Assessment of the interaction between the Canadian Regional Climate Model and lake thermal–hydrodynamic models

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Abstract

This paper describes our preliminary assessment of the system requirements (data, interface and process) for implementation of terms describing lake effects in the Canadian Regional Climate Model. We demonstrate test results for one-dimensional (1-D) and three-dimensional (3-D) models for lake hydrodynamics that have been tested and prepared for interfacing with atmospheric circulation models. We discuss the use of a physical interface model, Canadian Land Surface Scheme (CLASS), that is under consideration for the air–water interface. Our preliminary assessment indicates that it is technically feasible to apply the combination of small shallow lake (slab) model, 1-dimensional vertical model and 3-dimensional circulation model (for very large lakes), together with the current land–air linkage used in regional climate modelling in Canada. Whether we can discern the necessary conditions for invoking each of the models to the lakes present in individual regional climate grid cells is still to be determined.

Keywords: Climate change modelling; Regional climate models; Lake–air interaction; Sensitivity analysis; Lake impacts; Computer modelling

1. Introduction

Inclusion of a fully interactive coupling of a lake model with an atmospheric model for regional climate modelling is an important objective of current Canadian Regional Climate Model (CRCM) development. Lake surfaces have very different interactions with the atmosphere, as compared to land surfaces, particularly moisture evaporation, wind forcing and energy exchanges. These air–water interactions, however, are complex and continue to be a critical issue considering the millions of lakes in Canada that are neglected in the current climatic models. Only recently has the CRCM implemented a simple box lake model (Goyette et al., 2000) as an initial attempt to simulate the evolution of the water temperature and ice cover on the Laurentian Great Lakes. We recognize that this effort is a pioneering work, but point out that the box model accounts for surface energy exchanges only, and for simplicity, the seasonal variation of the mixed layer is not modelled explicitly. Our paper describes our approach for the next step in the derivation of a hierarchy of fully interactive lake models for the CRCM. We emphasize not only the air–water energy exchange, but also wherever applicable, the hydrodynamic current friction,

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the in-lake vertical temperature structure and seasonal processes.

Our principal objective is to provide a hierarchy of lake thermal models for inclusion within the CRCM, depending on lake size and available information. A number of temperature models have already been developed for lakes with small (e.g., <2 km²) and large (e.g., >100 km²) areas and for various depths (1 or 2 m to over 400 m). We are in the process of screening several candidates of models from which a generalized lake model for each lake size class can be derived. Model verification will be accomplished using a cross-section of small and large lakes over different climatic regimes of Canada and available observed data. The benefits of this research are twofold: providing more accurate feed-back from lakes to the climate models; and, assessing high priority climatic impacts on ecosystem components of lakes. This paper describes the technical challenges, the modelling approach required and the possible computational informatics solutions. It also documents the logical path forward and shares ideas on how to meet complex technical challenges surrounding the coupling of atmospheric models and lake models. Some preliminary results will be used to illustrate the individual models.

2. General descriptions of the models

2.1. Considering lakes in climate models

Currently lakes are not included in General Circulation Models. Only recently have there been initial steps at including lakes in regional-scale models. In Canada, there are more than a million lakes ranging from 1000 to 82,100 km². It is recognized that the heat and mass exchange of lakes have a profound effect on the local and regional climate. This occurs not only for large lakes but also for regions with an aggregate number of small to medium size lakes. Consequently, the inclusion of lakes within climate models is an important step in the improvement of forecasts from climate models.

2.2. Canadian Regional Climate Model (CRCM)

The influence of large inland water bodies in climate predictions has not received much attention in Global Circulation Models (GCMs), largely due to the coarse grid resolution. The finer grid-mesh of regional climate models (RCMs) (e.g. 15 × 15 km–25 × 25 km grid resolutions) have made it technically possible to incorporate directly the effects of large lakes. Regional climate models are valuable tools for examining climate processes at very high resolution over limited areas. They represent, in some sense, a compromise between GCMs, which run experiments on climate time-scales (years-centuries) but at coarse resolution, and Numerical Weather Prediction models which can run at much higher resolution (even globally) but for much shorter periods of time (days–weeks). RCMs are suitable for high-resolution simulations on climate time-scales, but are limited to domains less than global in extent.

The CRCM has been developed jointly by the Université du Québec à Montréal and the Meteorological Service of Canada (Caya and Laprise, 1999). It represents a marriage between the dynamical kernel of the fully compressible, and very efficient, semi-implicit, semi-Lagrangian model of Tanguay et al. (1990), and the complete physical parameterization package of the Canadian Centre for Climate Modelling and Analysis (CCCma) Atmospheric General Circulation Model (AGCM). The physics packages from the CCCma have been coupled to the CRCM (MacKay et al., 2003). Due to the fact that it is a limited area model, lateral boundary conditions must be specified — either from a GCM (e.g. Laprise et al., 1998) or operational analysis (e.g. MacKay et al., 2003).

