Off-line lake water and ice simulations: a step towards the interactive lake coupling with the Canadian Regional Climate Model

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Outline

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Lakes in Canada

9% of Canada’s surface is covered by lakes.

- Total: 2 millions lakes of all kinds and sizes.

Lakes influence the regional climate in many ways: thermal moderation, enhanced evaporation, etc.

- Large lakes: strong influence on the regional climate (lake-effect snow, the Great Lakes)
- Even small lakes are important for regions, where they are abundant: “cumulative effect” (most part of Canada, especially the Canadian shield)

In Canada, lakes form an important element of the climate system and must be taken into account in local climate simulations.

Objectives of this work: to test different lake models and to find candidates for interactive coupling with the Canadian Regional Climate Model (CRCM)
Lakes are complex inhomogenous 3D systems. Radiative processes, horizontal and vertical mixing, density stratification, water evaporation/condensation, ice/snow formation and thawing…

For RCM coupling, no detailed reproduction of lake state is required (or even possible):
- Input fields from RCM are homogenous on RCM grid tiles (10-50 km)
- No detailed description of most lakes is available
- Coupled lake models will act as parts of surface schemas:
  Only surface conditions will be used by RCM, no need to reproduce in details the interior, if surface is OK.
But lake models for RCM should be able to reproduce correctly most important lake patterns, including mixing regime, surface temperature behavior, ice onset and duration…
Lakes: thermal structure

The lake thermal regime depends on
- Density stratification
- Annual cycle of insolation (latitude)
- Mixing (wind-driven, etc.)
- Salinity (relatively rare in Canada)

Typical mixing regimes for temperate-latitude lakes:

- Freezing dimictic lakes

- Non-freezing warm monomictic lakes


Source: Minnesota Sea Grant, University of Minnesota
Lake models: candidates for coupling

Which interactive lake models could be used with CRCM? In this work, only 1D lake models are considered. In such models:

- Horizontal fluxes in lakes are ignored, horizontal homogeneity assumed.
- Only vertical processes are simulated.
- Few input data are required.
- Most kinds of lakes can be simulated.
- Relatively simple and computationally cheap.

Two 1D lake models, having water and ice/snow modules, are presently available:

  
  Coupling with RCM: RegCM3, MM4
- FLake (Freshwater Lake model): D. Mironov et al., [http://lakemodel.net](http://lakemodel.net)
  
  Coupling with RCM: RCA3

Off-line tests of models: estimation and validation

- Small lakes: single column mode, where the whole lake is modeled as a water column of the constant depths.
- Large lakes: multiple points simulation, imitating the current 45-km CRCM grid.

Input data in off-line tests: observations or re-analysis.
The model of S.W. Hostetler

• Eddy diffusion model:

\[
\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[(k_m + K(z,t))\frac{\partial T}{\partial z}\right] + \frac{1}{c} \frac{\partial \phi}{\partial z}
\]

with the parameterized eddy diffusion constant \(K(z,t)\).

• No explicit assumptions about the temperature profile. It depends on the \(K(z,t)\) vertical profile.

• Bottom: zero heat flux. \(T_{\text{bottom}}\) is usually at the maximum density temperature (4 °C) in deep lakes.

The water temperature profile structure in summer (Hostetler's model)
The FLake model

- The shape of the water temperature profile is prescribed (empirically-based):
  - The water temperature is constant in the mixing layer
  - Between the mixing layer and bottom, the temperature profile is given by a polynomial function, depending on the parameter $C_T$.
    The mixing layer depth $h$ and $C_T$ define the profile shape.

- By construction, the thermocline extends from the mixing layer depth $h$ to the lake bottom (no hypolimnion).
  - This gives unrealistic temperature profiles in deep lakes.
    A “virtual bottom” at 60 meters is used, if the depth exceeds 60 m.

- Bottom: either zero heat flux or sediment layer

- Ice/snow model: the same approach as in other layers, but the profile is linear. No minimal ice thickness is prescribed. To account for the presence of snow, the ice albedo is modified.
Lake simulations: small lakes

Source of data: the LTER NTL project (Wisconsin, USA). 11 lakes are observed since 1980th

- Sparkling Lake: dimictic freezing lake
  Lat. 46.003, Ion. -89.612, area: 0.64 km².
  Mean depth: 10.9 m, max. depth: 20 m.
  Secchi depth: 7.5 m.
- Simulations:
  perpetual year 2005, timestep: 1 hour,
  no sediments (FLake), vertical resolution: 1 m (Hostetler),
  maximum lake depth.
- Observed parameters, used as lake model input:
  Air temperature, wind force, relative humidity (raft data)
  Longwave and shortwave radiation downward
  (measured at the nearby airport)
- Observed data, used for comparison with model output:
  water temperature profiles, ice thickness,
  latent and sensible heat fluxes (Sparkling Lake only).

Observation raft on the Sparkling Lake
Source:
North Temperate Lakes
Long Term Ecological Research
NSF/ Univ. of Wisconsin-Madison
Lake simulations: small lakes

Sparkling lake, 2005: annual evolution

- Surface temperature: good for both models
  - Hostetler’s model: rapid shifts of temperature in autumn and spring
- Mixing layer depth: higher in FLake in spring (full overturning)
- Ice thickness and duration: good for both models
Lake simulations: small lakes

Sparkling lake, 2005: water temperature profiles

- Summer: good results for both models.

- Under the ice cover:

  Hostetler’s model profile is different from observed and FLake’s. Why?
  - Hostetler’s model: no effective eddy mixing in winter stratification.
  - The winter profile is “frozen” at 4°C.
  - Only a thin surface layer has to be heated up in spring or cooled down in autumn.
  - Surface temperature changes in overturning periods are rapid

  FLake has to cool down or to heat up the whole water column, from the bottom to the surface (thermocline)
  Surface temperature changes are slow.

