM) has been used in an operational forecasting system of the Great Lakes (Schwab & Bedford 1994). Currently, this model is run in nowcast and forecast modes using forcing from observed meteorological measurements. Recently, Huang *et al.* (2010a) assessed the performance of POM in Lake Ontario with observed forcing and atmospheric forecast forcing from the Environment Canada Global Environmental Multiscale (GEM) model in reproducing the circulation and temperature in the lake. In another study, the Canadian version of Diecast model (CANDIE) was applied to study the seasonal thermal structure and coastal circulation in Lake Huron (Sheng & Rao 2006). More recently, the Estuary, Lake and Coastal Ocean Model (ELCOM) was also used to simulate the thermal structure in the Great Lakes (Rao *et al.* 2009). Huang *et al.* (2010b) applied these three hydrodynamic models, namely POM, CANDIE and ELCOM, to inter-compare the solutions of the models with each other and with observations in Lake Ontario. In general, they found that all these models were able to reproduce the seasonal circulation and surface temperatures reasonably well.

In recent years efforts have been made to couple atmospheric models and climate models to lake models (Bates *et al.* 1995; Lofgren 1997). Studies have shown that inclusion of air-lake interactions leads to improved performance of climate models and as a result one-dimensional models are included in regional climate models. Since the cumulative effect of lakes on local climate is very important, attempts were made to include the lakes in atmospheric models, and simple models were developed to couple with regional climate models. For example, Goyette *et al.* (2000) developed a simple mixed layer model which was implemented in the Canadian Regional Climate Model for the Great Lakes. Martynov *et al.* (2010) used one-dimensional lake models to demonstrate their suitability for inclusion in the regional climate models. Both models were run offline for two small temperate lakes and for the Great Lakes, with observed forcing as well as forcing from the ERA40 reanalysis data. Although the models were able to simulate temperature and thermal structure in smaller shallower lakes, the models were unable to produce good results in larger lakes.

Furthermore, recent studies showed that atmospheric models coupled with 3D lake models could obtain more realistic local temperature, evaporation and convergence patterns compared to simulations without lake effects, for example, over Lake Victoria (Song *et al.* 2004) and Great Bear and Great Slave lakes (Long *et al.* 2007). Similar assessment has been carried out with a coupled atmosphere and ocean-ice model in the Gulf of St Lawrence (Pellerin *et al.* 2004). Encouraged by these results, a fully coupled 3D atmosphere-lake modelling system is being developed by Environment Canada to represent the complex air-lake interaction over the Great Lakes region. In this system, the hydrodynamic lake component is based on NEMO (Nucleus for European Modelling of the Ocean; Madec *et al.* 1998; Madec 2006), while the MESH (*Modélisation Environnementale Surface et Hydrologie*) model (Pietroniro *et al.* 2007; Deacu *et al.* 2012) forced by GEM is used to estimate tributary flow to the lakes (further details are discussed below). This coupled system should become part of Environment Canada's complete environmental forecasting system for the Great Lakes, including the weather, hydrology and water quality conditions. The argument for using NEMO instead of any other models

already applied in a lake context (some of them described below) is manifold. First, it is a state-of-the-art ocean model with an active ice and water quality component, well supported by a large community of users and researchers. Second, NEMO can run on massively parallel computers, which is of great importance to Environment Canada operations, thus allowing for higher resolution and therefore accuracy. Finally, collaborations among other Canadian agencies and with the French consortium Mercator are made easier with the use of a common modelling tool, i.e., NEMO. This approach is pursued, of course, as long as we can prove that the model can do as well as (or better than) any other models.

Before performing two-way coupling, it is important to assess the accuracy of NEMO simulations with observations in the Great Lakes. Therefore, the purpose of this paper is to provide a first assessment of the performance of the NEMO hydrodynamic model applied to the Great Lakes using GEM and MESH forcings. First, we will show that using *in situ* observations in Lake Ontario, the performance of the NEMO model is comparable to other hydrodynamic models. We then apply this version of NEMO in hindcasting mode from June 2004 to May 2009 to all Great Lakes and assess the performance using available data and analysis.

METHODS

Environment Canada's coupled lake-atmosphere-hydrological modelling system consists of the following components:

1. The NEMO hydrodynamic model applied for the Great Lakes.
2. The Canadian operational weather forecasting model (GEM model) in its RDPS (Regional Deterministic Prediction System) configuration.
3. The Coordinated Great Lakes River Routing Model (CGLRRM) for connecting channels (Tolson 2009).
4. The MESH land surface and river routing model (Pietroiro *et al.* 2007; Deacu *et al.* 2012) based on the Canadian version of ISBA (Interactions between Soil-Biosphere-Atmosphere; Bélair *et al.* 2003) and the river routing

module of WATFLOOD (Kouwen 1988; Bingeman *et al.* 2006).

Nucleus for European Modelling of the Ocean (NEMO)

NEMO (<http://www.nemo-ocean.eu>) is a community ocean and ice model developed originally in Europe (Madec *et al.* 1998; Madec 2006), and has evolved very substantially since its introduction in the 2000s. The ocean engine of NEMO is a primitive equation model (OPA; Madec *et al.* 1998) adapted to regional and global ocean circulation problems. It is intended to be a flexible tool for studying the ocean (or lakes) and its interactions with the other components of Earth's climate system over a wide range of space and time scales (Drillet *et al.* 2005; Barnier *et al.* 2006; Masson-Delmotte *et al.* 2006). Prognostic variables of the model are the 3D velocity field, a linear or non-linear sea surface height, temperature and salinity. In the horizontal direction, the model uses a curvilinear orthogonal grid, and in the vertical direction a full or partial step z-coordinate, or sigma-coordinate is provided. The distribution of variables is carried out on a 3D Arakawa C-type grid. Several choices are available to describe the vertical mixing in the model, including turbulent kinetic energy (TKE) closure (Gaspar *et al.* 1990; Blanke & Delecluse 1993), GLS (General Length Scale; Umlauf & Burchard 2003) and KPP vertical physics (non-local K-profile; Large *et al.* 1994). Within NEMO, the ocean (or lake) is interfaced with a sea-ice model (LIM 2; Fichefet & Morales Maqueda 1997, or LIM 3; Vancoppenolle *et al.* 2009a, b). The model also supports two-way grid embedding via the AGRIF library. An advantage of the NEMO model is its widespread use and continuous tuning by the scientific community (Drillet *et al.* 2005; Rattan *et al.* 2010). The current setup for the Great Lakes uses LIM2 which includes two layers of ice and one layer of snow. The NEMO model has been extensively tested and applied in Canada for global, basin and regional applications, in the CONCEPTS (Canadian Operational Network of Coupled Environmental Prediction Systems) program, Centre for Ocean Model Development for Applications (COMDA), and the Global Ocean-Atmosphere Prediction and Predictability (GOAPP) network funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) (e.g., Holloway &

Wang 2009; Zhu *et al.* 2009; Rattan *et al.* 2010; Wang *et al.* 2010).

GEM forcing

The hydrodynamic lake model is forced by the GEM atmospheric model in its RDPS configuration (Mailhot *et al.* 2006). With a horizontal resolution of 15 km GEM has advanced numerics and a sophisticated physics packages (Côté *et al.* 1998; Mailhot *et al.* 1998), and benefits from advanced data assimilation capacities (e.g., Gauthier *et al.* 2007; Laroche *et al.* 2007). It has been running operationally at the Canadian Meteorological Centre (CMC) since 1997 in order to provide short-range weather forecasts to Canadians. The modelled meteorological forcing data are taken from 6 to 18 hours GEM forecasts (two forecasts per day) for the full hindcast period at 3-hour frequencies. The lowest prognostic level (approximately 40 m) is used for air temperature, specific humidity, wind direction and wind speed. Other variables (precipitation, pressure, as well as short and long wave incoming radiation) are provided at the surface level.

The hydrological components

The hydrodynamic model is also forced by daily river flows provided by MESH which combines the surface component of GEM based on the ISBA model (Bélair *et al.* 2003) with a river router based on WATFLOOD (Kouwen 1988; Bingeman *et al.* 2006). It was developed for the Great Lakes by Pietroniro *et al.* (2007), and further improved by Deacu *et al.* (2012) and demonstrated that it can accurately predict net basin supply (NBS) to each of the Great Lakes (i.e., the net effect of precipitation, evaporation and runoff to the lakes). MESH predicts turbulent transfers of heat, moisture and momentum over both land and water. Although NEMO provides surface temperature and ice cover of the lakes, this is not used in the current MESH setup. Atmospheric forcings for MESH are provided directly by GEM, which relies on a daily analysis of surface temperature and ice cover over water (Brasnett 2008).