2.3. Thermal models applied to lakes

There are many well-calibrated thermal models and extensive databases to support research on development of coupled lake/CRCM modelling mainly concentrating on simulating the vertical temperature structure. In general the models are lake-specific, little testing has been done to assess the applicability over lakes of different morphometry and different climatic regions. There are models that assume uniform properties over the whole lake, i.e. the box models (Goyette et al., 2000). There are models that assume horizontal uniformity but allow for vertical details, i.e. one-dimension (1-D) models using various vertical turbulence formulations such as eddy diffusion integrated mixed layer models (McCormick and Lam, 1999). There are also models that simulate the full three-dimensional (3-D) details of the hydrodynamic circulation and thermal regimes. A recent survey of these models has been conducted by Lam and Schertzer (1999) for the Great Lakes.

3. Technical challenges

Our main study goal is to connect the regional climate model (top row of Fig. 2) with the lake models shown in different versions: simple box model, 1-D and 3-D models (bottom row of the figure). Much of the complexity of our modelling process involves the transfer of momentum. The mass and heat fluxes at the interface
between these two modelling regimes are complex and this complexity presents several technical challenges. The three major ones are the time step, the spatial regionalization problems, and the computational aspects. In this section, we discuss these three technical difficulties. In Section 4, we discuss possible solutions to these difficulties and propose a new model coupling approach.

3.1. Time step and model coupling issues

Model coupling between the CRCM and the lake model implies bi-directional flow of information. For example, the air temperature predicted by the CRCM is used as input to the lake model which predicts the surface water temperature that may alter the air–water energy transfer (e.g. evaporation) which in turn changes the air temperature in the CRCM. Also, the wind predicted by CRCM provides input for forcing the hydrodynamic current in the lake model which in turn changes the air–water friction and hence the wind. This circular dependence may require frequent consistency checks, feedback loops and iterative procedures. The time step for the CRCM is normally about 15 min, whereas the time steps used in lake models vary from minutes to hours, or even days. The synchronization of time steps, therefore, adds to the complexity of the model coupling.

3.2. Spatial scale and the regionalization problem

There are problems with spatial scales in the model coupling as well. The CRCM generally uses grid sizes of $15 \times 15$ to $25 \times 25$ km. For large lakes such as the Laurentian Great Lakes, this means that a lake can be covered by up to 50 CRCM grid cells and may require the use of lake models with fine model resolution and spatial details. On the other hand for small lakes, there may be many lakes within just one CRCM grid cell. For large lakes, there is a potential need for three-dimensional models. When coupled with CRCM, a 3-D model would simulate not only the vertical exchange across the air–water interface but also the horizontal transfer of...
energy and momentum in lake water that may subsequently affect the grid-to-grid distribution of heat and momentum fluxes in the CRCM. For small lakes, the question becomes one of aggregating results from several lakes in one CRCM grid — a regionalization problem.

3.3. Computational aspects

Suppose the above two problems are solved. We still need an efficient computational method to ensure that the CRCM and the hierarchy of lake models can run in cooperation with each other. The problem is how to design and implement a software system that can select the appropriate lake model, given the lake size and available data, to produce a consistent set of air–water energy fluxes and frictional forces; synchronize the model time steps with the CRCM; and, aggregate or distribute spatial results for use by the CRCM depending on the relative size of the lake within or covering the CRCM grid. Model coupling must consider also the problem of determining optimal time and spatial steps and computational methods.

4. Modelling approach

To overcome these technical challenges we have assembled a team of experts in regional climate modelling and lake thermal and hydrodynamic modelling. Due to the separate disciplinary approaches, the climate modellers and the lake modellers have each developed models quite independent of each other. The team agrees to save development time and cost by making use of existing models, or models that are under on-going development in each group, and couple them as effectively and accurately as possible. That is, we do not think it is effective to develop a new model that solves simultaneously both the governing equations for the climate model as well as the lake model. Neither do we think it is effective to use a 3-D lake hydrodynamic model for all small and large lakes, nor it is accurate to use a simple box model for all of them, particularly the large lakes. The logical approach is to use simple box models (e.g. Goyette et al., 2000) that consist of an upper layer and a lower layer for cases such as small lakes, since the processes follow simplified assumptions better. For large lakes, we need the 3-D models to accommodate successfully the vertical and horizontal distributions of heat and momentum in the lake. For lakes of intermediate size or deeper depths (>10 m), we may choose a 1-D model that has a finer resolution over the depth. Note that the 2-D models are not effective for our study because, while they may give an acceptable solution horizontally, they lack the vertical resolution required for simulating the thermal structures and fluxes correctly.
Specifically, we propose to use the following modeling approach. First, we separate the small lake models from the large lake models. For the large lake models, we may use a 3-D model and connect it directly, through a regionalization interface, to the regional climate model (Fig. 2). Since these components use similar time step sizes, there is no problem with consistency of time-scales. For the spatial scale, it is possible that one CRCM grid cell may contain several lake model grid cells because the spatial resolution of the lake model is usually finer. Thus, a regionalization interface with an appropriate spatial aggregate scheme is required to average the lake model results for each CRCM grid cell.

