Workshop on Parametrization of Lakes in Numerical Weather Prediction and Climate Modelling
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Coupling of the Canadian Regional Climate Model with lake models

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Outline

- Canadian Regional Climate Model (CRCM)
- Land surface modelling in CRCM: a short overview
- Lakes in Canada: abundance and diversity
- Lakes in CRCM: mixing layer model (S. Goyette)
- Lakes in CRCM: coupling with 1D lakes models
  - Lake models
  - Off-line lake model tests
  - Coupled CRCM-lakes simulations: first results
- Summary and future plans

Canadian Regional Climate Model

The Canadian Regional Climate Model (CRCM): http://www.cccma.ec.gc.ca/models/crcm.shtml

A good CRCM review: *Laprise R., “Regional Climate Modelling”, J. Comp. Phys., 227(2008) 3641-3666*

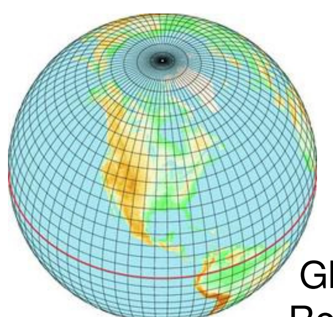
Current version: CRCM 4

- Dynamics: fully elastic non-hydrostatic formulation, semi-implicit semi-Lagrangian time scheme, based on the Mesoscale Compressible Community MC2 model
- Physical parameterisation : currently based on the GCMIII package of CCCMa with the surface schema CLASS 2.7.
- Horizontal resolution: 45 km, single-processor code

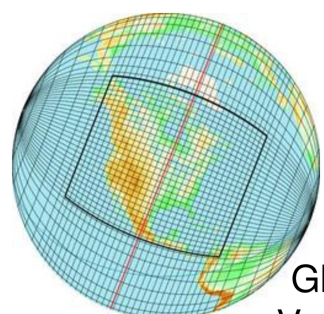
Towards CRCM 5: a high-resolution regional model

- Horizontal resolution: 10-20 km, fit for massively-parallelised computing
- Based on the existing dynamical core of the Global Environment Multi-scale (GEM) global model of RPN (Recherche en Prévision Numérique, Environment Canada) in the GEM-LAM configuration
- Physical parameterisation: RPN-GEM physical package with the surface schema ISBA (better suited for the NWP-use) and, alternatively, GCMIV with CLASS 3.3 for climate simulations.

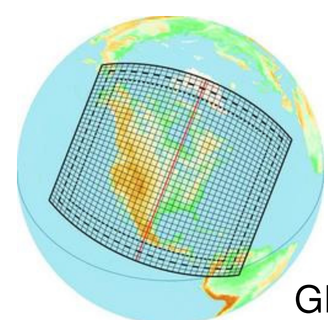
GEM configurations:



Global Regular



Global Variable



GEM - LAM

Land surface modelling in CRCM

Current surface scheme: CLASS 2.7
(Canadian LAnd Surface Scheme: *D. L. Verseghy, Atmosphere-Ocean, vol. 38, no. 1, pp. 1-13, 2000*)

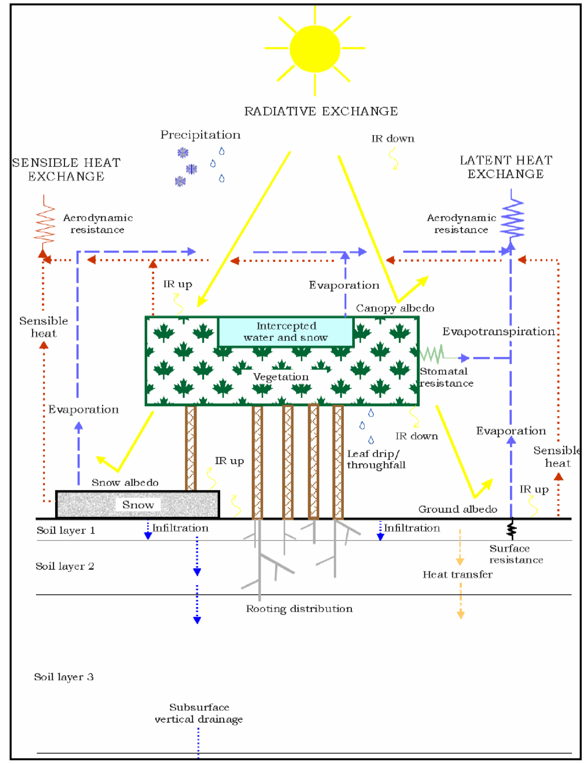
• Thermally separate vegetation canopy, snow cover and three soil layers (0.1, 0.25, 3.75m).

• Four main vegetation structural types (needleleaf trees, broadleaf trees, crops and grass)

• Up to four subareas allowed over each model grid cell: vegetation covered, bare soil, snow with vegetation and snow over bare soil

• One soil type for each grid cell

• A simple mixed layer lake model of the Great Lakes



CLASS2.7 structure (from Verseghy 2000)

CLASS 2.7 to CLASS 3.3:

• Optional mosaic formulation (subgrid lakes!)