NEMO is also coupled to the CGLRRM (Tolson 2009) which predicts outflow from the control structures at the

outlet of Lake Superior based on the regulation plan, as well as flows in the connecting channels of the Great Lakes system: St Marys river downstream of Lake Superior, St Clair River downstream of Lake Huron, Detroit River downstream of Lake St Clair and Niagara Falls downstream of Lake Erie. The model also provides an estimate of flows at the outlet of Lake Ontario at Cornwall following the same discharge equation used in MESH:

$$\text{Outflow}_{ont} = 555.823 * (H_{ont} - 0.0014 * (2000 - 1985) - 69.474)^{1.5}$$

where Outflow_{ont} is in m^3/s and H_{ont} is the absolute lake level following IGLD85 in metres. However, as this relation does not include impacts of regulation at Cornwall, the predicted lake level for Lake Ontario has limited skill.

The NEMO model is implemented over the Great Lakes at a 2-km horizontal resolution (Figure 1). The model bathymetry is generated from the Great Lakes' database of the NGDC (National Geographic Data Centre). The vertical discretization is based on 35 fixed z-levels with a nearly constant 1 m resolution in the first 10 layers and increasingly coarse resolution below, which allows a good representation of the surface and mixed layer processes. A compact grid of $355 \times 435 \times 35$ allows the integration of 1 year per clock day on a 16 cpu machine with a time step of 600 s. A total variation diminishing (TVD) advection scheme is used for tracers (temperature and salinity) and the bottom friction is treated implicitly. The TKE closure scheme (Gaspar *et al.* 1990) is chosen for solving of the vertical turbulence. Initial temperature conditions were taken from the National Oceanic and Atmospheric Administration/Great Lakes Environmental Research Laboratory (NOAA/GLERL) Great Lakes Surface Environmental Analysis (GLSEA; <http://coastwatch.glerl.noaa.gov/glsea/glsea.html>) for the surface with an exponential relaxation to 4°C at 20 m on 2 June 2004. The CORE bulk formulae (Large & Yeager 2004) for the computation of turbulence air-sea fluxes were used for the 5-year-long hindcast (see below the section Great Lakes configuration (one-way coupled model results)) while the Schertzer bulk formulae (Schertzer *et al.* 2003) were used for the model intercomparison (see the section below).

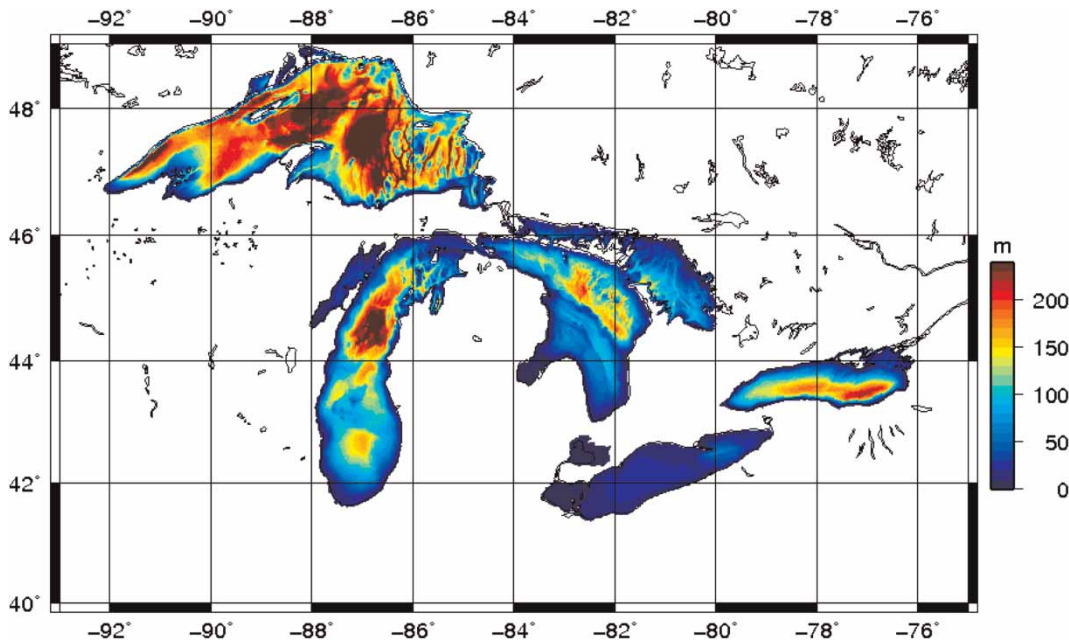


Figure 1 | Bathymetry of the hydrodynamic model for the Great Lakes.

RESULTS

Validation of NEMO through intercomparison of models in Lake Ontario

Huang *et al.* (2010b) assessed the performance of three hydrodynamic models in simulating seasonal thermal structure and circulation in Lake Ontario. A common configuration and observations from an intense campaign in 2006 using thermistor chains (eight stations) and an Acoustic Doppler Current Profiler (ADCP) (three stations) are available for this exercise (Figure 2). Three models were part of that intercomparison study (CANDIE; Sheng *et al.* 1998; POM; Mellor & Blumberg 1985; and ELCOM; Hodges & Dallimore 2006). In the current intercomparison exercise, the ELCOM model

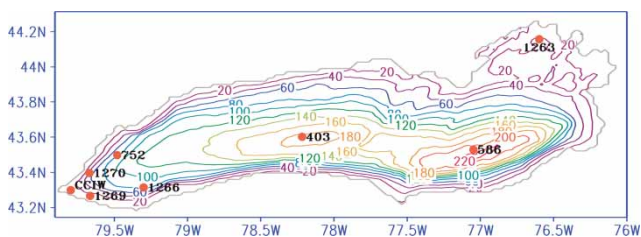


Figure 2 | Instrumented locations during the intensive 2006 campaign in Lake Ontario.

is not considered (due to licensing and proprietary issues). Using Huang *et al.*'s (2010b) configuration, the three models (CANDIE, POM and NEMO) were discretized with a 2-km grid over Lake Ontario. Higher vertical resolution (1 m) is used in the upper 20 m, and coarser resolution (2–10 m) is used below that. POM uses 31 sigma levels in the vertical. The models were validated against observations using metric errors. The error metrics were based on the root mean square (RMS) error of temperature and velocity, and bias and RMS error based on the GLSEA. The models were initialized with surface temperatures from GLSEA in April 2006 (vertically uniform). The atmospheric forcing was provided by the GEM regional model at 15-km resolution from the bottommost prognostic level (approximately 40 m) and the wind was rescaled to 10 m using a simple log law. A bilinear interpolation method is used to map the GEM forcing fields onto the model grids. In all the models the Schertzer bulk formula was used (Schertzer *et al.* 2003). All three lake models were run from 15 April (day 105) to 10 October 2006 (day 283).

As the main focus is comparative assessment of NEMO to other models and observations, only the error metrics are shown here. Although the three models obtained qualitatively similar results, there are some noticeable differences. In

terms of RMS errors of vertical temperatures the NEMO performance is slightly better than the other two models except at one station (Table 1). Similar results are obtained for velocity at ADCP stations (Table 2). The comparison of model results with GLSEA is also somewhat in favour of NEMO (Table 3). Interestingly, the largest error in sea surface temperature (SST) is seen in spring and fall when the models do not warm up/cool down at the same rate as in the observations. Upwelling and downwelling events are also an important source of error. Possible explanations are the lack of an accurate representation of the thin lake thermocline and some potential misrepresentation of the clouds in the deterministic atmospheric model which forces the lake models at the surface (i.e., cloud spinup and other parametrization issues, Gregory Smith, EC, personal communication).

Great Lakes configuration (one-way coupled model results)

Water levels and connecting channel flows

Simulation of water levels is of paramount importance in the water cycle prediction of the Great Lakes. Currently, this is

Table 1 | The RMS errors of temperature for the three models during summer 2006

Stations	CANDIE	POM	NEMO
CCIW	2.49	2.21	1.72
403	2.16	2.05	1.96
586	2.61	2.84	2.52
1263	2.43	2.46	2.58
1266	2.49	2.21	1.72
1269	2.80	2.49	2.48
1270	2.40	2.70	2.20
752	2.69	2.42	1.85
Mean	2.51	2.42	2.13

Table 2 | The RMS errors of velocity for the three models during summer 2006

Stations	CANDIE	POM	NEMO
1266	0.07	0.07	0.06
1269	0.05	0.06	0.04
1270	0.07	0.10	0.07
Mean	0.07	0.08	0.05

Table 3 | The surface temperature error (bias and RMS error, RMSE) between the models and GLSEA during summer 2006

Metric	CANDIE	POM	NEMO
BIAS	1.32	0.61	-0.19
RMSE	1.29	1.22	1.20

achieved either by calculating net basin supplies using component or residual methods (Neff & Nicholas 2005). Hydrodynamic models are rarely used for obtaining mean lake levels because of inherent issues of accounting net basin supplies to the lakes in long-term simulations. As one of the objectives of the hydrological system is the prediction of long-term water levels in the Great Lakes, we assess the water levels predicted by the current model setup. The time series of simulated daily water levels were compared to observed lake levels during 2004 to 2009 in all lakes (Figure 3). In the upper lakes (Superior and Huron–Michigan), the modelled water levels closely followed observed levels with slight underprediction. In Lake Superior and Huron, the elevation bias over the whole period is -3 and -2 cm, respectively, while the RMS error between modelled and observed water levels is 7 and 4 cm, respectively. The modelled phase is consistent with observations. However, in the lower Great Lakes (Lake Erie, Lake St Clair and Lake Ontario), the modelled water levels are significantly underpredicted with respective bias of 15, 12 and 33 cm. This was also reflected in large RMS errors of 17, 14 and 36 cm in these lakes. The largest error was found in Lake Ontario, where an ad hoc formulation for the outflow was used. This suggests that the ad hoc formulation used here, which represents pre-project outflow from Lake Ontario at Cornwall prior to the dam construction, is not adequate as the lake is now regulated. It would be possible to code in a regulation plan for Lake Ontario, based on plan 1958-D, which is currently used for managing the lake. However, lake managers frequently deviate from this plan in order to reduce the risk of downstream flooding. Furthermore, this plan is currently being reviewed and will likely be replaced by a more flexible adaptive management framework, as recommended by the International Lake Ontario–St Lawrence River Study Board.