At the air–water interface, we need to ensure consistent momentum, mass and heat flux transfer. For momentum transfer, we consider the consistency in the “bottom” frictional force in the CRCM and the wind forcing term acting on the lake surface in the lake model. For mass transfer, we consider the consistency in moisture evaporation and condensation in both models.

We also consider net solar, longwave, sensible and latent heat transfers. These fluxes can be iterated either at each time step (which is costly) or updated at regular time intervals (which may be optimized).

The small lakes are connected to the CRCM via the CLASS submodel that has implemented successively the momentum, moisture and transfers for the air–land surface. We can use existing modules in the CLASS model package to facilitate flux transfers across the air–water interface for lakes. Since one CRCM grid cell may contain both land and lake areas, so will one CLASS grid cell (that is, the CRCM and CLASS grid cells are the same). For each one such grid cell, there are possibly several lakes. We, therefore, require a regionalization procedure to aggregate lake model results before passing them on to the CLASS interface (Fig. 2). If some of these lakes are deep (e.g. lake depth \( > 10 \) m), we may need to use a 1-D lake model (Fig. 2). For the regionalization procedure, there are at least two ways to aggregate the results: (a) aggregate the model coefficients and input (lake area, volume, heat, etc.) by averaging them and then running the lake model with the averaged coefficients and inputs; or, (b) run the model with each lake with individual input and then average the results (Fig. 3). At this stage of development, the choice of regionalization methods may affect the results in coupling the lake model with the CRCM and require further research.

Since the time step of the box and 1-D models is generally larger than the time step of the CRCM and since the flux transfer from the lake via the CLASS model interface is basically a vertical process (i.e. neighbouring grid cells in both CLASS and lake models do not have a horizontal transfer component), the implementation of the lake models using the CLASS model interface can be performed with parallel computational algorithms, with the potential for implementation on parallel hardware, for better efficiency. The consistency of the flux transfer can be checked regularly according to the time step of the lake model because it is larger than that of the CRCM.

5. An example of model coupling mechanisms: energy flux considerations

The consistency of momentum, mass and heat transfer between the lake model and the atmospheric model is an important aspect in this study. As an example, we consider the energy fluxes between the lake surface and the atmosphere and examine some of the details involved in the design and implementation of model coupling mechanisms.

5.1. Components of lake energy flux

Fig. 4 provides a general schematic of the major processes included within a lake thermal model. The source terms for a thermal model derive from the surface heat budget components. The net radiative fluxes include incoming solar radiation (\( K_{\text{down}} \)), reflected solar radiation (\( K_{\text{up}} \)), incoming longwave radiation (\( L_{\text{down}} \)), and emitted longwave radiation (\( L_{\text{up}} \)). Turbulent exchanges are represented by the latent heat flux (\( Q_E \)) and sensible heat (\( Q_H \)) fluxes. Advection heat fluxes are associated with hydrological flows such as inflow (\( Q_I \)), outflow (\( Q_O \)), and others. During winter, ice formation and ice melt are sources of heat gain and loss. A portion of the surface energy passes through the air–water interface. Generally longwave fluxes are attenuated within the first few centimetres. Solar radiation can penetrate for several metres, however, depending on the mean vertical attenuation coefficient (\( \alpha_V \)). Heat fluxes and winds are
inputs to lake thermal models and they represent the linkage between the lake and the overlying atmosphere.

5.2. Energy flux considerations: using the CLASS model interface

To implement these heat fluxes used in lake thermal models as part of the transfer mechanism between the atmospheric and the lake models, we need an appropriate regionalization procedure as described in Fig. 2. For large lakes, the task is straightforward since the energy fluxes can be directly coupled to the regional climate model with a simple averaging scheme to aggregate and transfer the lake model results to the atmospheric model, together with a spatial interpolation scheme to downscale the atmospheric model results to the lake model. For small lakes the mechanisms require a more elaborate regionalization scheme (Fig. 5) and a connection through the CLASS model interface (Fig. 2), since there will invariably be land surfaces sharing the same CRCM grid along with the lakes.

