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Towards coupling a 3D hydrodynamic lake model with the Canadian Regional Climate Model: Simulation on Great Slave Lake

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Abstract

Recently, it has been recognized that large lakes exert considerable influence on regional climate systems and vice versa and that the Canadian Regional Climate Model (CRCM), which does not currently have a lake component, requires the development of a coupled lake sub-model. Prior to a full effort for this model development, however, studies are needed to select and assess the suitability of a lake hydrodynamic model in terms of its capability to couple with the CRCM. This paper evaluates the performance of the 3-dimensional hydrodynamic model ELCOM on Great Slave Lake, one of Canada's largest lakes in the northern climatic system. Model simulations showed dominant circulation patterns that can create relatively large spatial and temporal gradients in temperature. Simulated temperatures compared well with cross-lake temperature observations both at the surface and vertically. Sensitivity analysis was applied to determine the critical meteorological variables affecting simulations of temperature and surface heat fluxes. For example, a 10% increase in air temperature and solar radiation was found to result in a 3.1% and 8.3% increase in water surface temperature and 8.5% increase in latent heat flux. Knowledge of the model sensitivity is crucial for future research in which the hydrodynamic model coupled with the atmosphere will be forced from the CRCM output.

Keywords: 3D hydrodynamic lake model; Canadian regional climate model; Model verification; Sensitivity analysis

1. Introduction

There are as many as two million freshwater lakes of varying sizes covering 7.6% of Canada's total area. Nearly 14% of the world's lakes having surface areas greater than 500 km^2 are located in Canada, yet little is known of the heat and mass transfers and thermal regimes of these large deep lakes (Schertzer et al., 2004). Evaluation for modeling of lake thermal characteristics across lakes of different morphometric characteristics and climatic regions is required to meet Canada's needs for accurate weather forecasts and for more accurate climate/climate change impact analysis.

Large lakes are increasingly recognized as having an important influence on the regional atmospheric heat and moisture content and circulation; 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. A fully interactive coupling of a lake model with an atmospheric model for regional climate modeling is one option and an important objective of current Canadian Regional Climate Model (CRCM) development (Laprise et al., 1998, 2003).

Inclusion of lakes in the CRCM is an important advance required for Canada's high priority research on lake ecosystem responses to climate. Research on atmosphere-lake interactions has typically relied on using either historical or in situ observed data to force lake thermal models. This is not

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practical for climate impacts research over the vast number of lakes in Canada. Alternative methodologies include forcing a generalized lake thermal or hydrodynamic model with data from a coupled lake-climate model.

Only recently has the CRCM implemented a lake model (Goyette et al., 2000) as an initial attempt to simulate the evolution of the water temperature and ice cover on the Great Lakes. Another example is the implementation of a physically based column model, which includes the effect of ice (Hostetler et al., 1993). These efforts so far pertain to simple one column (1-dimensional; 1D) and box (2-dimensional; 2D) models. In these attempts for the CRCM, the lake is assumed to have uniform surface temperature. For small lakes, such assumption may be valid.

For large lakes, the surface temperature is not uniform and therefore requires a hydrodynamic model with finer spatial resolution architecture (Lam and Schertzer, 1999). Swayne et al. (2005) suggested a coupling approach utilizing a hierarchy of 1D, 2D and 3-dimensional (3D) lake thermodynamic models depending on the size of the lake and the available information.

This paper evaluates the predictive capability of the 3D *E*stuary and *L*ake *CO*mputer *M*odel (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. Sensitivity analysis was applied to determine the critical meteorological variables affecting simulations of temperature and surface heat fluxes. Knowledge of the model sensitivity is crucial for future research in which the hydrodynamic model coupled with the atmosphere will be forced from the Regional Climate model output.

2. The modeling approach

In the current version of the CRCM, there is no lake submodel component. Consequently, heat transfers computed by this version of CRCM over grids containing a mosaic of lakes can only represent the radiative and turbulent heat transfers over the grid assuming land and vegetative covers. The lack of a lake component can therefore result in errors in climate predictions, especially in lake rich regions. While future versions of the CRCM will eventually incorporate a lake component, results from the current CRCM model provide a special opportunity to study the sensitivity of such a model relative to the significance of including lake effects in regional climate models. That is, we use the results from the current CRCM model as input to a 3D lake hydrodynamic model and compare the results with those using observed meteorological data at the air-lake interface. This one-way coupling modeling approach (Kelly et al., 1998) is a necessary step towards developing fully coupled climate-lake models. Thus, our modeling approach for this study consists of the following steps:

(a) validate a selected 3D lake hydrodynamics model by using observed meteorological data as forcing input and compare the results to observed surface temperature over the lake;
(b) perturb the meteorological input individually and systematically and examine the predicted surface temperature for each perturbed input to determine which one is the most sensitive;
(c) re-run the lake hydrodynamics model by using the output from the current CRCM model as forcing input and compare the results with reference to the findings of (a) and (b).

3. The hydrodynamic model

During the last decade a series of 3D hydrodynamic models have been developed at different research institutes. An overview can be found in Lynch and Davies (1995), which includes the well known Princeton Ocean Model (Blumberg and Mellor, 1987; Schwab and Bedford, 1994; Simons, 1975). The model selected in this application is ELCOM, a 3D hydrodynamic model for lakes and reservoirs, and is used to predict the variation of water temperature in space and time (Hodges et al., 2000). The model applies hydrodynamic and thermodynamic models to simulate the temporal behavior of stratified water bodies with environmental forcing.