• Ability to model organic soils

• Ability to model lateral movement of soil water

• Enhanced snow density and snow interception

• New canopy conductance formulation

• Option for multiple soil layers at depth

• User-defined soil and vegetation types

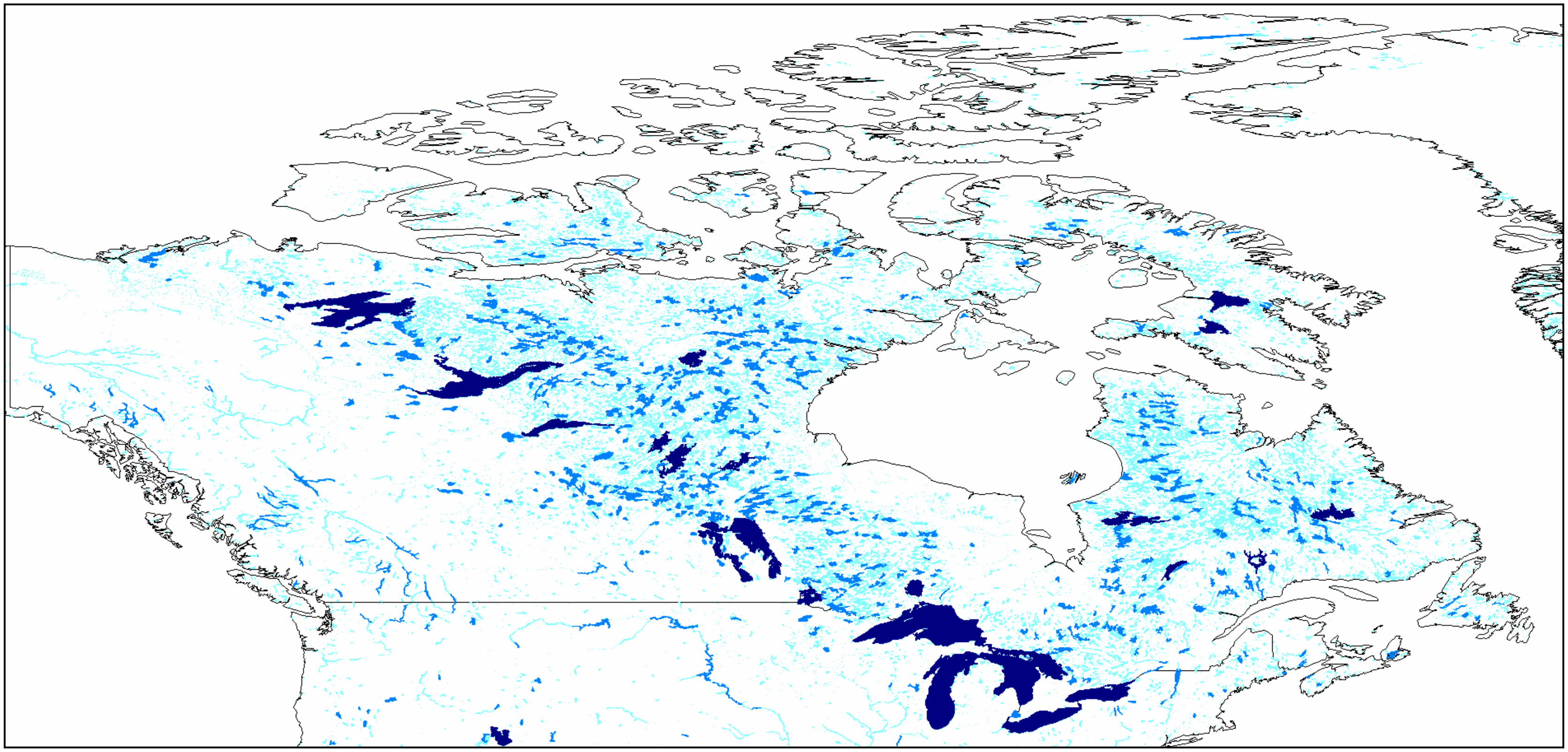
Other advanced land modelling elements in CRCM5:

• Dynamic vegetation: based on the Canadian Terrestrial Ecosystem Model (CTEM).

• Interactive permafrost: based on the Goodrich model

• Interactive lakes: coupling with 1D column lake models.

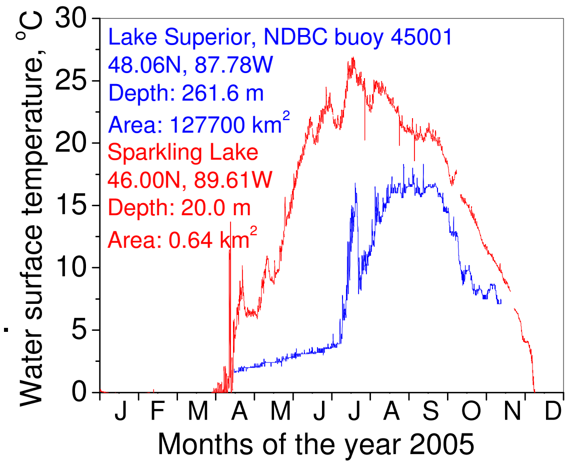
Lakes in Canada: abundance and diversity



