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Luis F. León

David C. L. Lam

William Schertzer

David Swayne

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A 3D Hydrodynamic Lake Model: Simulation on Great Slave Lake

Luis F. León[1], David C.L. Lam[2], William M. Schertzer[2] and David A. Swayne[3]

[1]University of Waterloo, Waterloo, ON, Canada: lfleonvi@uwaterloo.ca
[2]Environment Canada, National Water Research Institute, Burlington, ON, Canada.
[3]University of Guelph, Guelph, ON, Canada

Abstract: Large lakes are recognized as an important influence on the circulation of the atmosphere; in return the resulting meteorological forcing also affects the lake thermal structure. This interaction is complex and continues to be a critical issue considering the millions of lakes in Canada, many of which are large, and are unaccounted for in the current climatic models. This paper evaluates the predictive capability of the 3-D Estuary and Lake COmputer Model (ELCOM) using relatively high quality data collected on Great Slave Lake - one of the largest lakes of the world in Canada's northern climatic system. This assessment is an important step in our ongoing research to develop a coupled lake-atmosphere model - a major consideration in the development and testing of our lake model. A validation run is performed with 2003 data in the Great Slave Lake. Vertical thermistor chain data is compared against model calculations and mean circulation patterns are presented. Comparison runs were made with meteorological field data and with output from a Regional Climate Model (RCM) as input to the hydrodynamic model to determine the differences in forcing data affecting simulations of surface temperature and circulation.

Keywords: 3D Hydrodynamic Lake Model; Regional Climate Model; Lake Model Verification

1. INTRODUCTION

It is recognized that large lakes have an important influence on the circulation of the atmosphere; in turn, the meteorological forcing also affects the lake thermal structure. This interaction is complex and continues to be a critical issue considering the millions of lakes in Canada, many of which are large, and are unaccounted in the current climatic models as described by Swayne et al. [2005].

In a study funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), one objective was to determine the feasibility of a 3-dimensional lake thermal/hydrodynamic model to be coupled/interfaced with atmospheric models, in particular with respect to large lakes.

For a large deep lake such as Great Slave Lake, a 3-dimensional hydrodynamic model is required to simulate the considerable spatial and temporal variability, especially lake temperature in response to the climatic forcing.

During the last decade various 3-D hydrodynamic models have been developed as shown in Lynch and Davies [1995]. The model selected for further development and testing in this project is ELCOM described by Hodges et al. [2000]. Previous set up and validation of the model in Lake Erie, shown by Leon et al. [2005], provides enough confidence in the model.

2. ELCOM IN GREAT SLAVE LAKE

2.1 Model Setup

The Great Slave Lake is the 4th largest freshwater lake in Canada and the 12th largest lake of the world. It is located in the Mackenzie River Basin within Canada's northern climatic system.

The lake consists of a central basin and an eastern arm called Christie Bay (with a maximum depth of 700m). In this study we concentrate only on the central basin that has a surface area of 18,500km^2, maximum depth of 187.7m and total volume of 596km^3, as estimated by Schertzer [2000].

The top section of Figure 1 shows the bathymetry of the central basin of Great Slave Lake and the location of the sites with meteorological forcing data. The bottom part shows the model grid with a 2 x 2 km resolution and 30 vertical layers.

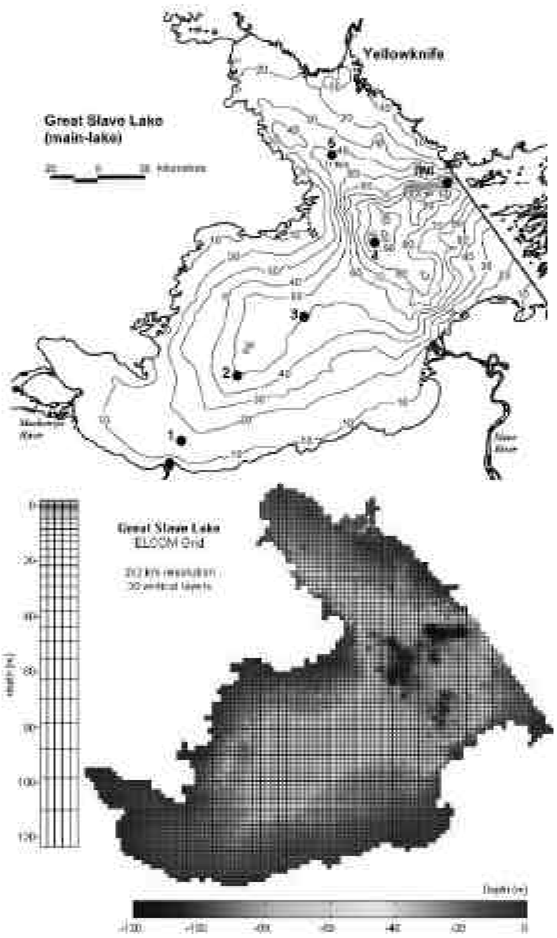

Figure 1. Bathymetry and location of buoys (top) and the model 2x2 km & 30 layers grid (bottom)