Observed profiles suggest that there is some mixing (current-driven?) even under the ice. FLake implicitly presumes it.
Lake simulations: Great Lakes

- Simulation period: 1971-2000, 10 years spin-up.
- Simulations timestep: 1 hour.
- FLake: « virtual bottom » at 60 m, if the depth exceeds 60 m.
- 144 points over the Great Lakes (horizontal resolution 45 km, corresponding to the current CRCM resolution)
- Input data:
  - ERA40 reanalysis (2.5°, interpolated)
- Validation data:
  - Buoy observation data
    (NOAA’s National Data Buoy Center)
  - NOAA Great Lakes Ice Atlas
  - G.J. Irbe 1992 Great Lakes surface water climatology, Environment Canada,
  - S. Goyette et al, 2000 (water surface climatology data)
Lake simulations: Great Lakes

Lake Superior, Buoy 45001, depth: 261.6 m and the nearest simulation point

- ERA40 interpolated air temperatures are different from locally observed: ERA40 mostly reflects the land observations, lake effects are hardly present.
- Surface temperature patterns, ice duration and thickness are not correctly reproduced by both lake models.
- Hostetler’s model predicts earlier and longer ice-cover period, lower mixing depth that FLake.
Lake simulations: Great Lakes

Lake Michigan, Buoy 45002, depth: 175.3 m and the nearest simulation point

- The Hostetler’s model produces much ice, even when there was no ice observed in this year.
- FLake predicts better the ice thickness, duration and presence/absence in different years, but it can hardly be considered a satisfactorily result.
- The Hostetler's mixing layer depth is consistently lower than simulated by FLake.
Lake simulations: Great Lakes

Lake Erie, 45005, depth: 12.6 m and the nearest simulation point

- The surface temperature in the shallow lake Erie is reproduced much better, than in deeper lakes.
- Simulated ice is much closer to observations, though again Hostetler gives more ice than FLake.
- Mixing layer depths, simulated by two models, are closer one to another.
Lake simulations: Great Lakes

Averaged annual water surface temperatures: comparison of simulations with observed climatology

- Shallow lakes are better reproduced than deep lakes.
- But even shallow lakes are not very good.

Possible reasons?
- Great Lakes are large and horizontally inhomogeneous lakes with strong currents, many other horizontal effects. 1D lake models are not able to take into account 3D patterns.
- ERA40 data, used in simulations, are rather land data for this region and do not reflect lake effects.
- Both tested 1D lake models are better fit for shallow lakes.

Hostetler’s model:
- No mixing in winter inversion and under the ice: can be valid only for very shallow, small and quiet lakes.

Even in the Sparkling lake, 0.5x1.5 km, some mixing is present under the ice.

FLake:
- The assumption of the thermocline, going up to the bottom, is not physically correct in deep lakes. A virtual bottom at 60 m is an arbitrary choice and does not solve the problem.
Lake simulations: Lake of Geneva

(In collaboration with the C3i team, University of Geneva)

- Depth: 309 m (maximal), size: 70x15 km
- Meromictic or monomictic mixing regime
- Non-freezing lake
- Simulated year 2004, starting in mid-December 2003

Both “our” lake models show their characteristic patterns:
- Hostelters’s model:
  - Shallow mixing layer
  - Thin thermocline
- FLake:
  - Better mixing layer depth and thermocline thickness
  - The virtual bottom at 60 meters
    constraints the profile evolution.
Conclusions

- Two 1D lake water/ice models were tested in different conditions: shallow subgrid lakes and the Great Lakes. Water and ice behavior was simulated and compared with observations.
- In the case of small shallow lakes, both models have successfully reproduced the annual water temperature evolution, latent and sensible heat fluxes, ice formation and break-up timing, and the ice thickness.
- In the case of Great Lakes, observed water temperature/ice cover is simulated reasonably well for lake Erie, unlike in the case of Superior/Michigan. In general, better results were obtained for Lake Erie, which is the shallowest of the five. This could be partially explained by the biases in the ERA40 reanalysis data (lakes treated as land points), and the lack of inclusion of complicated processes in the models, such as horizontal transfer of water and heat, water and wind ice drift, etc. The main reason, however, is that these models are by construction better fit to shallow lakes than to deep ones.
- Both lake models produce similar results for small shallow lakes. For Great Lakes the FLake model produces results that are closer to observations. Results suggest that both models can be used for simulating small shallow lakes and the FLake model appears to be a more reasonable choice in the case of deeper lakes.
- Other interesting 1D lake models exist and will be tested in similar conditions.

Current activity: Coupling the lake models with CRCM/CLASS

- Works have begun recently in collaboration with Michel Giguère and Richard Harvey (Ouranos). At first, resolved lakes will be coupled with CRCM4 / CLASS, then subgrid lakes are expected in CRCM5 / CLASS.
- The possibility to use different lake models is assumed. A kind of common interface?
Place and role of lake models in RCM

The role of lake model in the regional climate modeling is analogous to the role of surface schemes:

- The atmospheric module provides the surface conditions to the lake model: radiation fluxes, air temperature, wind force, humidity, precipitations.
- The lake model has to return the surface boundary conditions to the atmospheric module: lake surface temperature, latent and sensible heat fluxes, etc.

The lake model can be incorporated to the surface schema:

- For resolved lakes, providing the surface conditions on grid cells, covered by these lakes;
- For subgrid lakes: on corresponding mosaic elements.