The model solves the unsteady, viscous Navier–Stokes equations for incompressible flow using the hydrostatic

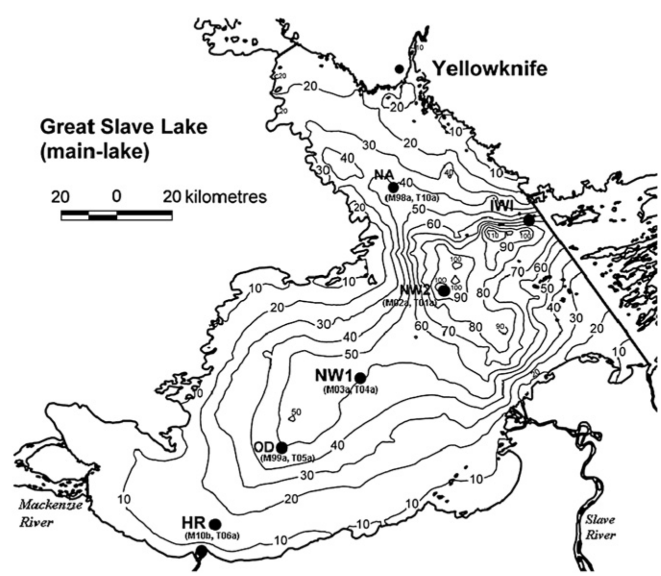

Fig. 1. Bathymetry and location of measurement sites for meteorology, radiation and physical limnology observations in Great Slave Lake (Schertzer et al., 2000, 2003). Note: Text also cites sites as 1 to 5 referring to HR, OD, NW1, NW2 and NA, respectively.

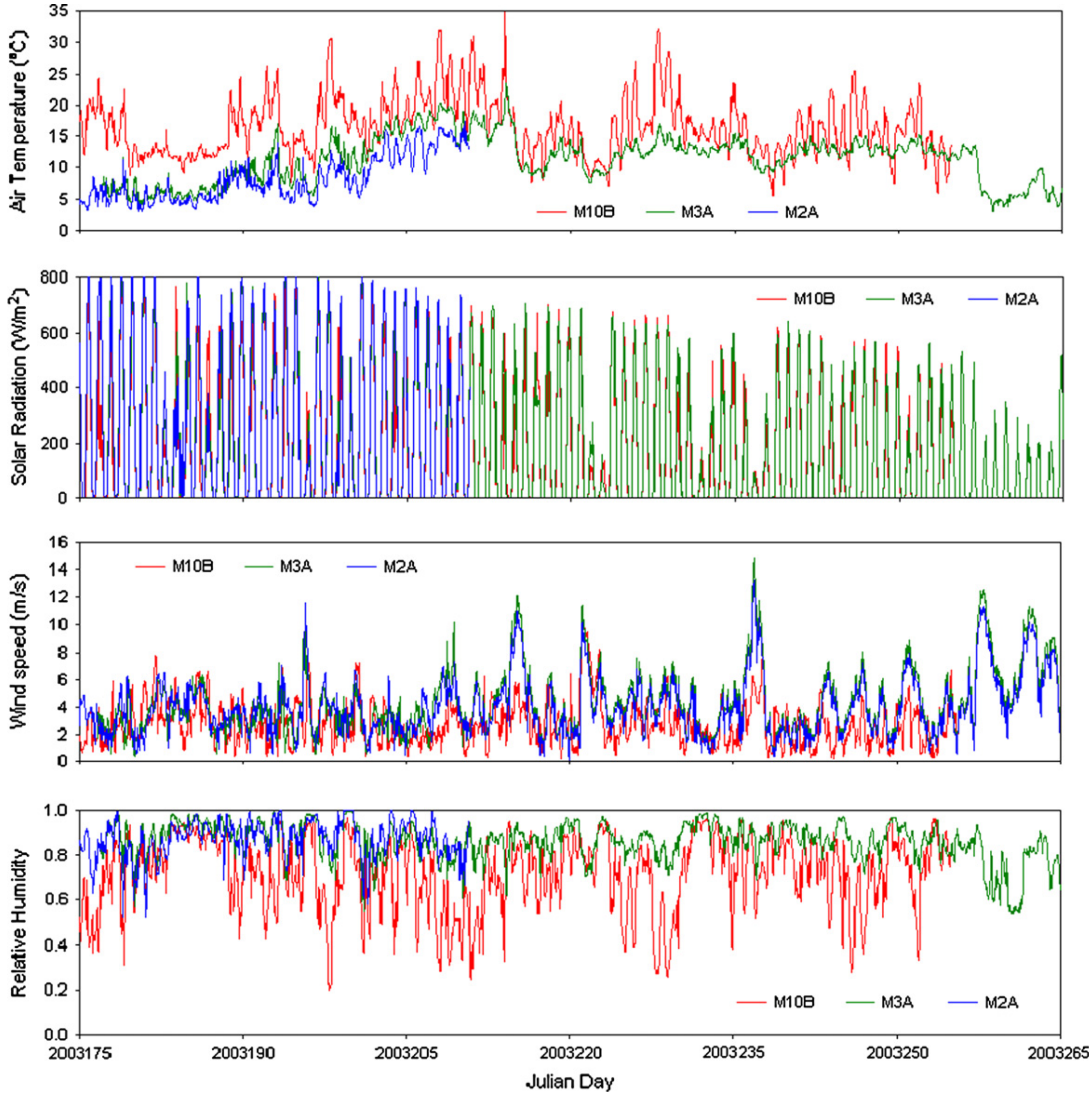

Fig. 2. Time series of meteorological data recorded at the Great Slave Lake buoys M10B, M3A and M2A (sites 1, 3 and 4) in 2003.

assumption for pressure. Heat exchange at the water surface is governed by the classical concepts of heat transfer and is separated into non-penetrative components of long-wave radiation, sensible heat transfer, and evaporative heat loss, complemented by penetrative short-wave radiation. Non-penetrative effects are introduced as sources of temperature in the surface-mixed layer, whereas penetrative effects are introduced as source terms in one or more grid layers on the basis of an exponential decay and an extinction coefficient.