Thus, the regionalization scheme for small lakes for the CLASS model interface (Fig. 5) will produce, for each CRCM grid cell, the information on the fraction of lake area (FK) as well as the net solar, net longwave, sensible and latent heat aggregated from all the lakes within this CRCM grid cell. The lake flux terms will then be combined with the land fluxes already implemented in the CLASS model, and prorated accordingly with the land information on fractions of bare ground cover (FG), land vegetation cover (FC), snow cover (FSNO) and vegetation cover with snow (FCS). These total contributions of energy fluxes from both land and lake will be made available for the atmospheric model. In return, a distribution, or downscale scheme, may be required to transfer similar information back from the atmospheric model to the lake model for model input and consistency check.

6. Modelling of lake temperature: initial approaches and results based on observed inputs

As indicated above, the goal of this investigation is to develop a coupled lake—atmosphere model scheme for input to CLASS and the CRCM. Since lake surface temperature is not known a priori, lake temperatures must be simulated in order to compute the surface heat, mass and momentum flux exchange between the lake and the atmosphere. As shown in Fig. 2, the modelling scheme is complex since lakes vary in spatial dimension. A hierarchy of lake models is required. The philosophy adopted here is to investigate the applicability of various levels of model complexity to describe the essential elements of the lake physics for small, medium and large lakes. The methodology adopted for model development and verification is to simulate the lake temperature and fluxes based on: (1) observations as data input, (2) one-way coupling to the atmosphere and (3) fully coupled mode. The results shown here relate to the initial mode of testing and verification of the various lake models using observations.

6.1. Box-model approach

We hypothesize that for small, shallow lakes a box model approach may be sufficient to derive the heat exchange between the lake and the atmosphere. The box
model approach can apply both to very small and to small—medium sized lakes.

In very shallow lakes wind speeds completely mix the water column and the lake is considered to be isothermal. Consequently the seasonal temperature changes with depth will be related to the surface temperature. In such lakes surface temperature values can be derived from AVHRR satellite, or longer-term mean temperature curves may be derived for application to such lakes. With assumed bathymetry the isothermal temperature profile based on surface temperatures can be used to generate a lake heat storage and the total surface heat flux can be computed as the change in heat storage at each time step.

In shallow-medium sized lakes wind is not sufficient to result in complete mixing and summer thermal stratification occurs. In this case a mixed layer model that accounts for only thermodynamic processes can be adopted. Goyette et al. (2000) describe an approach that consists of computing the temperature evolution of the upper mixed layer. The seasonal variation of the mixed layer depth is not modelled explicitly, rather it is represented as a slab of water of depth \( H \). The heat budget equation that governs the evolution of the slab of water is,

\[
\rho_w C_w H \frac{dT_w}{dt} = F_a + (F_h + F_b)
\]

where \( T_w \) is the temperature of the water slab, \( \rho_w \) is the density of water, and \( C_w \) is the specific heat of water. The net heat flux, \( F_a \) enters the layer from the top, \( F_h \) is the net energy entering from the sides, and \( F_b \) from the bottom of the mixed layer (Fig. 2). The net heat flux penetrating the water surface, \( F_a \), is computed based on surface net radiation and turbulent heat fluxes (e.g. Schertzer, 1987).

Research is being conducted on a range of small to medium sized lakes in Canada to quantify the magnitude and variability of the radiative and turbulent heat exchange with the atmosphere and the thermal response characteristics (e.g. Rouse et al., 2000, 2003; Oswald, 2002). Progress is being made on the development of the box model approach on a range of small lakes in the Mackenzie Basin (Binyamin et al., 2002). Since Canada has an abundance of small to medium sized lakes, understanding the contribution of these lake scales is critical for development of a coupled lake—atmosphere model. Initial research has included method developments for determining lake size distribution over regions. Remote sensing techniques (i.e. satellite observations) are required to determine lake areal extent over the large number of lakes in Canada. Research is being conducted to develop and verify solar and longwave models and evaporation computations especially in Canada’s northern climatic regions. Initial box model simulations have been conducted to compute heat storage for a column of water in selected lakes based on observed water temperature profiles.

### 6.2. 1-D thermal model approach

For large deep lakes, such as the Laurentian Great Lakes, the lake temperature structure is often simulated through application of 1-D temperature models. The 1-D temperature model results are representative of the “lake-averaged” or “basin-averaged” vertical temperature profile at each time step. Eddy diffusion type models have been applied in the Great Lakes for both temperature prediction and for applications in water quality models (e.g. Lam et al., 1987). Fig. 6 shows an example of the simulation of the vertical temperature structure for the central basin of Lake in 1983 summer using the model of Lam and Schertzer (1987).