Figure 4 shows flows in the connecting channels. The flow in Saint-Mary's River was underpredicted by the

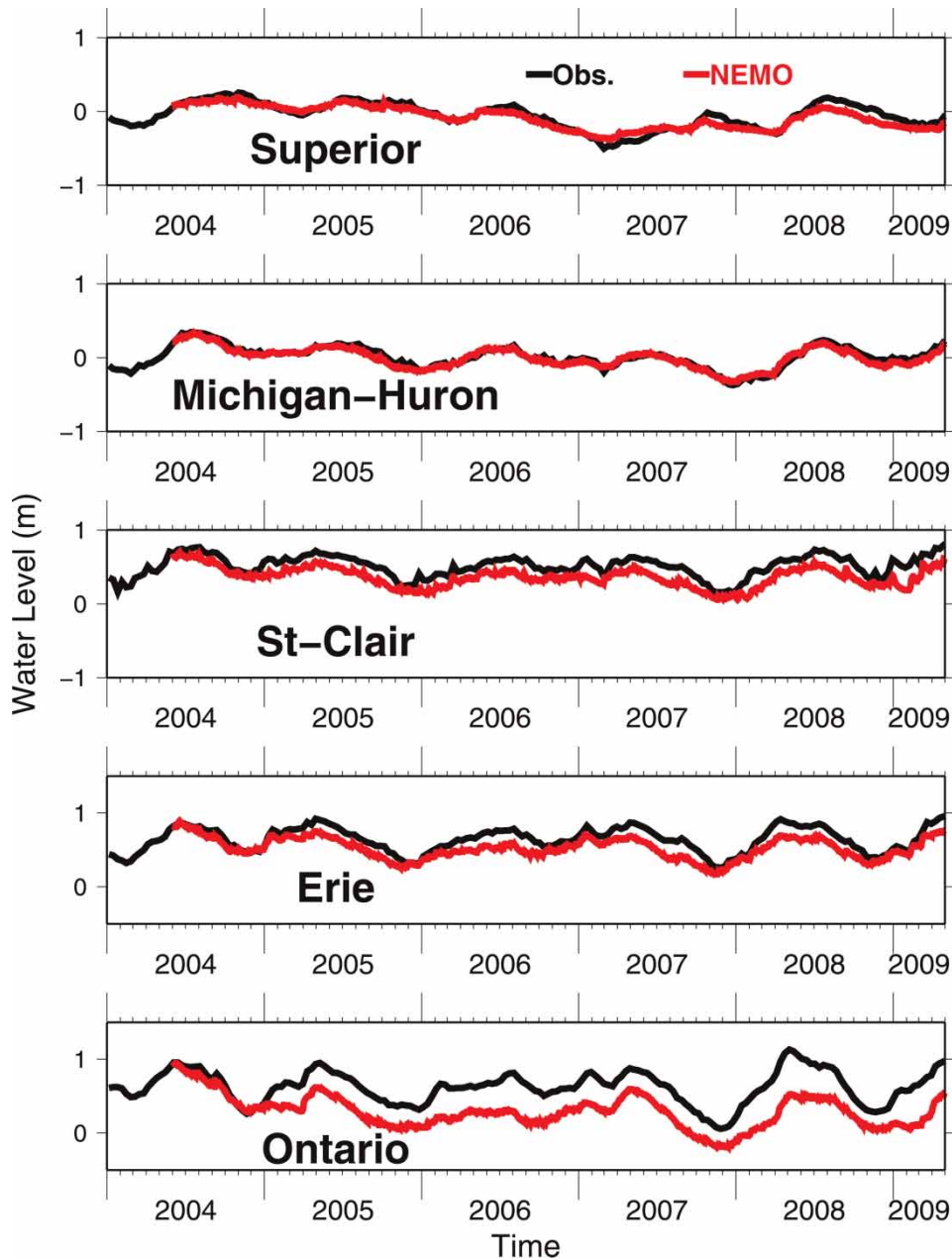


Figure 3 | Comparison of lake levels. Black, observations; red, modelled by NEMO (grey on the hardcopy edition; the full colour version is available online at <http://www.iwaponline.com/wqjrc/toc.htm>).

model and reaches the minimum regulation permissible limit many times. Yet, the modelled Lake Superior level was close to observations. This would indicate that the NBS is underpredicted for Lake Superior. Lake Huron–Michigan showed the opposite trend as the inflow was under-represented but the outflow and elevations were

reasonably well simulated. This situation also leads to underprediction of the net basin supplies. As we progress towards the lower lakes, it becomes, however, increasingly complex to describe the interactions between the different processes in simple terms. Deacu *et al.* (2012) noticed a similar problem in their study and circumvented

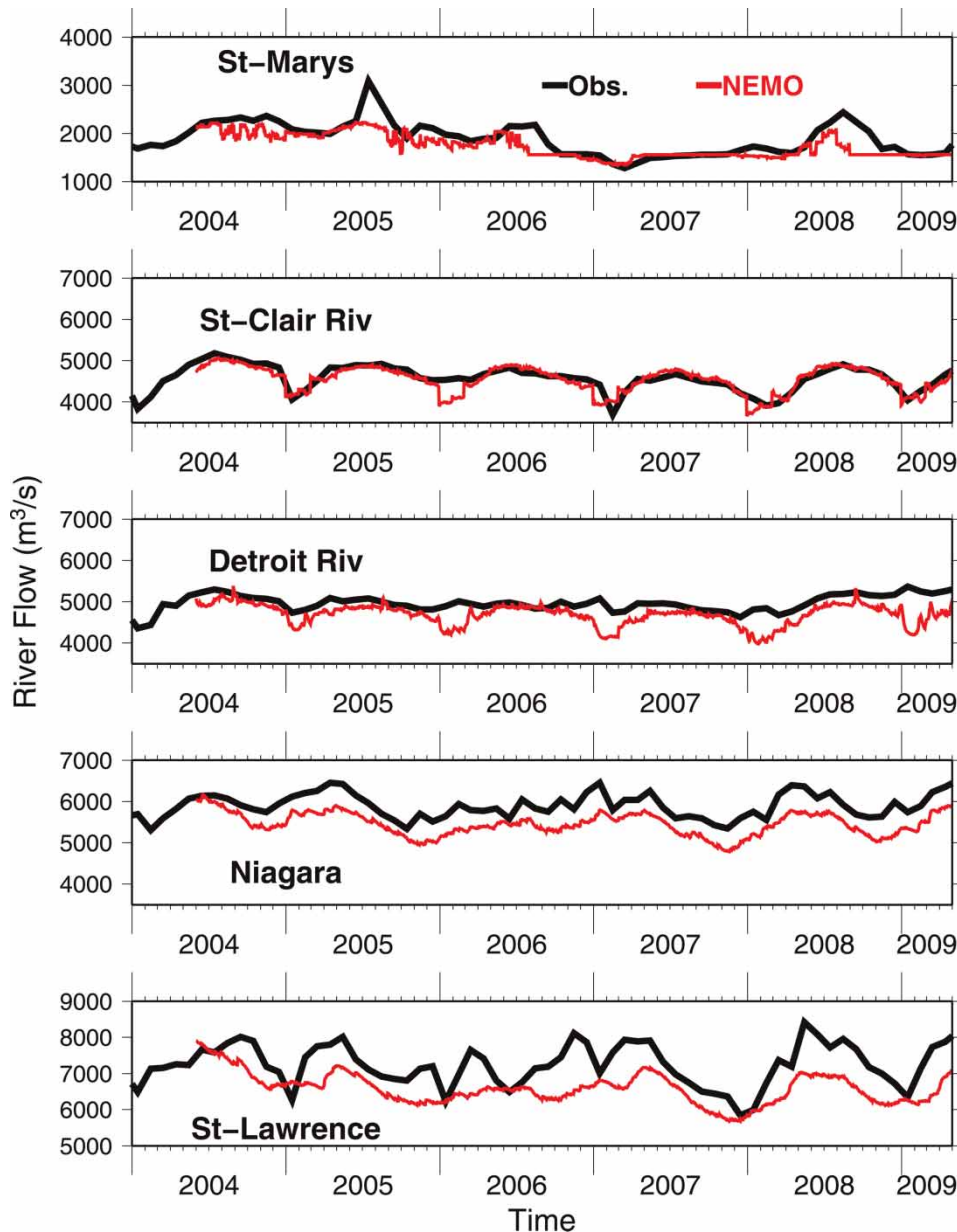


Figure 4 | The river flows through the connecting channels. Black, observations; red, model (grey on the hardcopy edition; the full colour version is available online at <http://www.iwaponline.com/wqjc/toc.htm>).

the problem by focusing on predictions of NBS instead of lake levels. However, the observations for verifying this are only available as a residual of a water balance calculation, which are more and more uncertain as we go downstream.