ELCOM computes a model time step in a staged approach consisting of introduction of surface heating/cooling in the surface layer. The solution grid uses rectangular Cartesian cells with fixed Δx and Δy (horizontal) grid spacing, whereas the vertical Δz spacing may vary as a function of the depth but is horizontally uniform. The solution is based in the Arakawa C-grid stencil where velocities are defined on cell faces with the free-surface height and scalar values on cell centers. The free-surface height in each column of grid cells moves vertically through grid layers as required by the free-surface evolution equation. Prior set up and validation of the model in the Laurentian Great Lakes, particularly in Lake Erie, provides enough confidence in the results of the 3D model (León et al., in press).

4. Field program

Great Slave Lake is located in the Mackenzie River Basin within Canada's northern climatic system. There is great interest in understanding the base climate condition and potential climate changes in this region as evidenced by current research conducted through the Global Energy and Water Cycle Experiment on the Mackenzie Basin (GEWEX-MAGS) as part of the World Lake Climate Program. Some of the largest changes in air temperatures anywhere in the world have been recorded in the Mackenzie Basin (Stewart et al., 1998). Fig. 1

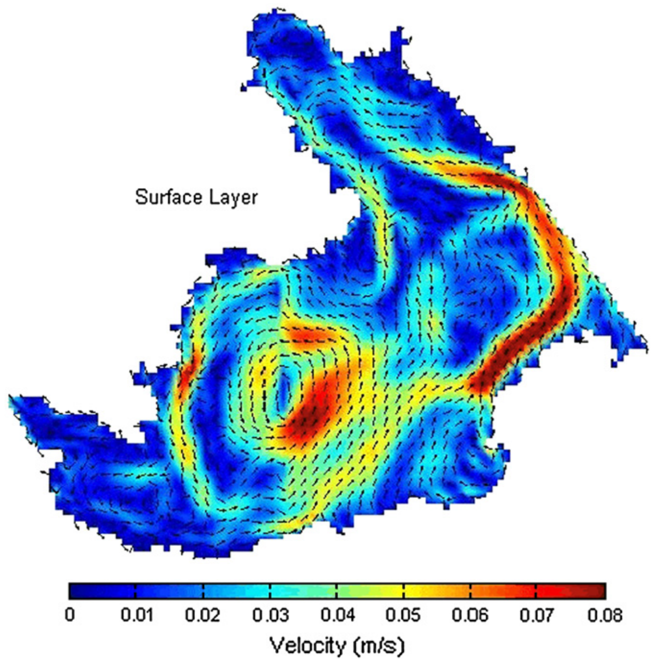

Fig. 3. Surface mean circulation pattern for 2003 in Great Slave Lake showing counter clockwise circulation and the presence of large gyres.

shows the bathymetry of the central basin of Great Slave Lake and the location of measurements conducted during this study. This lake is the 4th largest freshwater lake in Canada and the 12th largest lake of the world. The eastern arm, not shown, has a maximum depth of 700 m. The central basin has a surface area of 18,500 km^2, maximum depth of 187.7 m and volume of 596 km^3 (Schertzer et al., 2000).

Hydrodynamic simulations on lakes require detailed physical and meteorological input data. Differences in meteorological conditions have a critical influence on the magnitude and seasonality of lake response components. Vertical thermistor chain measurements are commonly used to validate the output from the model. With respect to the physical data, the depth values for a 2 km grid were extracted by superimposing the mesh on the polyconic projection of the Great Slave Lake (Schertzer, 2000). The model was setup with this matrix array that describes the bathymetry with 30 vertical layers.

Observations, supporting this investigation, included meteorology, radiation and currents from the summer field program July to mid-September, 2003 along a cross-lake transect (Fig. 1) (Schertzer et al., 2000, 2003). Meteorological observations (wind speed and direction, air temperatures, incident solar radiation, relative humidity) were obtained from both land and meteorological buoy deployments along the cross-section (sites labeled as *Mnn* in Fig. 1). Vertical temperature structure was observed from five thermistor chain moorings (sites labeled as *Tii* in Fig. 1). Current observations were also conducted at two sites (OD and NW2) adjacent to the meteorological buoys. Time series of the principal meteorological variables measured in the lake are shown in Fig. 2 for air temperature, solar radiation, wind forcing and relative humidity.

5. Model validation

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 surface currents for Great Slave Lake formed a relatively large counter-clockwise gyre, similar to the one reported for Lake Superior (Lam and Halfon, 1978), as can be observed in Fig. 3. Such dominant circulations patterns play an important role in the horizontal transport of heat in the lake and can create relatively large spatial gradients in surface temperature.

Fig. 4 shows a simulation of the surface temperature for Great Slave Lake at four time slices: (a) 10 July, 2003, (b) 20 July, 2003, (c) 20 Aug., 2003, and (d) 20 Sept. 2003 (based on León et al., 2005). These results illustrate the significant horizontal variations in surface temperature over the warming period. For example, for case (c) in Fig. 4, the surface temperature on the southern shore is about 16 to 18 °C, but is about 10 to 12 °C on the northern shore, with the coldest temperatures in the middle of the lake at about 6 to 8 °C. This spatial temperature distribution is also consistent with that reported for large lakes in northern regimes such as Lake Superior (Lam and Halfon, 1978). The spatial differences in temperature are significant and can result in large differences across the lake in terms of the air–water heat and mass exchange in weather and climate models. Spatial distributions of temperature, evaporation and heat fluxes can be computed directly at the specified grid location for the weather/climate model by aggregating the results from the finer grid system of the lake model.