Inland water bodies. Data sources: GLWD 1,2,3 databases, SWBD database (between 60°S and 60°N)

- 9% of Canada's territory is covered by lakes, especially abundant on the Canadian Shield. Their influence on the regional climate can be substantial in many areas.
- There are lakes of all kinds and sizes in Canada: from small tundra ponds to the Great Lakes.
  - Many large and deep lakes are resolved by CRCM (current resolution: 45 km, planned: 10 km)
  - Numerous small and shallow lakes remain unresolved at the CRCM resolution (subgrid lakes)
- Lake models have to deal with both resolved and subgrid lakes

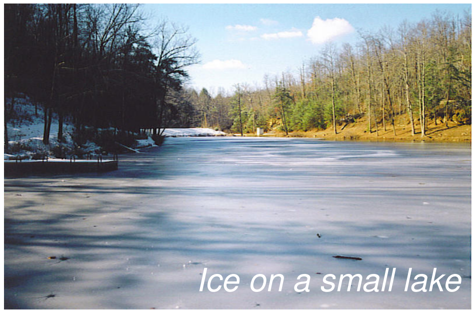
Lakes in Canada: abundance and diversity



Lakes of different kinds: large, medium, small - influence the climate and have to be taken into account by regional climate models.

Physical conditions and thermal regimes are different in lakes of different sizes and depths. Some examples:

- Water convection is often stronger in large, deep lakes because many physical mechanisms that cause water mixing, become important in these lakes. Under-ice convection can become important in such lakes.
- Deeper mixing layers in deep lakes than in shallow ones, leading to longer spring heating and lower maximum temperatures
- The sediment layer can be important in shallow lakes, but negligible in deep lakes
- The ice cover is less homogenous in large lakes, with ice breaking and drifting far from it's origin - influencing the surface albedo, evaporation, latent and sensible heat fluxes.


Ice on a small lake

It is known that lake models of different kinds (3D,1D,0D) suit better to large, medium and small lakes.

- Coupling different lake models in parallel with the regional climate models can be too complex and computationally expensive.
- For the sake of simplicity, it is preferable to use a single lake model for all kinds of lakes. It is important to determine, whether such compromise can be achieved.
- In CRCM, first lake model coupling was realized by S. Goyette: a mixed layer model, using heat flux residuals, is now part of the standard CRCM 4
- Coupling with 1D lake models is currently underway.


Ice on the Lake Erie

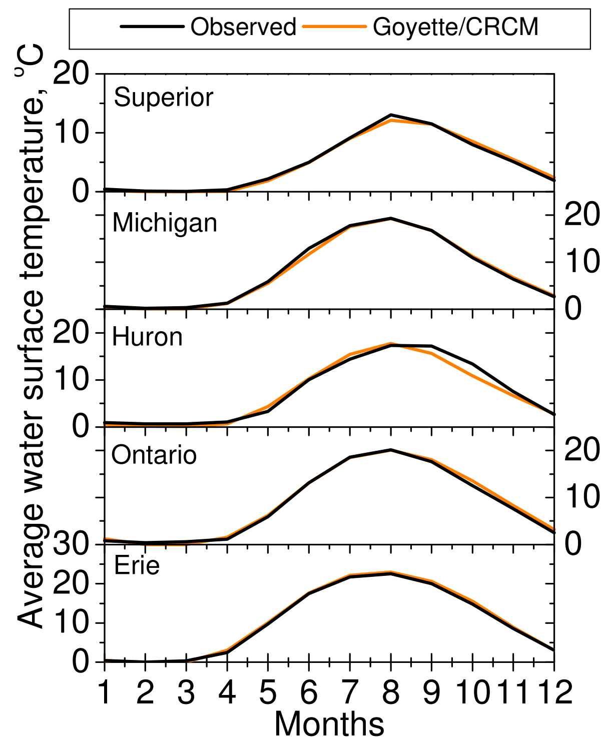
Lakes in CRCM: mixed layer model of the Great Lakes

*Goyette, S., N.A. McFarlane, and G. Flato, 2000: Application of the Canadian Regional Climate Model to the Laurentian Great Lakes Regions. Implementation of a Lake Model. Atmos. Oc., **38**, 481-503.*

- Lake water temperature: mixed-layer model
- Thermodynamic ice model with ice leads, simulating the ice redistribution in the Great Lakes
- Horizontal and vertical heat flux residuals, obtained from uncoupled simulations, are used to adjust the thermal balance in lake water and ice
- Air-lakes interaction: the same formulation as for the open ocean:

  - The neutral drag coefficient @ 10m height $C_D=1.3*10^{-3}$,
  close to experimental estimations over the Great Lakes
  (adjusted to the actual lowest model level)

  - The effects of atmospheric stability on surface drag
  are accounted for by a Richardson number dependence
  (*McFarlane, N.A et al, 1987: J. Clim., **5**(10), 1013-1044.*)



Main result: good reproduction of annual thermal cycle in Great Lakes

- Inconveniences:

  - An uncoupled simulation is required in order to produce residuals

  - Not applicable to subgrid lakes

Lakes in CRCM: 1D lake models

Two 1D lake models, having water and ice/snow modules, are currently considered for coupling with CRCM:

- The model of S.W. Hostetler: *Hostetler S.W., Bates G.T., Georgi F.,1993: J Geoph. Res., 98(D3), p 5045*

  Water: 1D heat diffusion equation is solved, eddy turbulence is parameterized by the enhanced thermal diffusion coefficient. Thermal convection is taken into account. Zero heat flux on the bottom.

