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Numerical modeling of hydrodynamics and tracer dispersion during ice-free period in Lake Winnipeg

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ABSTRACT

The three-dimensional hydrodynamic Estuary Lake Coastal Ocean Model (ELCOM) was used to study the water circulation and thermal structure of Lake Winnipeg, Canada. To assess the model performance, we simulated circulation and temperature distribution of the lake in 2007 and compared the model results with the field observations of water levels, temperature, and currents. The model showed considerable success in reproducing the thermal structure and circulation. The model predicted isothermal conditions in the South Basin and Narrows for the whole period and produced weak thermal stratification during the early summer in the North Basin. The modeled currents were used to examine the transport, dispersion of passive tracers, and local flushing time in the lake. Simulations using passive tracers qualitatively agreed well with the field measurements of hydrogen isotopes in Lake Winnipeg taken during the study period. The mean transport is towards the north in the lake with two cyclonic gyres in the North Basin and one gyre in the South Basin. The model results show that the local flushing time of Red River waters in the South Basin is about 45 days.

Introduction

Lake Winnipeg is the 10th largest freshwater lake in the world and the 5th largest in Canada. It has two distinct basins, the North Basin (100 km wide) and the South Basin (40 km wide), which are separated by the Narrows, a 2.5 km wide channel. The dual-basin lake is elongated in shape, extends 436 km from north to south, and is relatively shallow with a mean depth of 9 m and 12 m in south and north basins, respectively. With abundant wind energy and shallow water depths, little or no significant thermal stratification occurs in the lake (Kenney, 1979; Hamblin, 1976; Brunskill et al., 1980). The lake is subject to wind driven turbidity that stirs up sediments from the bottom (Brunskill et al., 1980). The Red, Winnipeg, and Saskatchewan rivers are the major rivers flow into Lake Winnipeg, contributing more than 70% of the water received. The Nelson River drains Lake Winnipeg and runs northward into Hudson Bay.

Significant changes in water transparency, biological species composition, primary productivity, and sediment chemistry suggest that the lake is on a trajectory of progressive eutrophication that may affect ecosystem sustainability (Lake Winnipeg Stewardship Board, 2006). Stressors on the lake require continued scientific attention to conditions in the lake that are essential to identify and quantify chemical inputs, organisms, and processes and to determine the effects on the lake ecosystem. One of the primary goals of the Federal Lake Winnipeg Action Plan is to generate basic understanding of the ecology of Lake Winnipeg in order to ensure that resource management decisions lead to restoring Lake Winnipeg and assuring its long term sustainability. The Red and Winnipeg rivers are the primary sources of flow and nutrients to the south basin of Lake Winnipeg, whereas the Saskatchewan River discharges into the north basin. There is little information on how materials and nutrients introduced primarily from the Red and Winnipeg rivers would deposit and mix within the lake in the South Basin. In addition to basin scale agricultural nutrient inputs, the city of Winnipeg also discharges treated sewage water to the lake through the Red River.

Brunskill et al. (1980) collected and analyzed several baseline physical, chemical, and biological samples from 50 lake-wide stations during 6 open water cruises. He examined both spatial and temporal variabilities in the physical, chemical, and biological components of the lake. Since 1969, there have been few smaller studies carried out by the Department of Fisheries and Oceans (DFO) and the Province of Manitoba. Einarrson and Lowe (1968) and Hamblin (1976) attempted to model the seiches and surges in the lake. They observed that the water levels may increase up to 2 m at the downwind shore locations during storms. Constrictions at the Narrows cause distinct wind-driven circulations in the north and south basins. Inter-basin water exchange is critical in transporting algae or nutrients from one basin to another. The water mass characteristics indicate that physical processes influence the water exchange flows (Brunskill et al., 1980). Water retention times of the south and north basins will be affected

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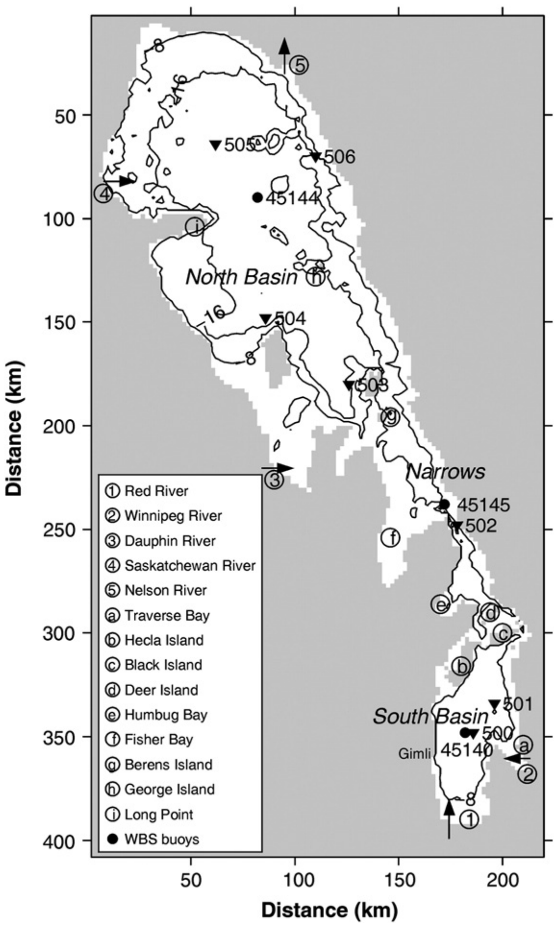