Fig. 5 shows measured and computed time series comparison for the top layer temperature at sites 1, 4 and 5 (shallow west, deep central and average north). The results show that the simulated results conform with the observed in terms of the spatial gradient from nearshore (site 1) to offshore (site 4). Table 1 presents, for all the stations, a comparison of the average percentage differences between modeled and measured top layer temperatures over the stratified period (14 July to 22 September, 2003). These and the results discussed earlier indicated the consistency in the computed and observed temperature, which is crucial to the development of a fully coupled climate-lake model for Great Slave Lake.

6. Sensitivity analysis

Uncertainty analysis is a non-trivial issue with linked atmospheric-lake models. There are uncertainties associated with hydro-meteorological processes (Avissar and Pan, 2000) and with in-lake processes (Beletsky and O'Connor, 1997). Recently more advanced methods for uncertainty analysis for large-scale integrated models are proposed (Babendreier and Castleton, 2005; Merritt et al., 2005; Pastres and Ciavatta, 2005). While such methods will be required when the regional climate model is actually coupled with the lake hydrodynamics model, we present results

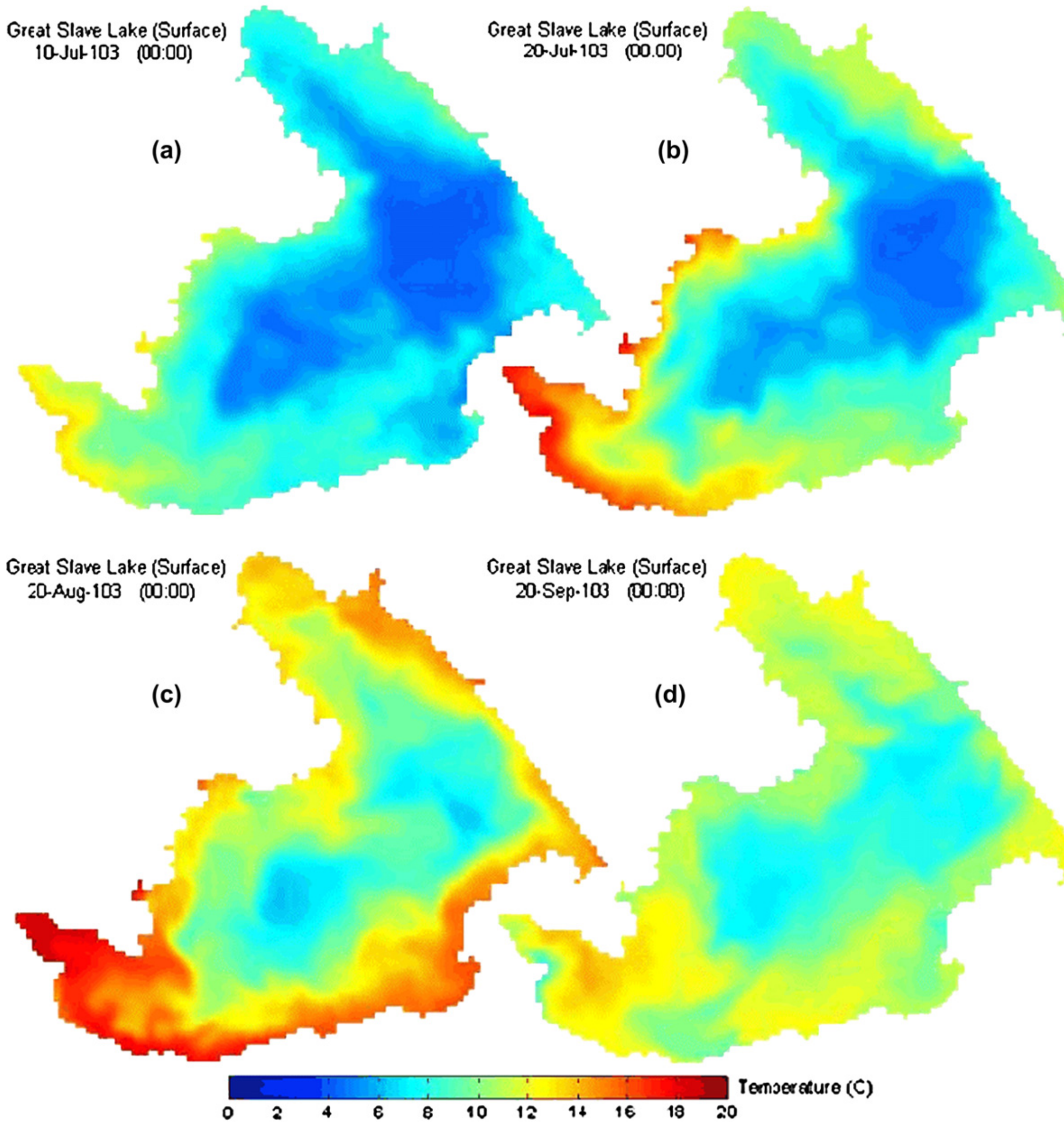

Fig. 4. Simulated surface temperature in Great Slave Lake at four time slices: (a) 10 July 2003, (b) 20 July 2003, (c) 20 Aug. 2003, and (d) 20 Sept. 2003.

from a linear uncertainty analysis for the present preliminary modeling study.