  Ice/snow: modified Patterson-Hamblin thermal balance model. *Patterson, J. C., and P. F. Hamblin. 1988. Thermal simulation of lakes with winter ice cover. Limnol. Oceanogr. 33: 328-338.*

  Fractial ice coverage: separate temperature profiles for ice-free and ice-covered tile fractions, then horizontal mixing, weighted by the ice coverage fraction. Simple ice redistribution mechanism is provided; it can be easlily modified or replaced by another mechanism.

- FLake (Freshwater Lake model): D. Mironov et al., http://lakemodel.net

  Water: self-similarity based parametric approach. Two explicit layers: the mixed layer and the thermocline

  Ice/snow, active bottom sediment layer : similar parametric approach.

  Ice cover: no fractional coverage, the same ice thickness everywhere. The parametric concept of the FLake model makes it more difficult to implement fractional ice cover mechanisms.

Before coupling with the CRCM, both lake models were tested in different conditions, representing the variety of Canadian lakes. Two extreme cases: small, shallow and large, deep lakes were studied.

Offline tests: small lakes

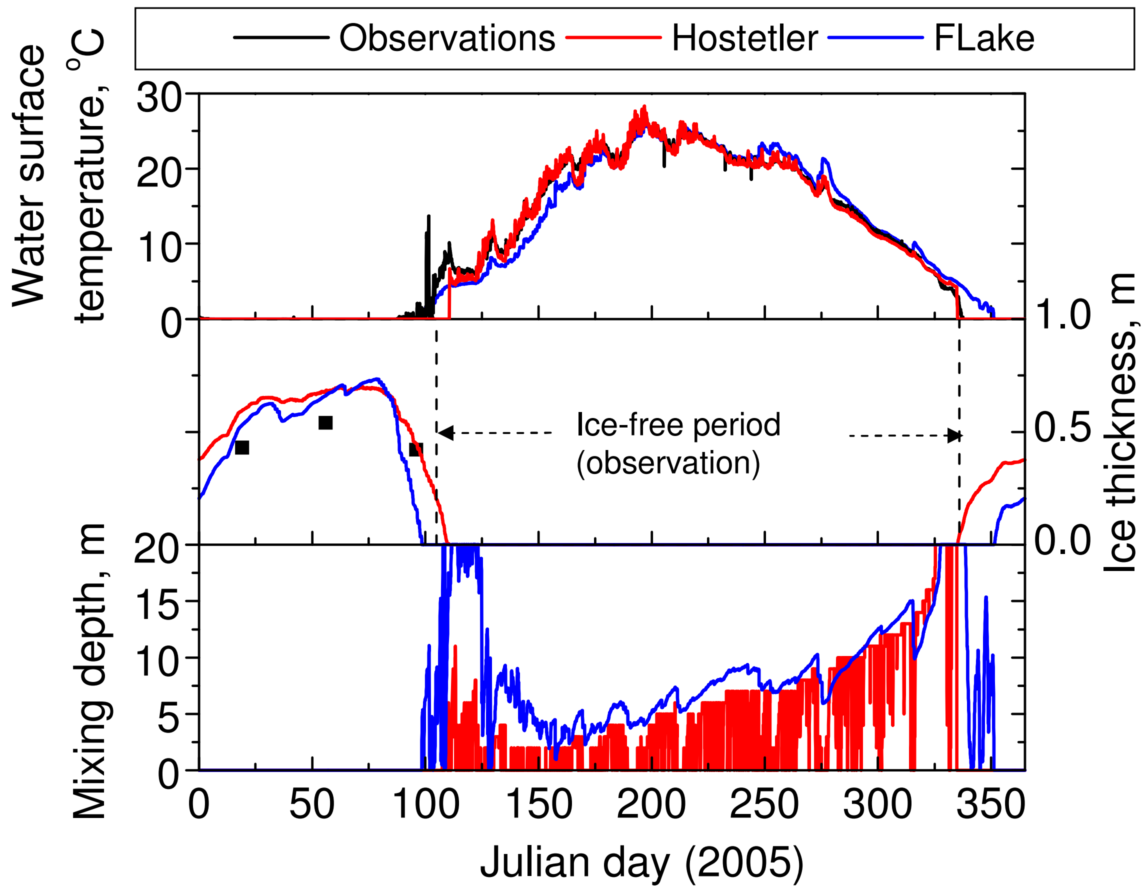
Sparkling Lake, Wisc., USA. Dimictic freezing lake, area: 0.64 km^2, max depth: 20 m, Sechhi depth: 7.5m