Fig. 1. Map of instrument locations and selected bathymetric features within the numerical model domain of Lake Winnipeg. River inflows and outflow are identified with arrows.

by these exchange dynamics. Kenney (1979) showed that significant water exchange takes place between the two basins through the Narrows. The surface currents driven by surface wind stress and water level oscillations are about 20–90 cm/s in the Narrows.

With the large surface area and shallow water depth, the water column in Lake Winnipeg is generally isothermal with some minor stratification established during weak winds in summer; however, most of that information is based on spatially few spot measurements. Environment Canada deployed two temperature moorings in 2006 to examine the development of thermal stratification and its impact in the lake (Rao, unpublished). These studies and ship based measurements carried out during this period suggest that thermal stratification develops in deeper sections and may play a role in the development of hypoxia in the North Basin. However, these studies were limited to very few observations and insufficient to describe the evolution of thermal stratification and seasonal and transient circulations in the entire lake. Numerical hydrodynamic models on the other hand are well suited to testing the nature of physical processes in complex coastal environments and are used extensively to explain processes that disperse and transport pollutants in the coastal waters and predict their effects on the ecosystem. Models are fundamental to the management of lakes because of the limitation of site measurements over temporal and spatial scales.

As part of this project, both field data collection and numerical model development were carried out in Lake Winnipeg. During 2007, we measured currents, water temperature, wind, solar radiation, water levels, waves, and some water quality parameters at fixed mooring stations in the South and North basins and in the Narrows. The Estuary Lake Coastal Ocean Model (ELCOM) has been used in several lakes (Hodges et al., 2000). Recently, this model has also been applied in the Great Lakes and its embayments (Leon et al., 2005; Rao et al., 2009). ELCOM has an advantage because it can be coupled with the water quality simulator Computational Aquatic Ecosystem Dynamics Model (CAEDYM). For these reasons, as a first step, ELCOM was chosen to simulate the circulation and thermal structure patterns in Lake Winnipeg.

The primary objective of this paper is to examine the 3D water circulation, temperature structure, and water levels in Lake Winnipeg based on the model results. Field data including water quality parameters and water isotopes collected in 2007 offered the opportunity to carry out a detailed verification of the hydrodynamic model for the lake. Dispersal patterns of nutrients, pollutants, and of marine organisms that are passive or have limited locomotion are highly dependent on the hydrodynamics of the lake. Because of this, as a secondary objective, model currents were used to investigate the transport and dispersion of passive tracers and estimate local flushing time in Lake Winnipeg. The simulated circulation and estimates of mixing and flushing are critical in assessing the fate and transport of water quality constituents in the lake.

Materials and methods

Field observations

From May to October, 2007, we obtained a time series measurements of vertical temperature structure, currents, light transmission, and bottom layer oxygen at several moorings. The air temperature, wind speed and direction, relative humidity, and solar radiation data were obtained from a meteorological buoy which was deployed at station 501 in the South Basin and a land station which was established on George Island and was later relocated to Gimli airport. Fig. 1 shows the positions of the mooring stations and land based station at Gimli. Water temperature data were obtained from 6 thermistor strings located at stations of 500, 502, 503, 504, 505, and 506. The Onset Tidbit type thermistors were deployed on moorings at 1–3 m intervals in the vertical. Temperature data were recorded at 10 min interval and it is accurate to the order of 0.2 °C. Because of the missing of the upper part (spar buoy) on retrieval, temperature

Table 1
Mooring positions during 2007 in Lake Winnipeg.

Station no.	Type	Instrument/depth
500	ADCP and temperature chain	Temperature/ADCP (1, 2,4, 6, 8, 10, 11,11 m)
501	Meteorology	
502	ADCP and temperature chain	Temperature (**1**, **3**, **4**, **6**,8, 10, 11, 12, 13,14, 15, 16, 17,17.6 m)
503	Temperature chain	Temperature (**1**, **3**, **4**, **6**,8, 10, 11, 12, 13,14, 15, 16 m)
504	Temperature chain	Temperature (1, 3, 4, 4,6, 8, 9, 10, 11, 12,13, 14, 15, 16 m)
505	ADCP and temperature chain	Temperature/ADCP (**1**, **3**, **4**, **6**, 8, 10, 11, 12, 13,14, 15, 16, 17, 18,16.6, 18.1 m)
506	Temperature chain	Temperature (1, 2, 4, 6, 8, 10, 13, 14, 14.4 m)
Gimli airport	Meteorology	

Tidbits in bold were not recovered due to the damage of spar buoys.