A principal objective of our long-range research plan is to develop a coupled lake and atmosphere model for weather and climate predictions. Normally, a fully coupled model will not utilize observed over-lake data. However, at this stage of our model development, we need to conduct a series of sensitivity analyses, first using observed over-lake data and then CRCM output as input to the hydrodynamic model. The purpose of this series of sensitivity analyses is to provide important information of the relative importance of different input variables on the simulated temperature and heat fluxes. The model validation result presented above is encouraging and forms the basis for the following sensitivity analyses.

6.1. Sensitivity of model simulations forced with field observations

Great Slave Lake 2003 meteorological time-series used in the model validation are incorporated in this sensitivity analysis. ELCOM is run successively by changing the primary meteorological input variables (e.g. air temperature, solar radiation and wind speed etc.) by ±10% and recording the effect on simulated temperature and heat fluxes. Fig. 6 illustrates the sensitivity of surface water temperature and evaporative heat flux to such a change in model input. For example, a 10% increase in air temperature and solar radiation input has the potential to produce a 3.08% and 8.27% increase in the water surface temperature respectively, and a 8.5% decrease in the evaporative heat flux. These results demonstrate

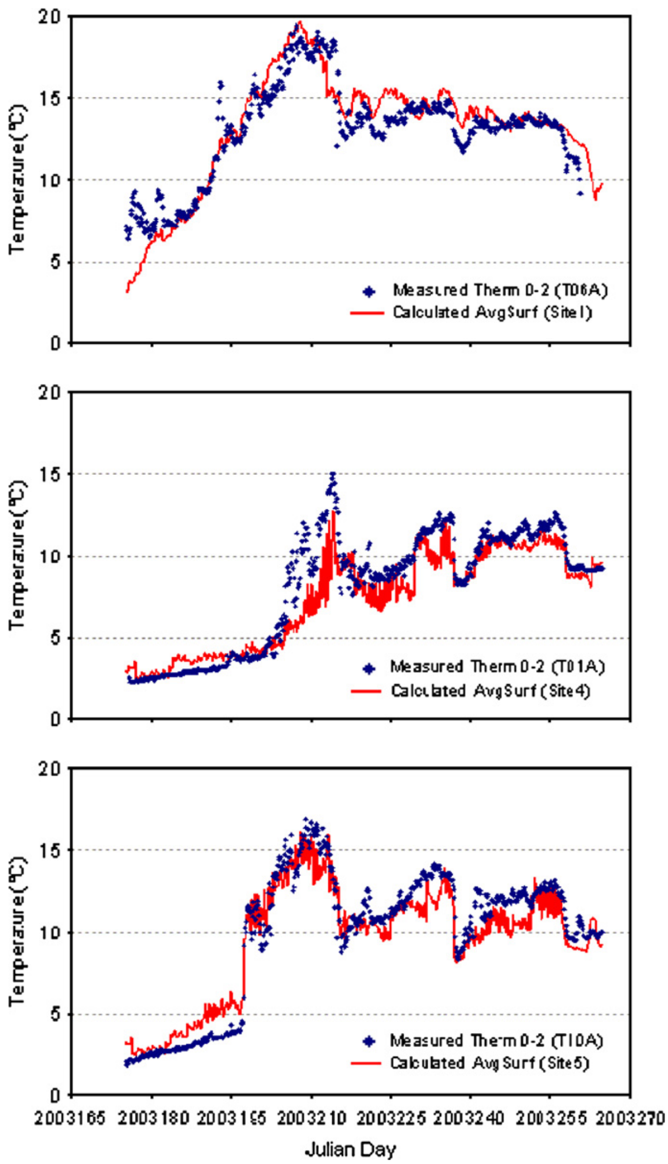

Fig. 5. Comparison between computed average surface temperatures (average at 2 m) with measured temperatures (0–2 m depth). Measured temperatures are at thermistor sites (T06a, T01a and T10a).

that accuracy in the model simulation is dependent on representative over-lake data. Large deviations in the input data series, especially for critical inputs can have a measurable and detrimental impact on the model simulations.

Table 1
Differences between modeled and measured top layer temperatures over the stratified period (14 July–22 September, 2003)

Site # (label)	Thermistor chain #	Meteorological buoy #	Max. depth chain (m)	Temperature average difference (%)
1 (HR)	T06a	M10b	12	+2.70
2 (OD)	T05a	M99a	56	+4.32
3 (NW1)	T04a	M03a	56	−3.72
4 (NW2)	T01a	M02a	100	−2.23
5 (NA)	T10a	M98a	60	−1.78

6.2. Comparison of CRCM output time-series with observations: effect of surface temperature using sensitivity analysis

In this study, we want to compare the sensitivity on model results between using observed data as input against using the CRCM results as input. The former case (using observed data as input) has been discussed above (Fig. 6) and the latter case (using CRCM results as input) requires a one-way coupled lake-atmosphere model (i.e., the lake model will be forced with CRCM output at each time step). The current version of the CRCM provides output for a grid resolution of 25 km; however, the CRCM does not have a lake component and therefore the resulting outputs do not have the benefit of moderation of the surface temperature or fluxes that occur based on the presence of the lake. The sensitivity of the ELCOM model output using the current CRCM data input is therefore a measure of the impact on the hydrodynamic solution with CRCM input without the presence of a lake. We have selected the CRCM output at a single cell at the coordinates of the center of Great Slave Lake to be used as input to ELCOM.