Although, in general, the lake levels are reasonably well predicted, the evaporation predicted in NEMO using the

CORE bulk formulae is somewhat strong in the upper lakes (not shown) and likely explains weaker than observed flows in some of the connecting channels. A few corrections have been tested in GEM bulk formulae to fix evaporation issues (Deacu et al. 2012). Once they are operationally tested, they will be ported to NEMO in future versions.

Temperature

One of the priorities of this Great Lakes forecasting system is to predict good quality surface and water column temperatures in all the Great Lakes at a reasonable spatial resolution for coupling with the atmospheric model. These predictions will also help to forecast temperatures at water intakes and assess upwelling and downwelling events in the lakes. In general, model

predicted surface temperatures are in good agreement with satellite derived GLSEA data. Figure 5 shows a comparison of observed and modelled surface temperatures on a typical day (1 July 2005). The surface water temperatures of Lake Ontario and Erie are reasonably well predicted. However, surface temperatures of Lake Superior have a significant warm bias. Some discrepancies could also arise because satellite-derived temperatures are skin temperatures, whereas model produced temperatures are in the

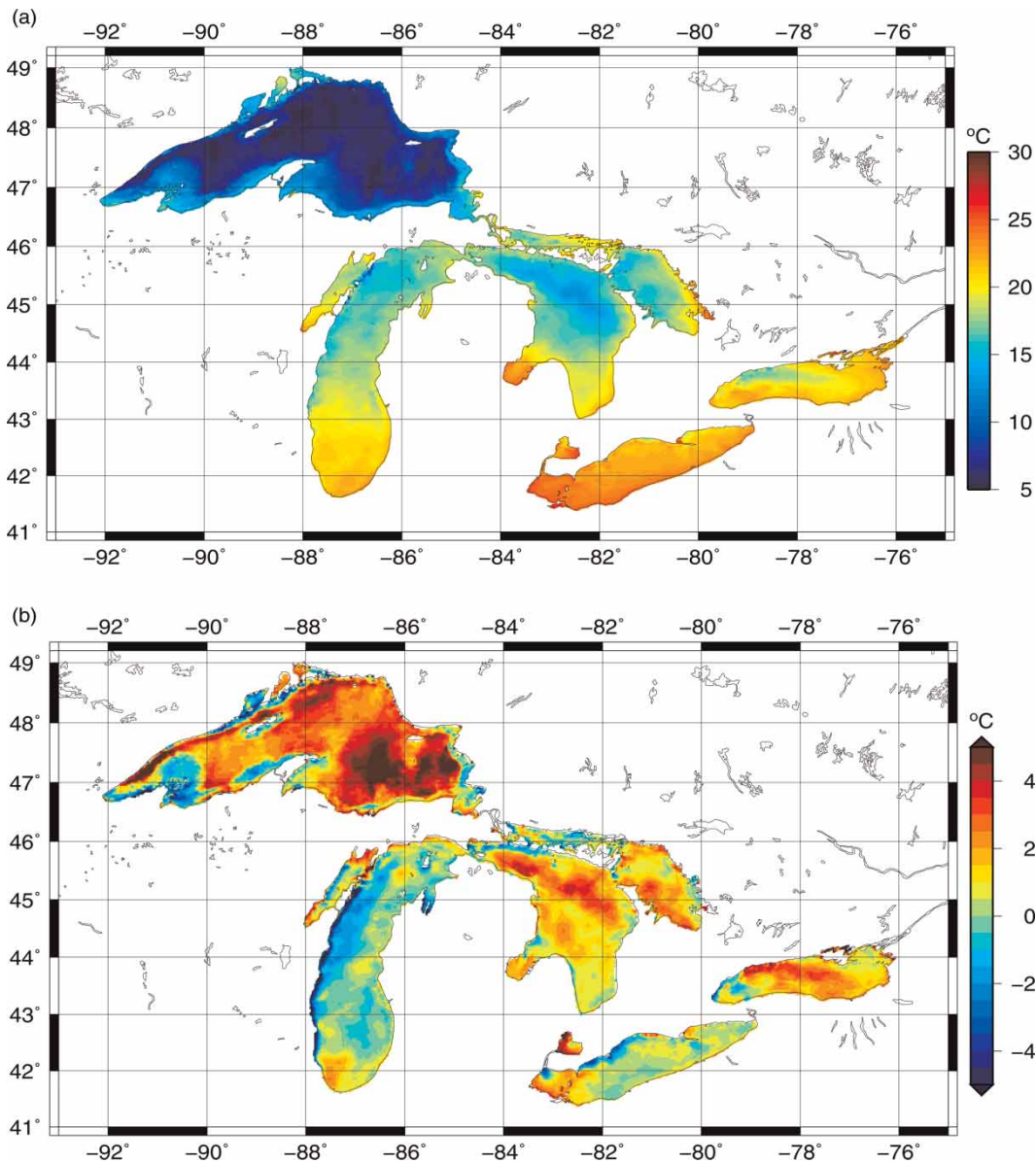


Figure 5 | (a) Surface lake temperature from GLSEA and (b) departure of the model from GLSEA for 1 July 2005.

upper 1 m or so. Another potential source of discrepancy is the cloud representation in GEM and related overestimation of short wave radiation (see comment in the section Validation of NEMO through intercomparison of models in Lake Ontario).

The lake averaged surface temperatures were compared with CMC analysis (Brasnett 2008) combined with GLSEA analysis for each lake in all the years. An example is shown for 2005, other years have similar features (Figure 6). For Lake Superior, the bias is particularly strong during warm-up (June) and cool-down (October–November) with values of up to 4 °C in spring and 2 °C in fall. The same warm-up problem is also visible in Lake Huron, Erie and Ontario (3 °C in May for Lake Ontario). The best match is obtained in Lake Michigan year-round with a bias of less than 1 °C while a warm bias appears in Lake Huron and Lake Erie during summer (1–2 °C). The warm-up problem, especially in Lake Superior, is depicted in the spatial map for 1 July 2005 (Figure 5).

The time series of temperature profiles show the development of stratification in each lake during 2004–2009

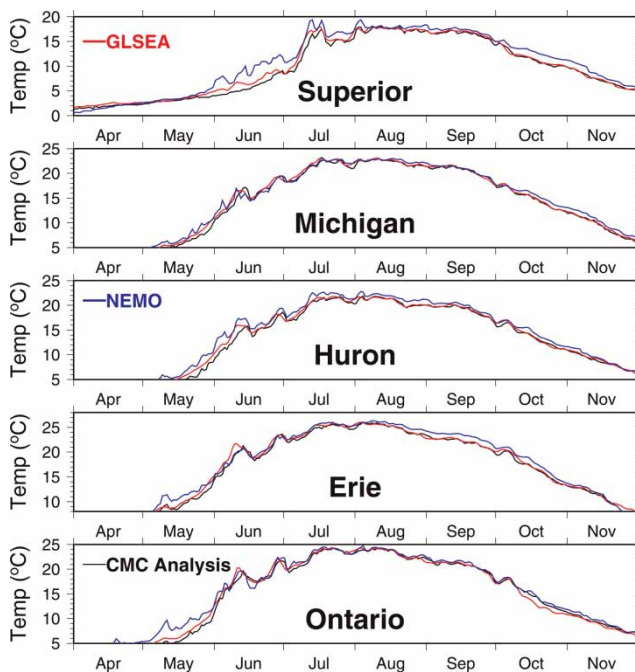


Figure 6 | A comparison of mean surface temperatures for Lakes Superior, Michigan, Huron, Erie and Ontario during the year 2005 (black, derived from CMC SST analysis; red, from GLSEA; blue, the model (the last two lines are grey and dashed, respectively, on the hardcopy edition; the full colour version is available online at <http://www.iwaponline.com/wqrcj/toc.htm>)).