The meteorological data (wind speed, direction, air temperatures, solar radiation, relative humidity and cloud cover) were obtained from deployments (buoys shown in Figure 1) during the Canadian Global Energy-Water Cycle Experiment Enhanced Study as described in Schertzer et al. [2003].

The year selected for the simulation was 2003, where validation (vertical temperature structure) data were available at five sites (water temperature moorings) for three months (end of July to mid September). Sensor depths were standardized to allow for comparability of thermal profiles (see Schertzer et al. [2003]).

Time series of the main meteorological variables measured in the lake are shown in Figure 2 for air temperature, solar radiation and wind forcing.

2.2 Simulation Results

One of the main outputs of the 3D hydrodynamic model is the lake circulation. The lake responds to the meteorological forcing by heat exchange at the air-water interface and the currents are responsible for redistribution of heat both horizontally and vertically.

The computed average surface currents for Great Slave Lake formed a relatively large counter-clockwise gyre as shown in Figure 3 (left). The dominant circulations play a decisive role in the horizontal transport of heat in the lake creating relatively large spatial gradients in the surface temperature.

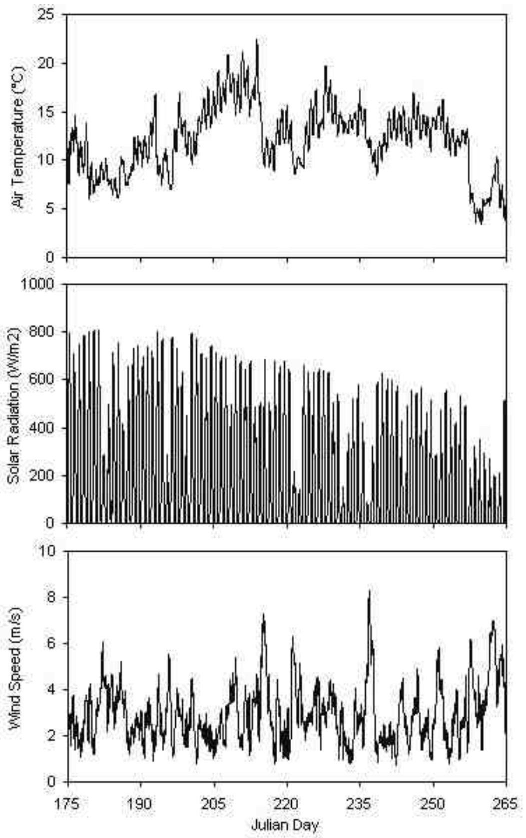

Figure 2. Time series of average meteorological data recorded at the Great Slave Lake buoys

Also in Figure 3 (right) a snapshot of simulated surface temperature for Great Slave Lake is shown for Aug 20, 2003. This result illustrates the large horizontal variations in surface temperature over the warming period.