The meteorological output time series from the CRCM reflect conditions based on assumptions on other landscapes and can have seasonal differences compared to the conditions observed at the surface buoys on the lake. Fig. 7 shows a preliminary comparison between the CRCM and the over-lake time-series for air temperature, solar radiation and wind speed. The average differences over the time-series are +25% for air temperature, +10% for solar radiation and +12% for wind speed (Fig. 7). Based on the linear sensitivity shown in Fig. 6 it is possible to estimate the potential impact on hydrodynamic simulations using such inputs. For example, a significantly increased air temperature can result in increasing surface water temperature by +7.7%. Similarly the surface temperature can be expected to change by +8.2% and −1.8%, respectively, using the CRCM time-series (without the inclusion of lakes).

6.3. Impact of CRCM inputs on model simulations

The above analyses pertain to the sensitivity of individual components on simulated output of surface temperature and heat fluxes and are instructive since it establishes the impact of the critical input variables. However, knowledge of the combined effects of such impacts is also crucial to understanding whether use of CRCM input to the lake model has a significant effect on the simulation accuracy. For example, whether effects of the individual perturbations can be combined as a linear sum is of particular interest.

If the linear sum model is correct, then we expect that the combined effects of air temperature, solar radiation and wind speed from the CRCM (without the inclusion of lakes) will produce an increase of the simulated surface water temperature on the order $(7.7\% + 8.2\% - 1.8\%) = +14.1\%$. Fig. 8 shows a preliminary evaluation of the combined effects of CRCM inputs to the hydrodynamic model for surface temperature. In this example, a CRCM input, which does not include

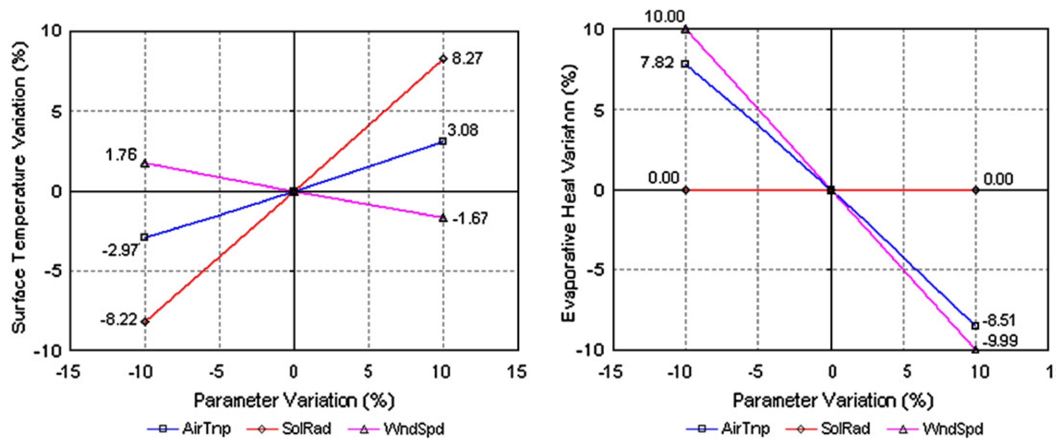

Fig. 6. Sensitivity analysis (output variation) for surface temperature (left) and evaporative heat flux (right) due to change in the main meteorological forcing data.

the effect of lakes, can result in a +15.5% increase in the simulated water surface temperature, very similar to the expected impact based on linear sensitivity analysis. Such error will have a significant impact on simulation of the required fluxes to feedback to the CRCM at each time-step.

Accuracy in the modeled surface temperature is important especially for deriving the surface heat fluxes required for the CRCM 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. A comparison between observed and modeled vertical temperature structure in Great Slave Lake using lake meteorological observations is shown in Fig. 9 for Site 4. Fig. 9a shows the observed isotherms at Site 4. Fig. 9b shows the difference between simulated vertical temperature (not shown) using observed input and observed temperature in Fig. 9a; Fig. 9c shows a similar difference map but using the CRCM output as input.

It should be noted that the observed results refer to measurements obtained along the vertical line at one site whereas the computed results are for the vertical column within