(Figure 7). In general, the model is able to predict the overturns in spring and fall reasonably well. Furthermore, the general range of predicted temperatures was within the observed ranges in these lakes. The model was also able to reproduce some of the interannual variability of the thermal structure. The predicted thermocline structure is comparable to other models in Lake Ontario (Huang *et al.* 2010b). Although the model predicted the occurrence of the seasonal thermocline in each lake at the right depths (20–30 m), the structure appears to be rather diffusive (e.g., Lake Ontario), especially in the central basin of Lake Erie where the thermocline dramatically disappears too soon. A typical difficulty in numerical lake models is representing the sharp thermocline found in observations in Lake Erie.

Ice cover

The prediction of winter ice on the Great Lakes is important for several applications, including to determine the annual thermal cycle of the lake and for assessing the long-term trends of surface water temperatures. However, until recently, the modelling of ice cover and extent has not received similar attention as in the oceans (Wang *et al.* 2010; Oveisy *et al.* 2012). The LIM2-NEMO package is used for the first time to assess the formation and extent of ice cover during the 2004–2009 ice seasons. The mean ice concentration was computed for each lake and compared with the analysis by the Canadian Ice Service (CIS) in Figure 8. The comparison shows that the model results are generally comparable to observations with slight underestimation in Lake Huron and Lake Erie. The interannual variability of ice cover is also well reproduced in the model. Direct comparisons show however that NEMO ice edge tends to be somewhat smooth. This is likely due to the crude thermodynamics used in LIM2.

Circulation

Boyce *et al.* (1989) noted that with the exception of circulation associated with the intermediate phase of the thermal bar and the hydraulic component in shallow basins or narrows, circulation in the Great Lakes is dominated by wind. Beletsky *et al.* (1999) compiled the mean

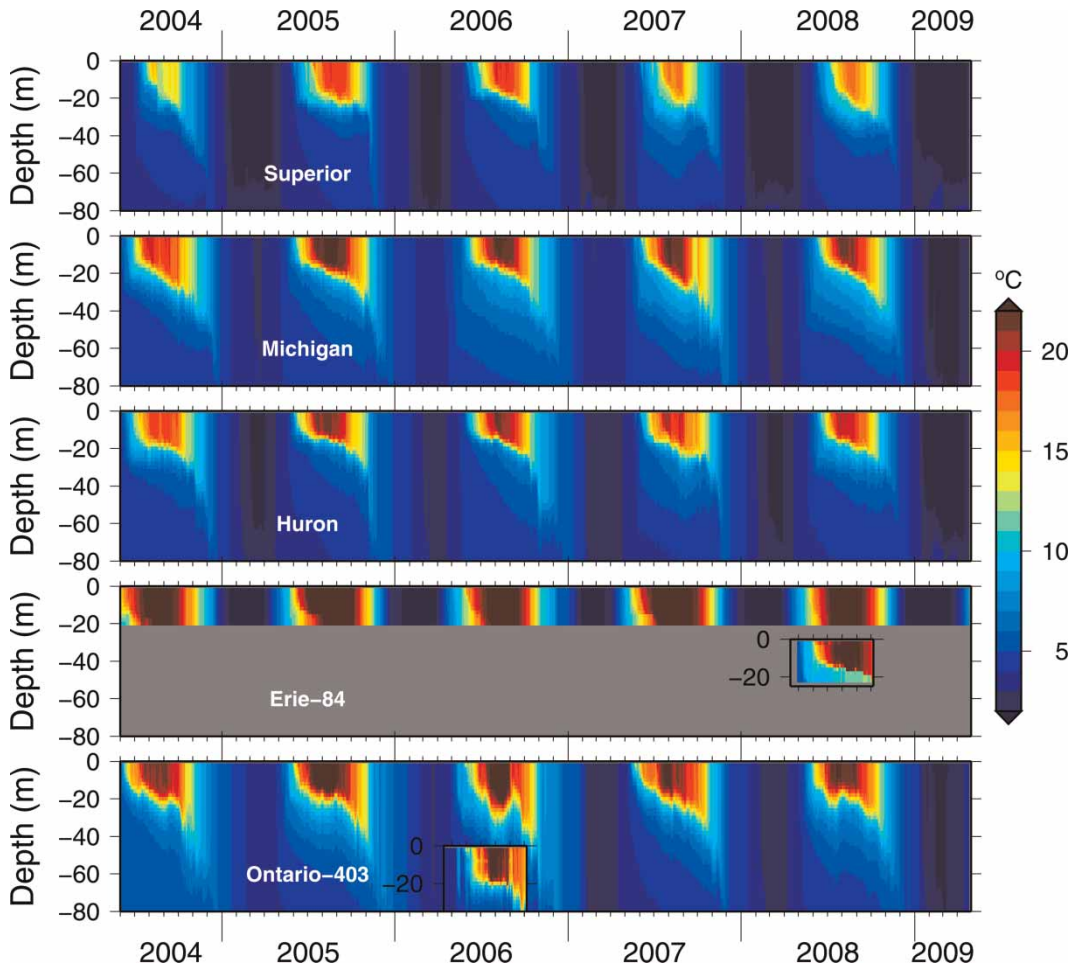


Figure 7 | Vertical profiles of temperature at an arbitrary offshore location in Lakes Superior, Michigan, Huron, at Station 84 in Lake Erie and Station 403 in Lake Ontario. The insets of the two bottommost panels correspond to observations at the same location for respectively summer 2008 (Station 84 in Lake Erie) and 2006 (Station 403 in Lake Ontario).

circulation in the Great Lakes based on several experimental data sets conducted over the years. Storm-induced currents in the Great Lakes can be quite strong (up to several tens of cm/s), but the average (seasonal means) currents are rather weak throughout most seasons of the year (on the order of only a few cm/s). The average magnitude of summer circulation in the Great Lakes is 1.0–2.4 cm/s, while mean summer currents can be as small as 0.1 cm/s at certain locations and the maximum current speed can reach up to 7 cm/s (e.g., Keweenaw current in Lake Superior). Currents typically change their direction with depth, and their speed decreases, which reflects the importance of baroclinic effects in the presence of the seasonal thermocline. The summer

circulation pattern is mostly cyclonic in the upper Great Lakes, whereas in Lake Erie the anticyclonic gyre dominates and only a smaller cyclonic gyre is present in the western part in Lake Erie. In Lake Ontario the cyclonic circulation in the central part is a dominant feature with stronger eastward current near the south shore. Cyclonic circulation persists in the winter. Winter currents are generally stronger than summer currents, and, therefore, annual circulation patterns closely resemble winter circulation patterns.

As shown in Figure 9, mean annual surface currents follow the prevailing winds over the Great Lakes. In Lake Superior, the Keweenaw current is a persistent feature of summer circulation and simulated well (Chen