Data sources: the LTER NTL project buoy measurements and nearby airport's meteorological data

Simulation: perpetual year 2005, timestep: 1hour, no sediments (FLake), no snow

- Surface temperature: good for both models
  - Hostetler's model: rapid temperature changes in autumn and spring
- Mixing layer depth: higher in FLake in spring (full overturning)
- Ice thickness and duration: good for both models

Small, shallow lakes: good performance of both models



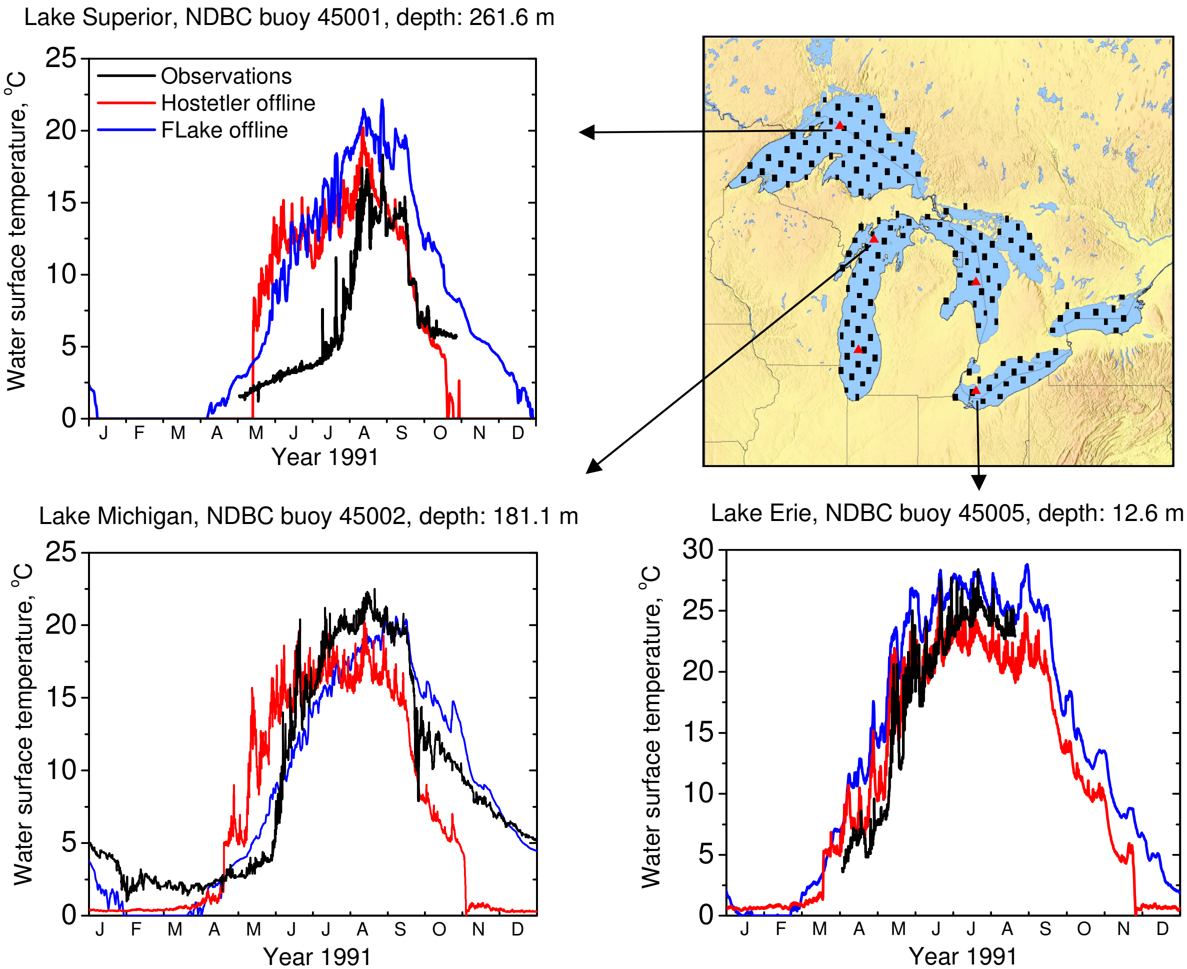
Offline tests: the Great Lakes

Simulation period: 1971-2000, 10 years spin-up. Timestep: 1hour. Horizontal resolution: 45 km