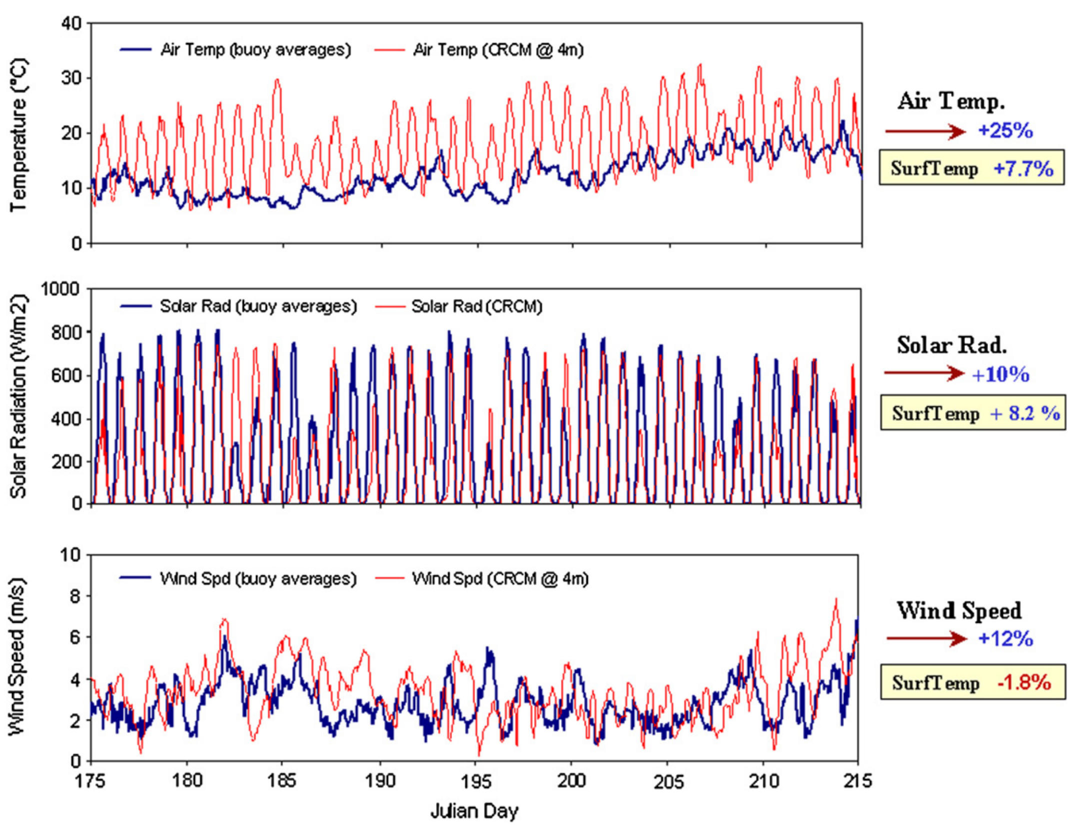

Fig. 7. Time series for meteorological forcing data (CRCM results and buoy measurements) with expected variation percentage in the water surface temperature output from ELCOM based on the linear sensitivity analysis (i.e. if air temperature difference is 25%, then a water surface temperature increase of 7.7% is expected in the model output).

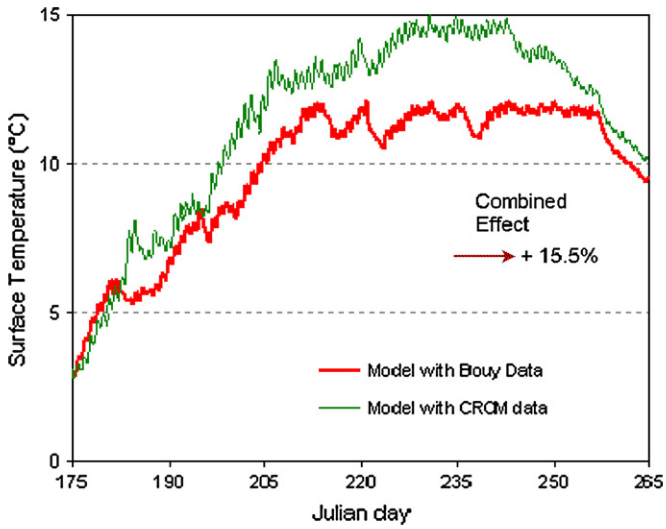

Fig. 8. Comparison of modeled surface temperature using CRCM input (without the effects of lakes) in ELCOM and measured buoy values. The combined effect of differences in individual CRCM input variables on simulated surface temperature is +15% over the time-series.

a 2 km × 2 km grid cell. Therefore, the differences shown in Fig. 9b and c serve only for the purpose of a relative comparison. It shows that simulated temperatures using buoy data as input are consistently under-predicted in the upper layer (0 to 25 m depth) whereas the simulated temperature using CRCM results (without lake effects) as input produces relatively higher errors and are also under-predicted except in early July and early September in the same layer. For the lower layer (25 to 100 m depth), the simulated temperatures using CRCM as input produce also relatively higher errors.

7. Discussion and conclusions

We have successfully applied a 3D hydrodynamic model to Great Slave Lake. The ELCOM model has been used as representative of a class of 3D models, which has capability of simulating surface fluxes, thermal structure and hydrodynamic components in large deep lakes. Great Slave Lake has been chosen as a test lake largely based on the relatively high quality of its meteorological and lake temperature observations along the major axis of the lake. The lake is of particular importance since it is located within the northern climatic system in the Mackenzie Basin of Canada, an area currently experiencing some of the largest warming anywhere in the world. This research presents initial results of ongoing research to develop a coupled lake-atmosphere model for weather and climate applications.

Model validation was conducted focusing on accuracy in 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. 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 near-shore zone in the temperature response.

In particular, the shallow south shore becomes significantly warmer than the rest of the central basin. Comparison of the simulated and observed top layer temperatures shows average seasonal temperature in the stratified period with differences on the order of +0.7 °C for the shallower western part of the basin and differences of the order −1.1 °C in the deeper mid-lake. Some of the inaccuracy in the model simulations is attributed to ignoring the major hydrological inflow from the Slave River or outflow through the Mackenzie River due to unavailability of flow or temperature data. Flows are on the order of 5000+ m^3/s. In addition, we have assumed a no-flux condition at the boundary between the central basin and the eastern arm of the lake. However, these discrepancies are relatively small and the hydrodynamic model is deemed to be sufficiently accurate for the sensitivity analysis of the model results obtained with CRCM input.

A sensitivity analysis was conducted to provide information on the expected impact of key meteorological inputs on the simulation of surface temperature and heat fluxes. A linear effect is assumed (Fig. 6), which indicated that significant impacts in the model simulations could be expected depending on the quality of the input data. For example, air temperature and solar radiation are amongst the most critical inputs to the 3D hydrodynamic model. Changes on the order of 10% can result in ~8.5% increases in simulated surface temperature and evaporative heat flux which is significant.