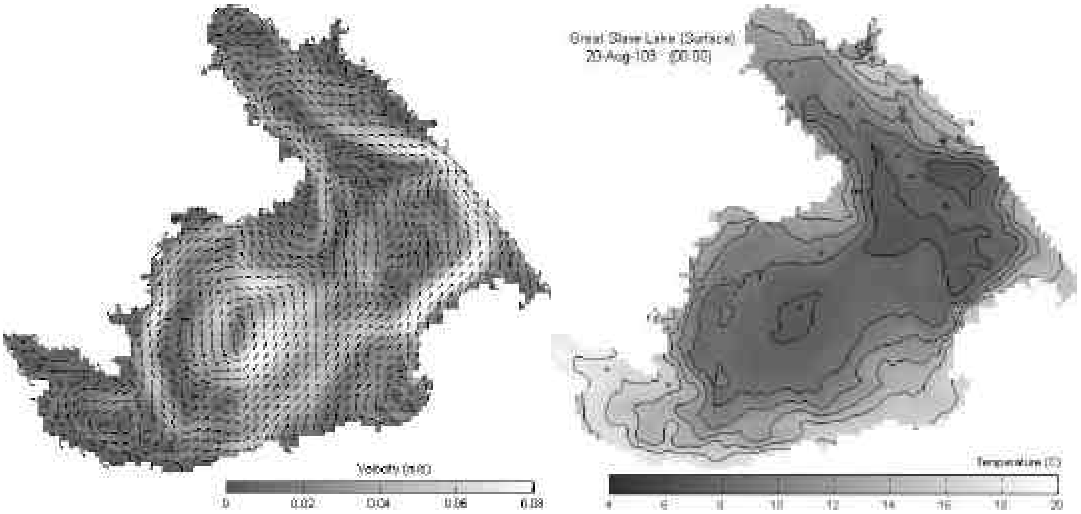

Figure 3. Model results for 2003 in Great Slave Lake. Surface mean circulation showing a main counter clockwise circulation pattern and the presence of large gyres (left) and a snapshot of the surface temperature distribution in Aug 20, 2003 (right).

In this simulation, a no flux condition has been imposed between the central basin and the Christie Arm, and inflow from the Slave River and outflow through the Mackenzie River have been set to zero. It should be noted that including the major inflows and outflows in future runs are expected to further improve the simulations.

2.3 Validation

While climate models will interface with the lake model through the surface temperature and heat fluxes, accurate prediction of the in-lake thermal structure is of importance to the consistency in the air-water physical processes and to applications in studying weather and climate impacts on lake water quality and ecosystems.

In particular, the heat content of the lake will be significantly affected by the vertical thermal structure and thereby affect the weather and climate predictions. Thus, it is important to verify the model results for the vertical temperature structure computed by the 3D lake model.

In this respect, the computed results agreed well with the observed at the various buoy locations as shown in Figure 4 which shows, as an example, measured and computed surface temperatures at sites 4 & 5 (deep central and average north).

The results showed the warming of the upper layer in July with some cooling events happening early in August and September, due to wind storms and cooler air temperatures (see Figure 2).

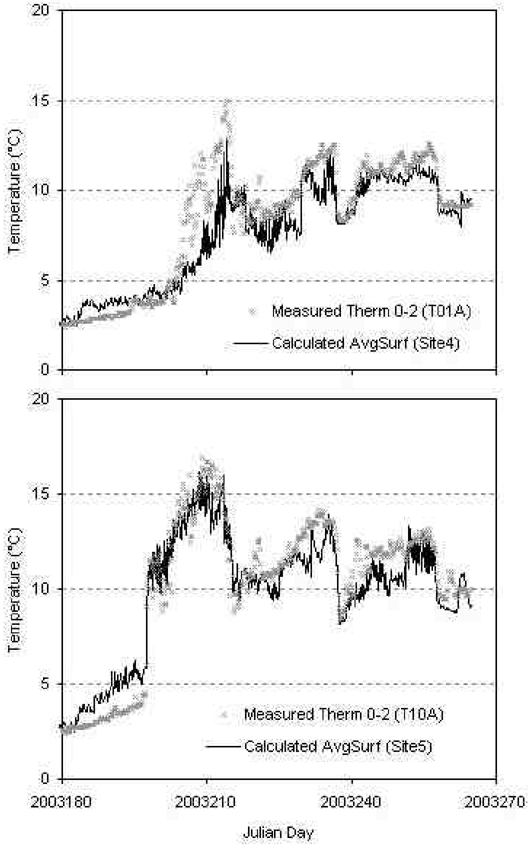

Figure 4. Comparison between computed average surface temperatures (top layer) with measured temperatures (average 0-2m depth) for sites 4 & 5 (deep central and average north).

3. SCENARIO WITH RCM OUTPUT

As mentioned in the introduction, and aiming to test the feasibility of coupling a 3-dimensional lake hydrodynamic model to a climate model, an scenario was prepared using the output data from a regional climate model to be used as the input forcing data for ELCOM.

The rationale behind this test is that, an ideally coupled model will not utilize observed over-lake data. Rather the input to the hydrodynamic model at each time step will be from the RCM output. In addition, the results from this exercise will provide important information of the relative importance that different input parameters have on simulated temperature and heat fluxes.

It is worth mentioning that the RCM output was estimated without considering interaction between the water surface and the atmosphere. This means that the meteorological variables, in particular the air temperature and solar radiation, represent the results assuming that the interaction in the bottom layer of the climate model is land instead of water.