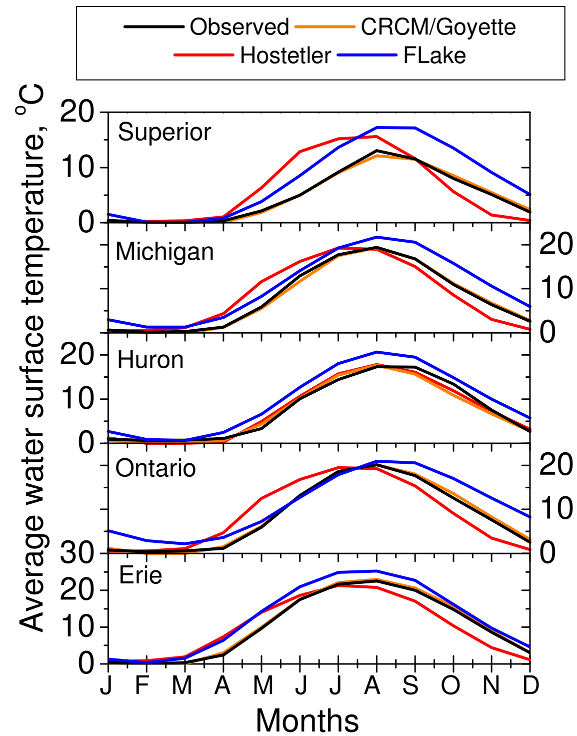
Input data: ERA40 reanalysis at 2.5º, interpolated to 144 points over the Great Lakes, simulating the CRCM grid

Validation data sources: NDBC buoy observations, NOAA Great Lakes Ice Atlas

Observed and simulated water surface temperatures



Water temperature climatology



Offline Great Lakes tests: both models have problems with deep lakes.

Coupling with lake models

This work is currently in the research phase: debugging and first runs are being carried out.

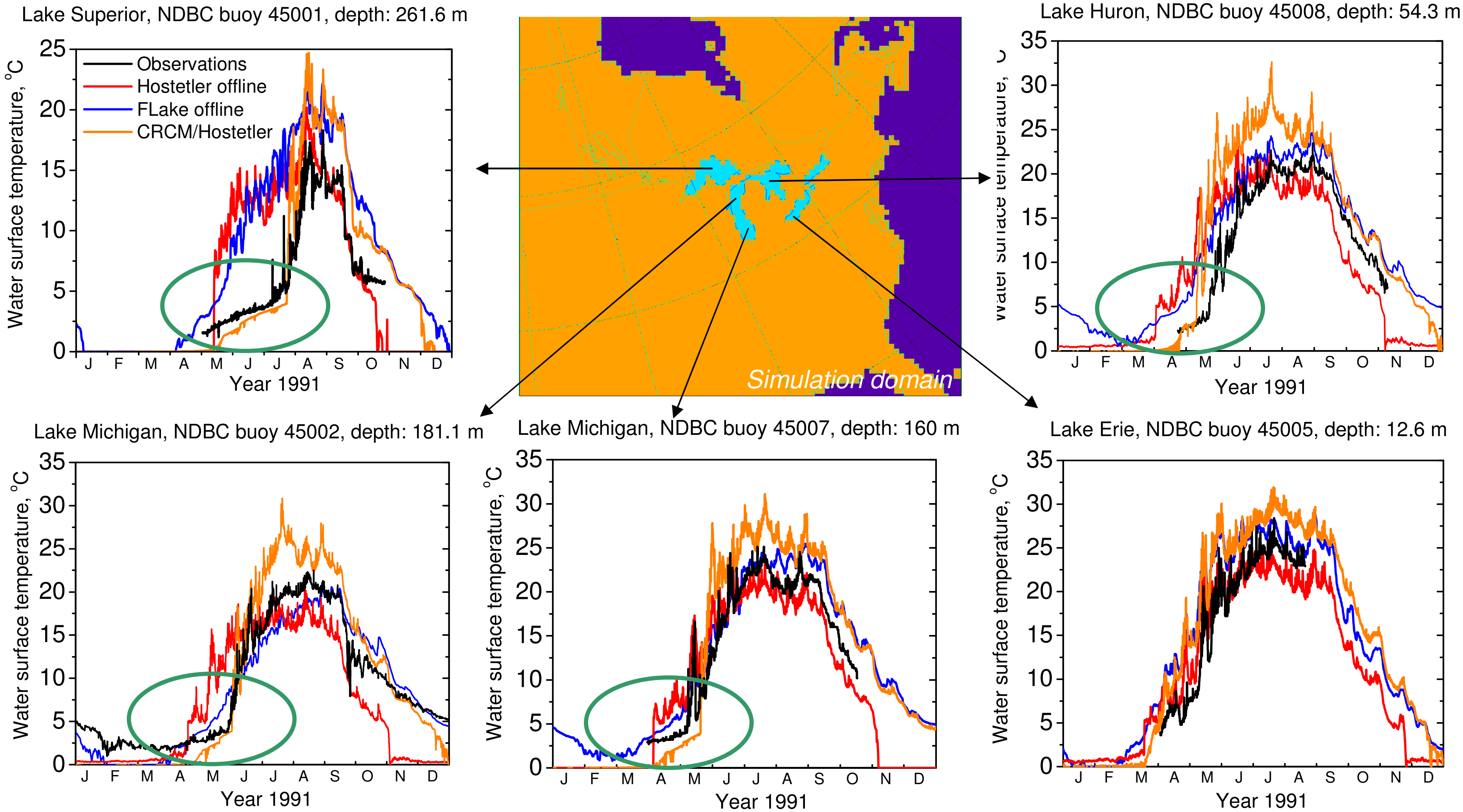
- A CLASS/lake models interface was added, forming input and output data for lake models.
- The switch LAKE in the CRCM input file "PARAMETRES" defines the lake model choice:

LAKE = {
- 0 no interactive lakes
- 1 S. Goyette's model (requires previously calculated residuals)
- 2 Hostetler's model
- 3 FLake model
- … New options can be added in future

- Only lakes, resolved at 45 km, can be dealt with under current CRCM/CLASS versions.
- Air-lake interactions, water/ice albedo: now as in S. Goyette model.
- No snow over ice (yet)
- Hostetler: real bathymetry, FLake: maximum depth: 60 meters.
- FLake: continuous ice cover, no ice redistribution within tiles
- Hostetler's model: continuous ice cover or ice redistribution, following *McFarlane, N.A. et al, 1992: The Canadian Climate Centre Second-Generation General Circulation Model and Its Equilibrium Climate. J. Climate,* ***5****, 1013-1044.*

Coupling with lake models

First coupled simulation: year 1991, LAKE=2 (Hostetler), driven at the boundaries by the NCEP/NCAR reanalysis
Grid: 80×90, horizontal resolution: 45 km. Lakes: only the Great Lakes (other lakes are masked out)



This coupled simulation reproduces much better the observed temperature patterns, than offline ones.
Long spring water warming from 0°C to 4°C in deep lakes is reproduced in coupled simulations. Why?
Too high water temperature in summertime: air/lake interactions need to be adjusted.

Coupling with lake models

The initial water temperature profile (the 1st of January 1991) in the presented coupled simulation was linear, with 0°C at the surface and +4°C at the bottom. This is not an equilibrium profile for the Hostetler's model. In wintertime and in presence of ice, the Hostetler's model would produce an almost neutral equilibrium profile at +4°C, with a thin cold layer close to the surface.

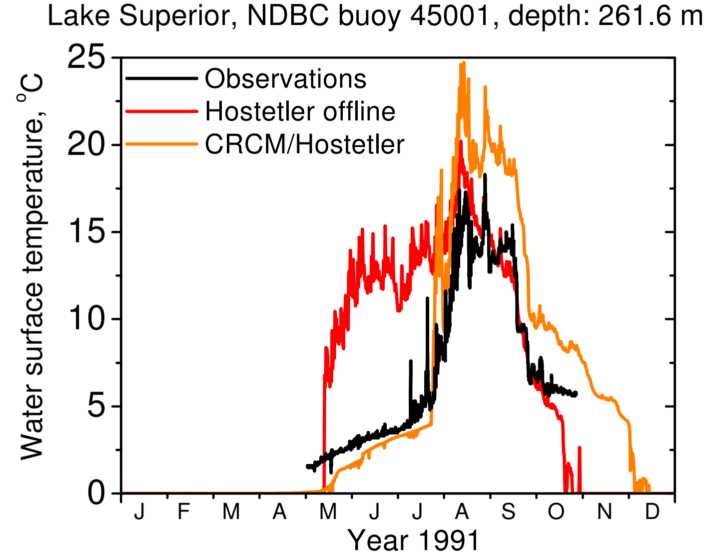
The spring water warming is very different in these two cases.

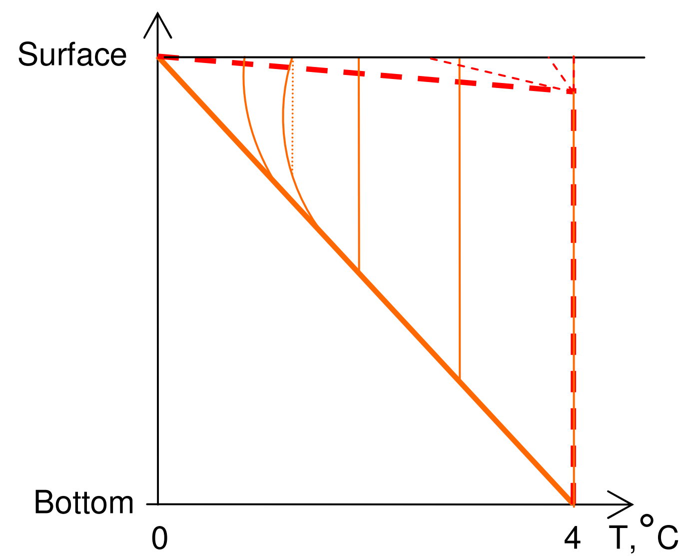
• Linear temperature profile under the ice:
The water surface heats up after the complete ice melting → temperature inversion → deep convection → slow water surface heating from 0°C to 4°C.

• Constant temperature profile under the ice (equilibrium profile):
The water surface heats up after the complete ice melting → only the thin upper layer has to be heated up → the water column remains stable → no convection → very rapid water surface heating from 0°C to 4°C, as demonstrated by offline simulations.

Linear temperature profile under the ice: impossible with the standard Hostetler's model, but… approximating the actual situation in large and deep lakes with mixing, stronger than in the Hostetler's model.

An unintentional, but useful insight on possible ways of modelling deep lakes with 1D models.