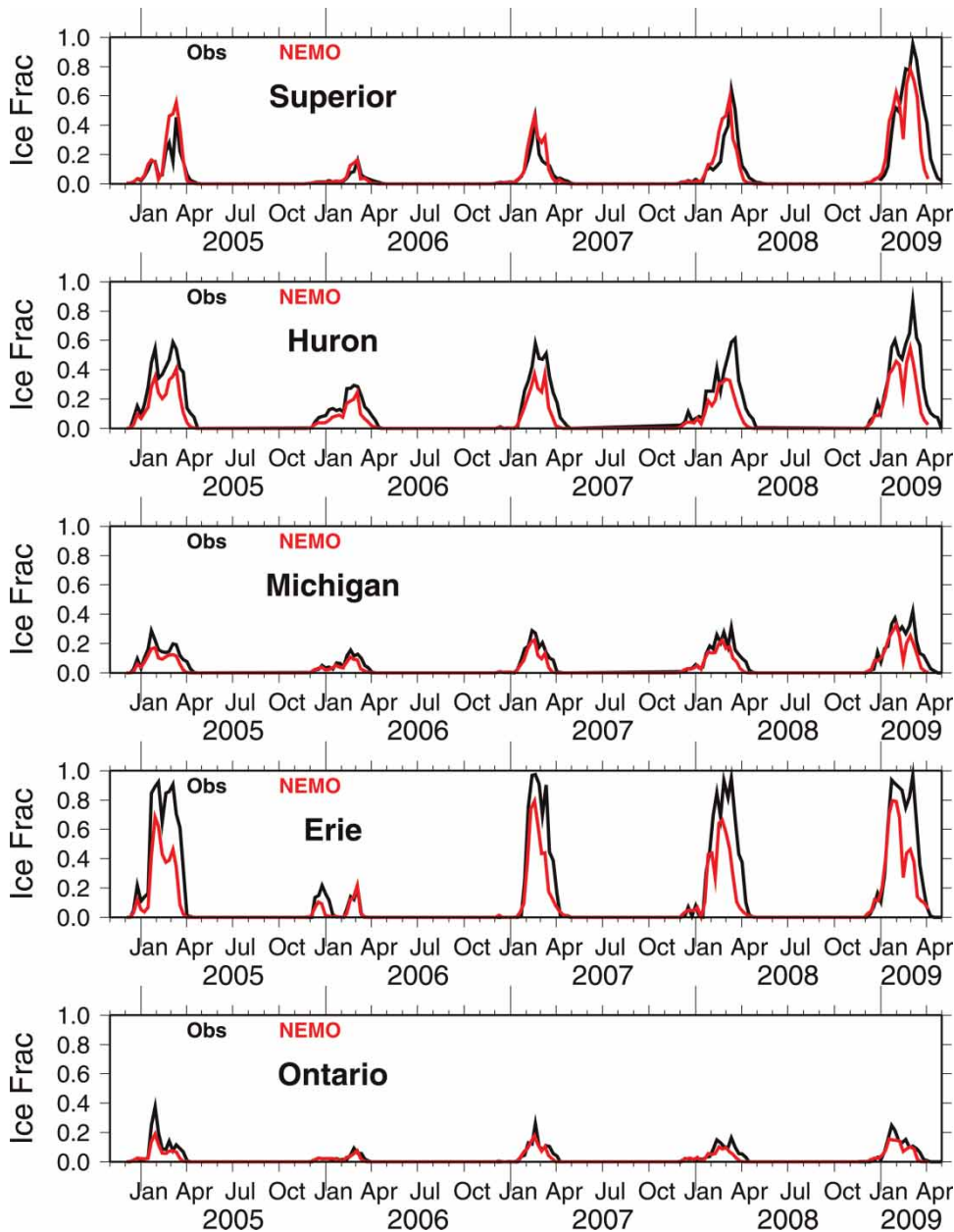


Figure 8 | Comparison of weekly observed (black) and modelled (red) (grey on the hardcopy edition; the full colour version is available online at <http://www.iwaponline.com/wqrjc/toc.htm>) mean ice concentration in the Great Lakes.

et al. 2001). The surface currents produced by the model in Lake Michigan and Lake Huron are also comparable to other model studies (Beletsky *et al.* 1999; Sheng & Rao 2006).

The mean velocities for 2006 are calculated as a large observational database is available during this period in Lake Ontario (Huang *et al.* 2010a). The depth-averaged

circulation shows a cyclonic circulation occupying a large portion of Lake Ontario (Figure 10), which is consistent with results from Huang *et al.* (2010a). Mean currents obtained are in the order of 2–7 cm/s, which are in good agreement with observed currents in the lake (Beletsky *et al.* 1999). Some features in velocity appear to be oriented along the bathymetry – in Lake Huron and Lake Ontario, in

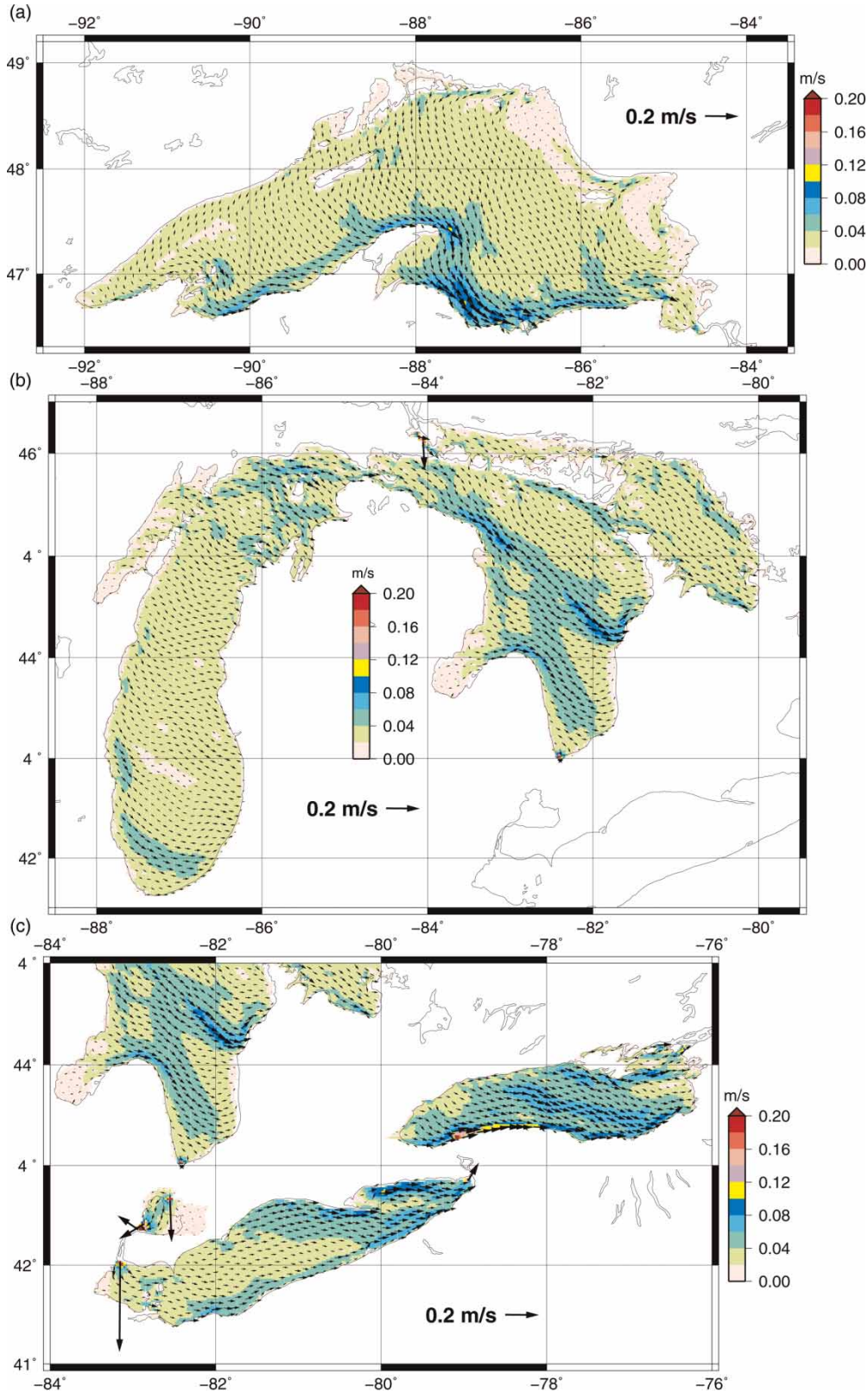


Figure 9 | Mean surface velocity for 2006 in (a) Lake Superior, (b) Lakes Michigan-Huron and (c) Lakes St Clair, Erie and Ontario.