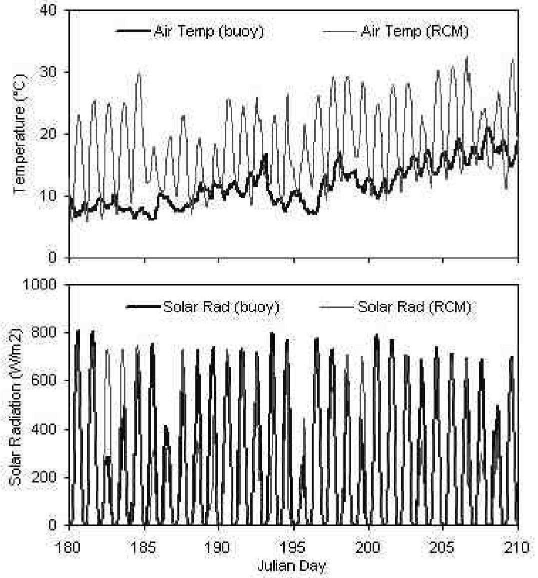

Figure 5. Time series for July, 2003 with forcing data (buoy measurements and RCM output)

Figure 5 shows an example of a subset of the time series (one month) comparing the differences in air temperature and solar radiation between the buoy data and the RCM output to be used as forcing input into the hydrodynamic model.

Table 1 presents the numeric differences between the buoy data and the RCM output for maximum, minimum and average values of the main forcing parameters (air temperature, solar radiation and wind speed).

Table 1. ELCOM Input/Output Differences
Comparison between Buoy - RCM forcing values

Parameter	Buoy	RCM	Average Difference
ELCOM Input			
Air Temperature (°C)			
Max	22.4	32.6	
Average	12.0	14.9	25%
Min	3.5	-4.8	
Solar Radiation (W/m2)			
Max	749.6	808.9	
Average	182.1	199.5	10%
Min	0.0	0.0	
Wind Speed (m/s)			
Max	8.3	10.6	
Average	2.9	3.3	12%
Min	0.7	0.1	
ELCOM Output			
Surface Water Temperature (°C)			
Max	12.1	15.0	
Average	9.8	11.2	15%
Min	2.8	2.8	
Evaporative Heat Flux (W/m2)			
Max	-1.0	0.0	
Average	-23.7	-21.8	-8%
Min	-118.7	-112.3	

At the same time, and using the ELCOM average output for the whole lake, the temperature of the surface water and the evaporative heat flux were extracted and compared with the previous run that used the buoy data. Such results (max, min and averages) are also presented in the table.

Remembering that the meteorological output time series from the RCM reflect conditions based on assumptions on other landscapes rather than water, what this means is, comparing the differences to the conditions observed at the surface buoys on the lake, that an increase of +25% in air temperature, +10% in solar radiation and +12% in wind speed, produced a +15% change in the estimated surface water temperature and a decrease of –8% in the evaporative heat flux.

Based on these results it is possible to estimate the potential impact on hydrodynamic simulations using such inputs.

4. CONCLUSIONS

ELCOM, as the 3D hydrodynamic model selected for this study, was successfully applied to Great Slave Lake, one of the largest northern lakes in Canada. The lake is of particular importance since it is located within the northern climatic system of the Mackenzie River watershed.

The simulated circulation in Great Slave Lake is complex and provides a basis for future physical limnological research to understand the lake physics. The complexity in the circulation pattern is reflected in the simulated spatial distribution of surface temperature.

As expected the deeper mid-lake areas lag the nearshore zone in the temperature response. In particular, the shallow south shore becomes significantly warmer than the rest of the central basin.

Model validation was done focusing on accuracy in the simulations for water surface temperature, vertical temperature isotherms and fluxes. Spatial distributions of the mean circulation pattern for Great Slave Lake represents the first simulation of the currents conducted on this lake.

While the impact of individual components on simulated output of surface temperature and heat fluxes is instructive since it establishes the impact of the critical input variables, knowledge of the combined effects of such impacts is crucial to understanding whether use of RCM input to the lake model has a significant effect on the simulation accuracy.

Accuracy in the modeled surface temperature is important especially for deriving the surface heat fluxes required for the RCM at each time step. With respect to the aquatic ecosystem, the consistency of the temperature structure within the water column is also crucial for analyses of the climatic effects on lake physics, biology, chemistry and water quality.

5. ACKNOWLEDGEMENTS

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