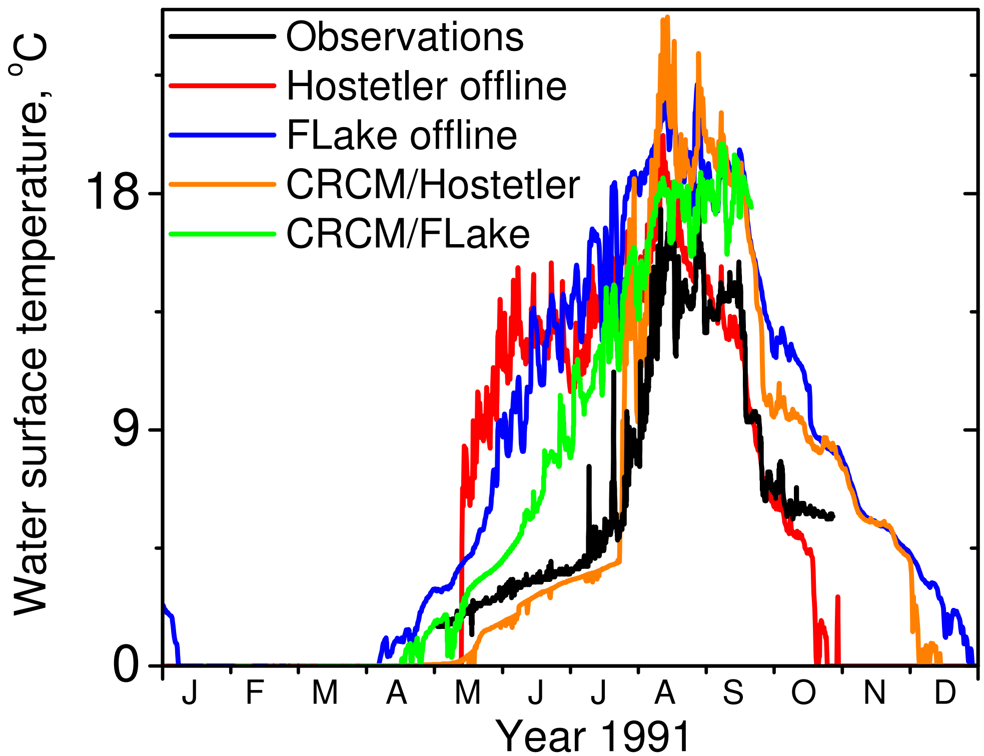


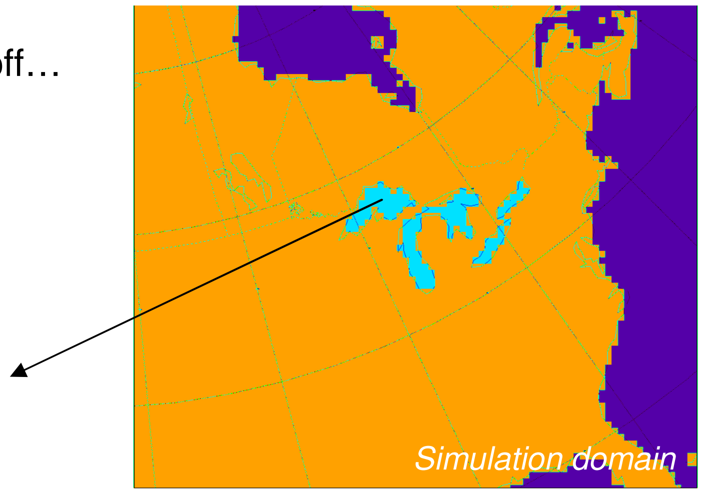
Coupling with lake models: FLake

First coupled simulation: year 1991, LAKE=3 (FLake), driven at the boundaries by the NCEP/NCAR reanalysis
Grid: 80×90, horizontal resolution: 45 km. Lakes: only the Great Lakes (other lakes are masked out)

The simulation was not finished because the computer was turned off…

Lake Superior, NDBC buoy 45001, depth: 261.6 m





Summary

- A new version of the Canadian Regional Climate Model will include several advanced land modelling elements, among them interactive lakes.
- Lakes are a substantial element of the Canadian climate system. Both small, shallow and large, deep lakes are important for the regional climate and have to be taken into account in the Canadian regional climate simulations.
- Offline tests have shown good performance of 1D lake models in small and shallow lakes. Substantial problems exist, however, with large and deep lakes (the Great Lakes).
- First coupled CRCM -1D lake model simulations were carried out. The simulation with the Hostetler's model revealed the importance of the correct model initialisation as well an interesting dependence of the model behavior on the initial temperature profile.

Future plans

- Lakes are introduced in the CRCM in a step-by-step manner:

  - Mixed layer model of Stephan Goyette (the Great Lakes only)

  - Offline 1D lake model tests and validation

  - Coupling with 1D lake models
    Surface schema / lake models interface for resolved lakes (CRCM4/CLASS2.7) - *current phase*
    Tests and validation of coupled model - *current phase*
    Correction of lake models and of the air-lake interaction parameterization
    Multi-decadal simulations, climate change simulations

  - Implementation of lake coupling to subgrid lakes, using the mosaic approach (CRCM4/CLASS3.3, then CRCM5/CLASS 3.3 and later versions)