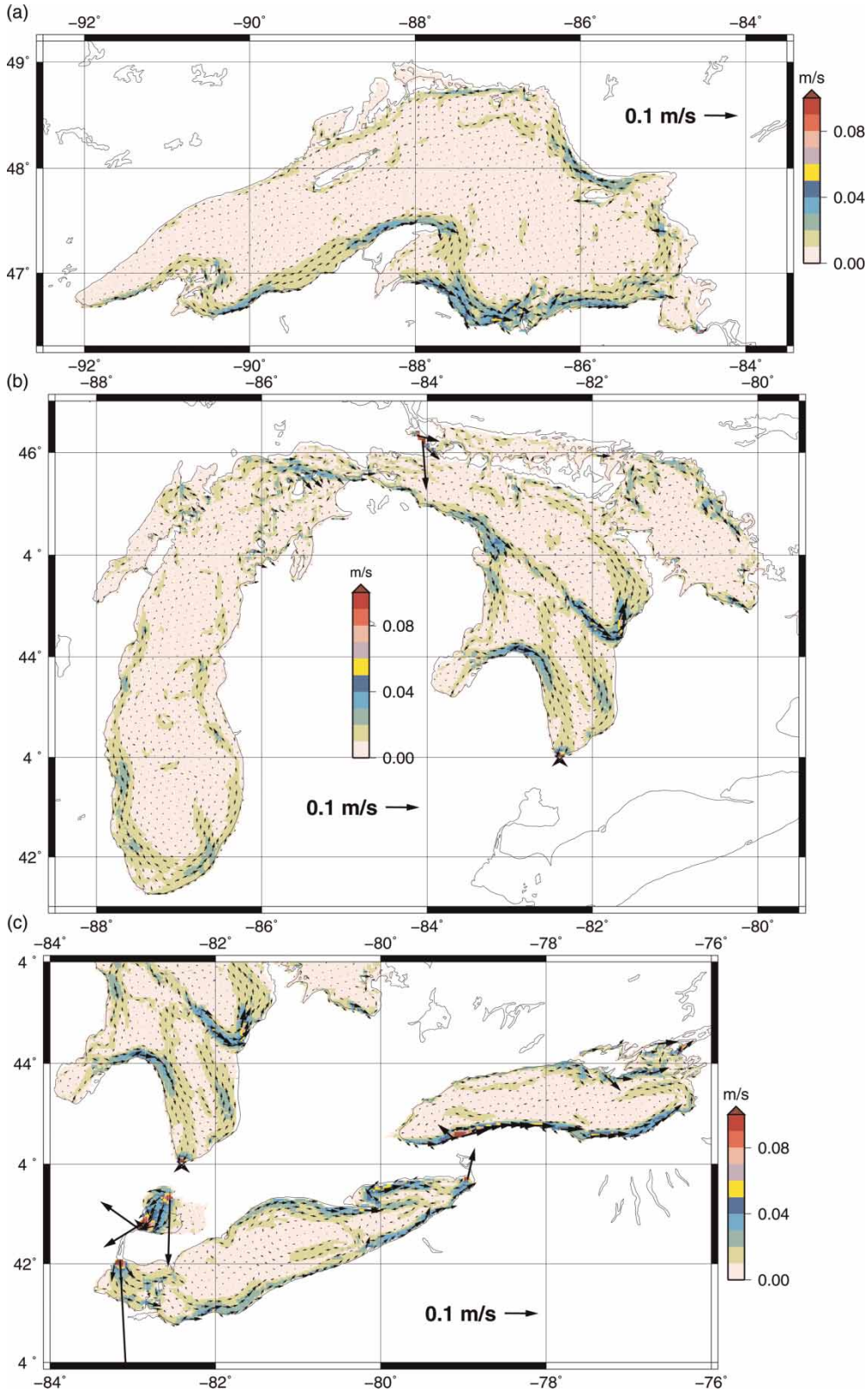


Figure 10 | Mean depth-averaged velocity for 2006 in (a) Lake Superior, (b) Lakes Michigan-Huron and (c) Lakes St Clair, Erie and Ontario.

particular. A typical cyclonic circulation is found in most of the lakes.

CONCLUSIONS

The overall goal of this project was to develop a coupled lake–hydrology–atmosphere model for the Great Lakes basin. In this study, the first version of the one-way coupled hydrodynamic model (NEMO) applied to the Great Lakes has been assessed. The coupled hydrological, atmospheric and lake models predicted seasonal water levels in the upper lakes reasonably well; however, due to lack of proper formulations, the levels in the lower lakes are not very accurate. The ice concentration over all lakes over the hindcasting period of 2005–2009 was very encouraging despite the relative simplicity of the ice component (LIM2) in NEMO.

The lake model performed reasonably well in predicting seasonal and synoptic variability of temperature and currents in all the lakes. The simulation of thermal structure in the central basin of Lake Erie is too diffused, which is an ongoing issue in many lake models. Attempts are underway to further improve thermal structure predictions in the Great Lakes. Although not assessed here, the choice of a vertical coordinate that is near-neutral to the passage of internal seiches and waves seems to be crucial to predict thermal structure more accurately. This can be achieved in future studies due to availability of mixed coordinates in the NEMO model. The currents predicted in this system have reasonable accuracy for use in practical water quality and transport problems in the lake.

The present system under development is currently being tested two-way coupled to the Canadian operational atmospheric model GEM (with the river router WATROUTE already integrated into the modelling system). Numerical experiments will be carried out with and without lake components on assessing the surface meteorological fields over the Great Lakes basin. The modelling system will also be spatially expanded to include a downstream finite element model covering the St Lawrence River and upper estuary. Extension of the model to the Lake Champlain watershed is also under discussion which will allow more accurate flood risk forecasting for the Quebec region. We finally

envision the extension of the system to the whole St Lawrence watershed, including the Gulf of St Lawrence, where NEMO will cover all inland and coastal waters.

ACKNOWLEDGEMENTS

Environment Canada and the Search and Rescue New Initiatives Fund (SAR NIF) provided funding for the project. Dr Anning Huang set the initial grid and common data set for validation of models.

REFERENCES

- Anyah, R. O. & Semazzi, F. H. M. 2004 [Simulation of the sensitivity of Lake Victoria basin climate to lake surface temperatures](#). *Theor. Appl. Climatol.* **79**, 55–69.
- Barnier, B., Madec, G., Penduff, T., Molines, J.-M., Tréguier, A.-M., Le Sommer, J., Beckmann, A., Biastoch, A., Böning, C., Dengg, J., Derval, C., Durand, E., Gulev, S., Rémy, E., Talandier, C., Theetten, S., Maltrud, M. E., McClean, J. & De Cuevas, B. 2006 [Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy-permitting resolution](#). *Ocean Dyn.* **56**, 543–567.
- Bates, G. T., Hostetler, S. W. & Giorgi, F. 1995 [Two-year simulation of the Great Lakes region with a coupled modeling system](#). *Mon. Weather Rev.* **123**, 1505–1522.
- Bélair, S., Crevier, L.-P., Mailhot, J., Bilodeau, B. & Delage, Y. 2003 [Operational implementation of the ISBA land surface scheme in the Canadian regional weather forecast model. Part I: Warm season results](#). *J. Hydromet.* **4**, 352–370.
- Beletsky, D., Saylor, J. H. & Schwab, D. J. 1999 [Mean circulation in the Great Lakes](#). *J. Great Lakes Res.* **25**, 78–93.
- Bennett, J. R. 1977 [A three dimensional model of Lake Ontario's summer circulation: I. Comparison with observations](#). *J. Phys. Oceanogr.* **7**, 591–601.
- Bingeman, A. K., Kouwen, N. & Soulis, E. D. 2006 [Validation of the hydrological processes in a hydrological model](#). *J. Hydrol. Eng.* **11**, 451–463.
- Blanke, B. & Delecluse, P. 1993 [Variability of the tropical Atlantic ocean simulated by a general circulation model with two different mixed layer physics](#). *J. Phys. Oceanogr.* **23**, 1363–1388.
- Boyce, F. M., Donelan, M. A., Hamblin, P. F., Murthy, C. R. & Simos, T. J. 1989 [Thermal structure and circulation in the Great Lakes](#). *Atmos.-Ocean* **27**, 607–642.
- Brasnett, B. 2008 [The impact of satellite retrievals in a global sea-surface-temperature analysis](#). *Q. J. R. Meteorol. Soc.* **134**, 1745–1760.
- Chen, C., Zhu, J., Ralph, E., Green, S. A., Wells Budd, J. & Zhang, F. Y. 2001 [Prognostic modeling studies of the Keweenaw](#)