Since the development of a coupled lake-atmosphere model is a long-term research objective, we have extended the sensitivity analysis to provide information on the potential simulation error when the 3D model will be required to use CRCM output as forcing data instead of over-lake observations. Error in using the current CRCM output (without a lake component) led to ~15.5% error in the 3D model simulation of surface temperature and increased error in the vertical temperature structure compared to observations. This error analysis on the combined effects of using CRCM forcing data is consistent with the linear sensitivity analysis results of the individual components based on observations, i.e. the combined effect can be approximated linearly by the accumulation of the individual effects. This finding is significant in that a first order sensitivity analysis of the different meteorological factors affecting the heat fluxes at the air–water interface can be obtained with the linear sensitivity analysis approach presented. Also, comparing the simulated water temperatures for the vertical column at a selected site obtained with the CRCM forcing input and the buoy data forcing input, we concluded that simulated water temperatures using the current version of CRCM results as input (i.e. without lake effects) may lead to inaccuracy in water quality simulation and inconsistency problems both at the air–water boundary and in the water column.

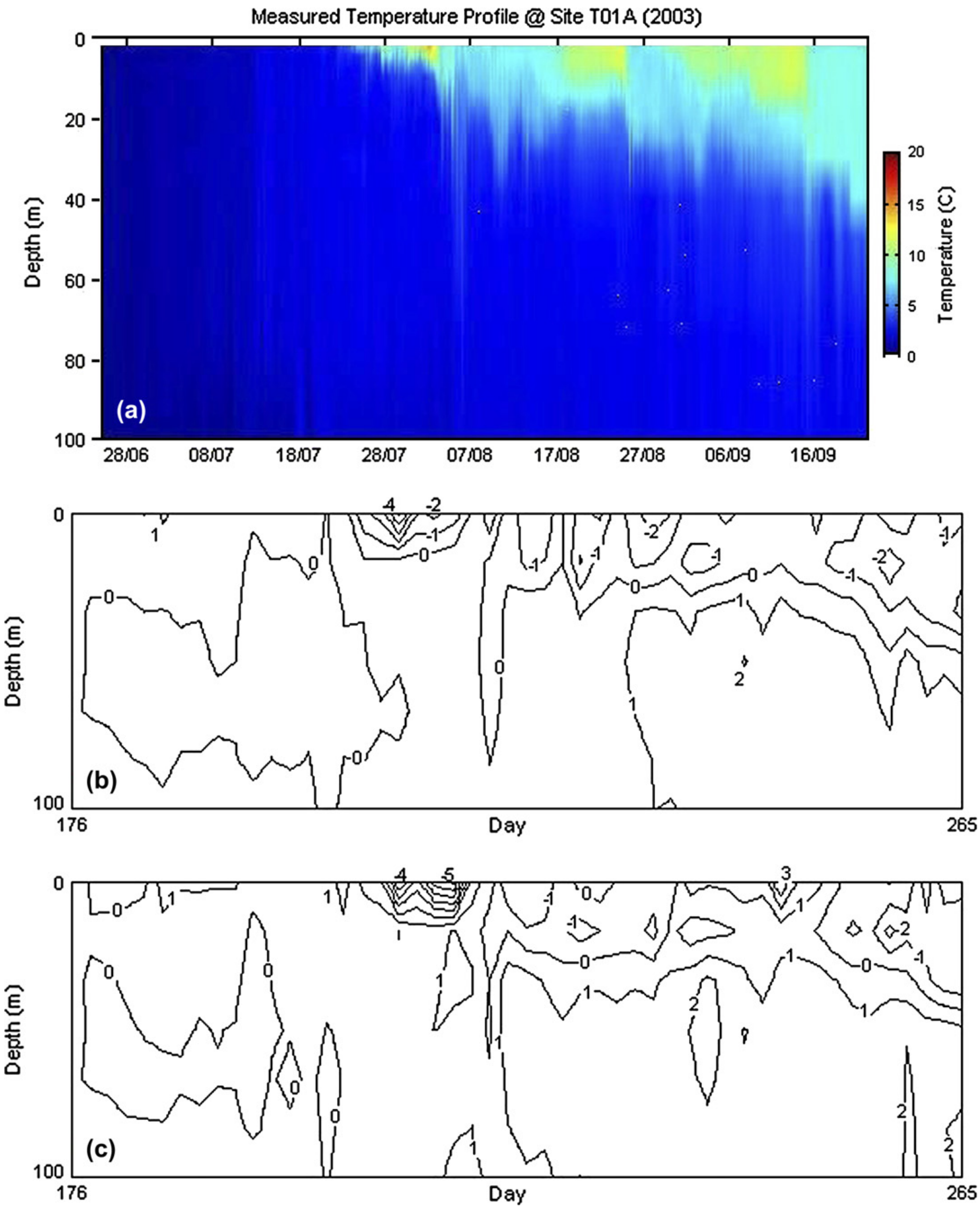

Fig. 9. (a) observed vertical temperature isotherms over time at Site 4. (b) Difference between ELCOM simulated vertical temperature (not shown) using field data input and measured temperatures shown in (a). (c) Same as (b) but using the CRCM output as input to ELCOM.

From these analyses, it is clear that a coupled lake-atmosphere model is required within the regional climate model to account for the effects of lakes, which are known to have large seasonal lags in temperature and fluxes compared to other landscape types. As indicated, our long-term objective is to develop a coupled lake-atmosphere model that can be integrated within the CRCM framework. This research clearly indicates that large errors, especially in lake-rich areas, can be expected without inclusion of a lake component in the regional climate model. Next steps in this research will include testing of the ELCOM and other 3D models such as the Princeton Ocean Model (POM: Great Lakes version) on a range of large deep lakes in Canada.

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