The simulation is initialized with a known vertical temperature profile and the simulation commences over the portion of the year representing the thermally stratified season. The excellent agreement between simulations and observations provides confidence in this type of model for basin or lake-averaged temperature predictions. Surface and bottom temperatures at the mid-survey times are indicated in Fig. 6. Accurate simulation of the surface temperature is critical for computation of the radiative, turbulent and momentum exchanges between the lake and the atmosphere.

![Fig. 6. Simulation of the 1-D temperature structure of the central basin of Lake Erie using the Lam and Schertzer (1987) model (based on Schertzer and Sawchuk, 1990). Lighter curves represent the daily-simulated temperature profile. Dots represent the observed temperature based on lake surveys. The dark curve represents the simulation at the mid-point of the lake survey. The horizontal bar above indicates the month (June, July, etc.). The endpoint temperatures in °C are labelled for each major curve (measured results superposed) and the temperature profiles are plotted successively in linear proportion.](image-url)
(e.g. Schertzer, 1997). Inclusion of a physically based ice model (i.e. Patterson and Hamblin, 1988) allows this scale of model to be applied over an annual cycle. For example, Boyce et al. (1993) have simulated the annual temperature cycle for Lake Ontario using the 1-D model DYRESM (Imberger and Patterson, 1981) under current climate and changed conditions.

6.3. 3-D hydrodynamic model approach

The CLASS model has a spatial resolution similar to the CRCM although it can be modified for coarser or finer resolution. As indicated above, matching such scales for a large lake is possible through use of a 3-D hydrodynamic model. The 3-D hydrodynamic model is forced with surface meteorology and is used to simulate the lake circulation and temperature field. There are several hydrodynamic models that have been developed and applied to large deep lakes such as the Laurentian Great Lakes. For example, Simons (1976) developed and applied a numerical model of Lake Erie to compute water transports on the basis of continuous wind observations from shore-based meteorological stations. A vertically integrated model was used for quasi-homogeneous conditions and a two-layer model was employed to simulate summer stratification. Fig. 7 shows an example of the computed Lake Erie water circulation for selected periods in the upper layer (epilimnion) and the lower layer (hypolimnion). The model results show the feasibility of using the 3-D hydrodynamic model in quasi-operational applications for simulating the lake circulation and temperature between grid elements.

The 3-D model approach is complex and data intensive. An advantage of the approach is that simulation of lake surface temperatures is performed at grid scales commensurate with that of the CLASS scheme. Fig. 8 shows an example of the lake-wide surface temperature of Lake Erie for May 16, 1983 from satellite image. The image shows the complexity of simulating Lake Erie. Because of its 3 basin structure (depths: west basin 10 m, central basin 25 m, east basin 64 m), the modelling approach adopted must be capable of simulating the wide variability in the lake dynamics. Again accuracy of the temperature simulations is critical for computation of the radiative, turbulent and momentum flux exchange between the lake and the atmosphere. Research is on-going to test a hierarchy of modelling approaches for development of a coupled lake—atmosphere model.

7. Conclusion

Development of a coupled lake—atmosphere model is very important for regions with a large number of lakes, such as Canada, and has implications for increasing the accuracy of climate forecasting. Our research is in the initial stages, but we have made critical advances in understanding the problem complexities and development of solutions. Since there exists a Canadian Regional Climate Model (CRCM) that has been linked to land surfaces through the Canadian Land Surface Scheme (CLASS), our research focuses on development of the coupled lake—atmosphere model(s) within this
scheme. Our initial research has successfully identified a hierarchy of lake models that can be applied in the box, 1-D and 3-D modes. The next stage of the lake modelling research is to extend the models that have been currently verified with existing meteorological forcing data, to be run in modes both linked and then coupled to the atmospheric models. This introduces a number of modelling complexities such as parallel processing and linking of spatial and temporal scales in the lake and atmospheric physics. From a software design point of view, we have concluded that in order to couple the wide range of lake scales to the regional climate model a reliable interface such as the CLASS model is required. This “adaptor” pattern of software design is necessary because we need to pass the essential information between models without disturbing existing codes. In this paper, we have identified some of the major technical challenges for this study and have proposed new modelling approaches to meet these challenges. The next steps will be to continue the lake model development and cross-evaluation with existing and new data, as well as to develop the modelling and regionalization interfaces to ensure that the lake models can be coupled effectively and accurately to the regional climate model.

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