- current in Lake superior. Part I: Formation and evolution. *J. Phys. Oceanogr.* **31**, 379–395.
- Côté, J., Gravel, S., Methot, A., Patoine, A., Roch, M. & Staniforth, A. 1998 The operational CMCMRB global environmental multiscale (GEM) model. Part I: Design considerations and formulation. *Mon. Weather Rev.* **126**, 1373–1395.
- Deacu, D., Fortin, V., Klyszejko, E., Spence, C. & Blanken, P. D. 2012 Predicting the net basin supply to the Great Lakes with a hydrometeorological model. *J. Hydrometeorol.* Accepted for publication online. Available from: <http://dx.doi.org/10.1175/JHM-D-11-0151.1>.
- Drillet, Y., Bourdallé-Badie, R., Siefridt, L. & Le Provost, C. 2005 Meddies in the Mercator North Atlantic and Mediterranean Sea eddy-resolving model. *J. Geophys. Res.* **110**, C03016.
- Fichefet, T. & Morales Maqueda, M. A. 1997 Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. *J. Geophys. Res.* **102**, 12609–12646.
- Gaspar, P., Gregoris, Y. & Lefevre, J. 1990 A simple eddy kinetic energy model for simulations of the oceanic vertical mixing: tests at Station Papa and long-term upper ocean study site. *J. Geophys. Res.* **95**, 16179–16193.
- Gauthier, P., Tanguay, M., Laroche, S., Pellerin, S. & Morneau, J. 2007 Extension of 3D-Var to 4DVar: implementation of 4D-Var at the meteorological service of Canada. *Mon. Weather Rev.* **135**, 2339–2354.
- Goyette, S., McFarlane, N. A. & Flato, G. 2000 Application of the Canadian Regional Climate Model to the Laurentian Great Lakes Regions. Implementation of a Lake Model. *Atmos.-Ocean* **38**, 481–503.
- Hanrahan, J. L., Kravtsov, S. V. & Roebber, P. J. 2010 Connecting past and present climate variability to the water levels of Lakes Michigan and Huron. *Geophys. Res. Lett.* **37**, L01701.
- Hodges, B. R. & Dallimore, C. 2006 *Estuary, Lake and Coastal Ocean Model: ELCOM. Users Guide*. Centre for Water Research, University of Western Australia Technical Publication, 62 pp. Available from: http://www.cwr.uwa.edu.au/services/models/elcom_science_2_2_0/ELCOM_Science.pdf.
- Holloway, G. & Wang, Z. 2009 Representing eddy stress in an Arctic Ocean model. *J. Geophys. Res.* **114**, C06020.
- Huang, A., Rao, Y. R. & Lu, Y. 2010a Evaluation of a 3-D hydrodynamic model and atmospheric forecast forcing using observations in Lake Ontario. *J. Geophys. Res.* **115**, C02004.
- Huang, A., Rao, Y. R., Lu, Y. & Zhao, J. 2010b Hydrodynamic modeling of Lake Ontario: an intercomparison of three models. *J. Geophys. Res.* **115**, C12076.
- King, J. R., Shuter, B. J. & Zimmerman, A. P. 1997 The response of the thermal stratification of South Bay (Lake Huron) to climatic variability. *Can. J. Fish. Aquat. Sci.* **54**, 1873–1882.
- Kouwen, N. 1988 WATFLOOD: a micro-computer based flood forecasting system based on real-time weather radar. *Can. Water Resour. J.* **13**, 62–77.
- Large, W. & Yeager, S. 2004 Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. CGD Division of the National Center for Atmospheric Research, NCAR Technical, Note: NCAR/TN-460 + STR. Available from: http://www.cgd.ucar.edu/oc/pubs/04pubs_files/TN460.pdf.
- Large, W. G., McWilliams, J. C. & Doney, S. C. 1994 Oceanic vertical mixing: A review and a model with a non-local K-profile boundary layer parameterization. *Rev. Geophys.* **32**, 363–403.
- Laroche, S., Gauthier, P., Tanguay, M., Pellerin, S. & Morneau, J. 2007 Impact of the different components of 4D-Var on the global forecast system of the Meteorological Service of Canada. *Mon. Weather Rev.* **135**, 2355–2364.
- Lofgren, B. M. 1997 Simulated effects of idealized Laurentian Great Lakes on regional and large-scale climate. *J. Climate* **10**, 2847–2858.
- Long, Z., Perrie, W., Gyakum, J., Caya, D. & Laprise, R. 2007 Northern lake impacts on local seasonal climate. *J. Hydrometeorol.* **8**, 881–896.
- Madec, G. 2006 NEMO: the OPA ocean engine, Note du Pole de Modelisation, Institut Pierre-Simon Laplace. Available from: http://www.nemo-ocean.eu/Media/Files/Doc_OPA8.1.
- Madec, G., Delecluse, P., Imbard, M. & Lévy, C. 1998 OPA 8.1. Ocean General Circulation Model reference manual. Note du Pole de Modelisation, Institut Pierre-Simon Laplace. Available from: http://www.nemo-ocean.eu/content/download/21612/97924/file/NEMO_book_3_4.pdf.
- Masson-Delmotte, V., Kageyama, M., Braconnot, P., Charbit, S., Krinner, G., Ritz, C., Guilyardi, E., Jouzel, J., Abe-Ouchi, A., Crucifix, M., Gladstone, R. M., Hewitt, C. D., Kitoh, A., LeGrande, A. N., Marti, O., Merkel, U., Motoi, T., Ohgaito, R., Otto-Bliesner, B., Peltier, W. R., Ross, I., Valdes, P. J., Vettoretti, G., Weber, S. L., Wolk, F. & Yu, Y. 2006 Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints. *Clim. Dynam.* **26**, 513–529.
- Martynov, A., Sushama, L. & Laprise, R. 2010 Simulation of temperate freezing lakes by one dimensional lake models: performance assessment for interactive coupling with regional climate models. *Boreal. Env. Res.* **15**, 143–164.
- Mailhot, J., Bélair, S., Benoit, R., Bilodeau, B., Delage, Y., Fillion, L., Garand, L., Girard, C. & Tremblay, A. 1998 Scientific description of RPN Physics Library, version 3.6. Recherche en Prévision Numérique, 188 pp. Available from: <http://collaboration.cmc.ec.gc.ca/science/rpn/physics/physic98.pdf>.
- Mailhot, J., Bélair, S., Lefaiivre, L., Bilodeau, B., Desgagné, M., Girard, C., Glazer, A., Méthot, A., Patoine, A., Plante, A., Talbot, D., Tremblay, A., Vaillancourt, P. & Zadra, A. 2006 The 15-km version of the Canadian regional forecast system. *Atmos.-Ocean* **44**, 133–149.
- Mellor, G. L. & Blumberg, A. F. 1985 Modeling vertical and horizontal diffusivities with the sigma coordinate system. *Mon. Weather Rev.* **113**, 1380–1383.
- Neff, B. P. & Nicholas, J. R. 2005 Uncertainty in the Great Lakes Water Balance, Date Posted: November 23, 2005: U.S. Geological Survey Scientific Investigations Report

- 2004–5100, 42 p. Available from: <http://pubs.water.usgs.gov/sir2004-5100/>.
- Obolkin, V. A. & Potemkin, V. L. 2006 The impact of large lakes on climate in the past: a possible scenario for Lake Baikal. *Hydrobiologia* **568(S)**, 249–252.
- Oveisy, A., Boegman, L. & Imberger, J. 2012 Three-dimensional simulation of lake and ice dynamics during winter. *Limnol. Oceanogr.* **57**, 43–57.
- Pellerin, P., Ritchie, H., Saucier, F. J., Roy, F., Desjardins, S., Valin, M. & Lee, V. 2004 Impact of a two-way coupling between an atmospheric and ocean-ice model over the Gulf of St. Lawrence. *Mon. Weather Rev.* **132**, 1379–1398.
- Pietroniro, A., Fortin, V., Kouwen, N., Neal, C., Turcotte, R., Davison, B., Verseghy, D., Soulis, E. D., Caldwell, R., Evora, N. & Pellerin, P. 2007 Using the MESH modelling system for hydrological ensemble forecasting of the Laurentian Great Lakes at the regional scale. *Hydrol. Earth Syst. Sci. Discuss.* **3**, 2473–2521.
- Rao, Y. R., Marvin, C. H. & Zhao, J. 2009 Application of a numerical model for circulation, temperature and pollutant distribution in Hamilton Harbour. *J. Great Lakes Res.* **35**, 61–73.
- Rattan, S., Myers, P. G., Treguier, A.-M., Theetten, S., Biastoch, A. & Boening, C. 2010 Towards an understanding of Labrador Sea salinity drift in eddy-permitting simulations. *Ocean Model.* **35**, 77–88.
- Schertzer, W. M., Rouse, W. R., Blanken, P. D. & Walker, A. E. 2003 Over-lake meteorology and estimated bulk heat exchange of Great Slave Lake in 1998 and 1999. *J. Hydrometeor.* **4**, 649–659.
- Schwab, D. J. & Bedford, K. W. 1994 Initial implementation of the Great Lakes forecasting system: a real-time system for predicting lake circulation and thermal structure. *Water Poll. Res. J. Can.* **29**, 203–220.
- Sheng, J. & Rao, Y. R. 2006 Circulation and thermal structure in Lake Huron and Georgian Bay: application of a nested-grid hydrodynamic model. *Cont. Shelf Res.* **26**, 1496–1518.
- Sheng, J., Wright, D., Greatbatch, R. & Dietrich, D. 1998 CANDIE: a new version of the DieCAST Ocean Circulation Model. *J. Atm. Oceanic Tech.* **15**, 1414–1432.
- Simons, T. J. 1980 Circulation models of lakes and inland seas. *Can. B. Fish. Aquat. Sci.* **203**, 146.
- Song, Y., Semazzi, F. H. M., Xie, L. & Ogallo, L. J. 2004 A coupled regional climate model for the Lake Victoria Basin of East Africa. *Int. J. Climatol.* **24**, 57–75.
- Tolson, B. 2009 Rationalizing the Decline in Lake Michigan-Huron Water Levels Using the Coordinated Great Lakes Routing & Regulation Model, Final report to St. Clair Task Team Hydroclimate TWG, Nov 7, 2009. Available from: http://pub.iugls.org/en/St_Clair_Reports/Hydroclimatic/Hydroclimate-06.pdf.
- Umlauf, L. & Burchard, H. 2003 A generic length-scale equation for geophysical turbulence models. *J. Mar. Res.* **61**, 235–265.
- Vancoppenolle, M., Fichefet, T., Goosse, H., Bouillon, S., Madec, G. & Morales Maqueda, M. A. 2009a Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation. *Ocean Model.* **27**, 33–53.
- Vancoppenolle, M., Fichefet, T. & Goosse, H. 2009b Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 2. Importance of sea ice salinity variations. *Ocean Model.* **27**, 54–69.
- Wang, Z., Lu, Y., Wright, D. & Dupont, F. 2010 Sea ice sensitivity to the parameterization of open water area. *J. Occup. Oceanogr.* **3**, 1–7.
- Zhu, J., Demirov, E., Dupont, F. & Wright, D. 2009 Eddy-permitting simulations of the sub-polar North Atlantic: Impact of the model bias on water mass properties and circulation. *Ocean Dynam.* **60**, 1177–1192.