The Canadian Small Lake Model:
Representing Lakes in Canada's Operational NWP and Climate Prediction Systems

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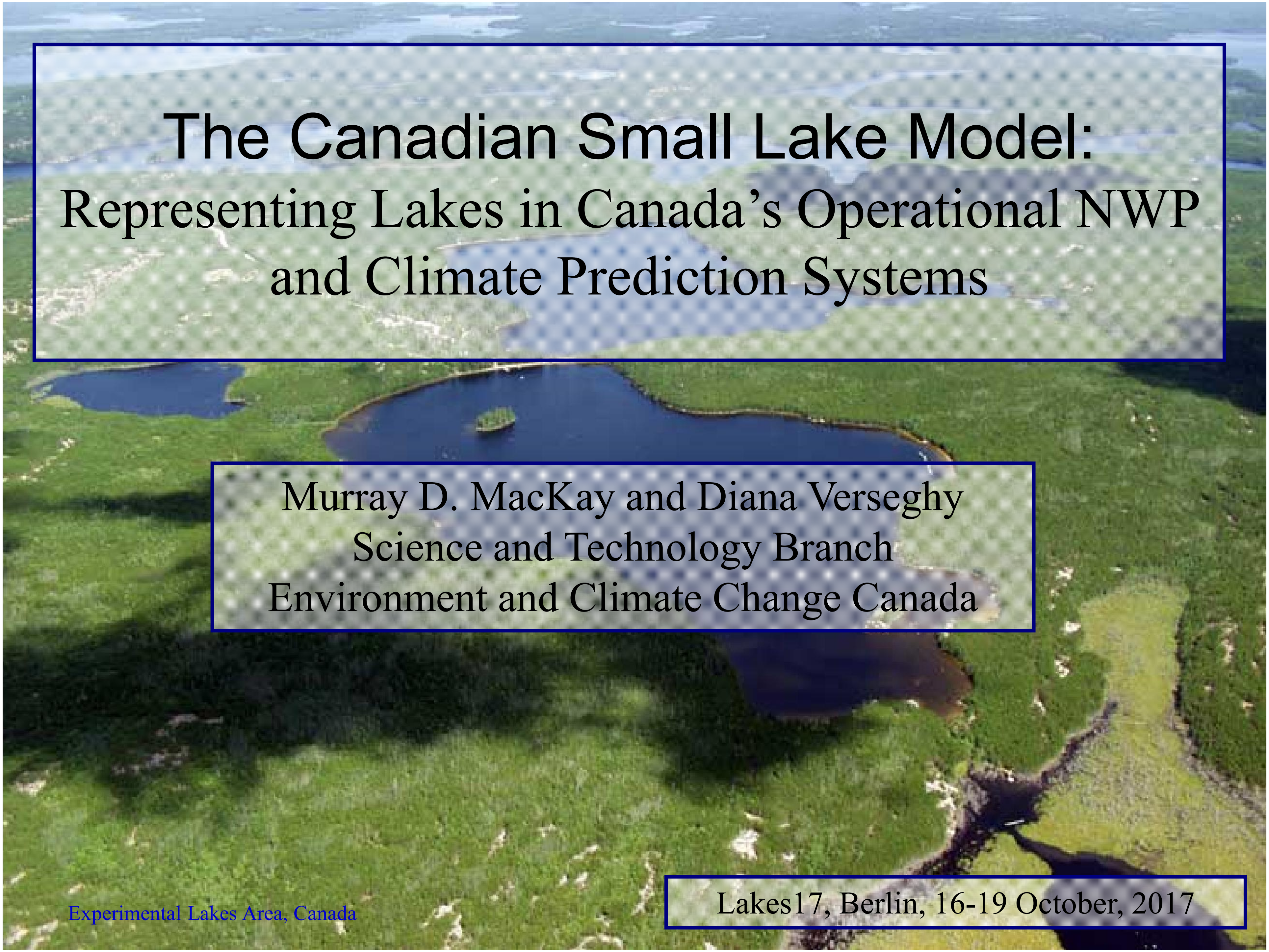
Lakes17, Berlin, 16-19 October, 2017



Experimental Lakes Area, Canada

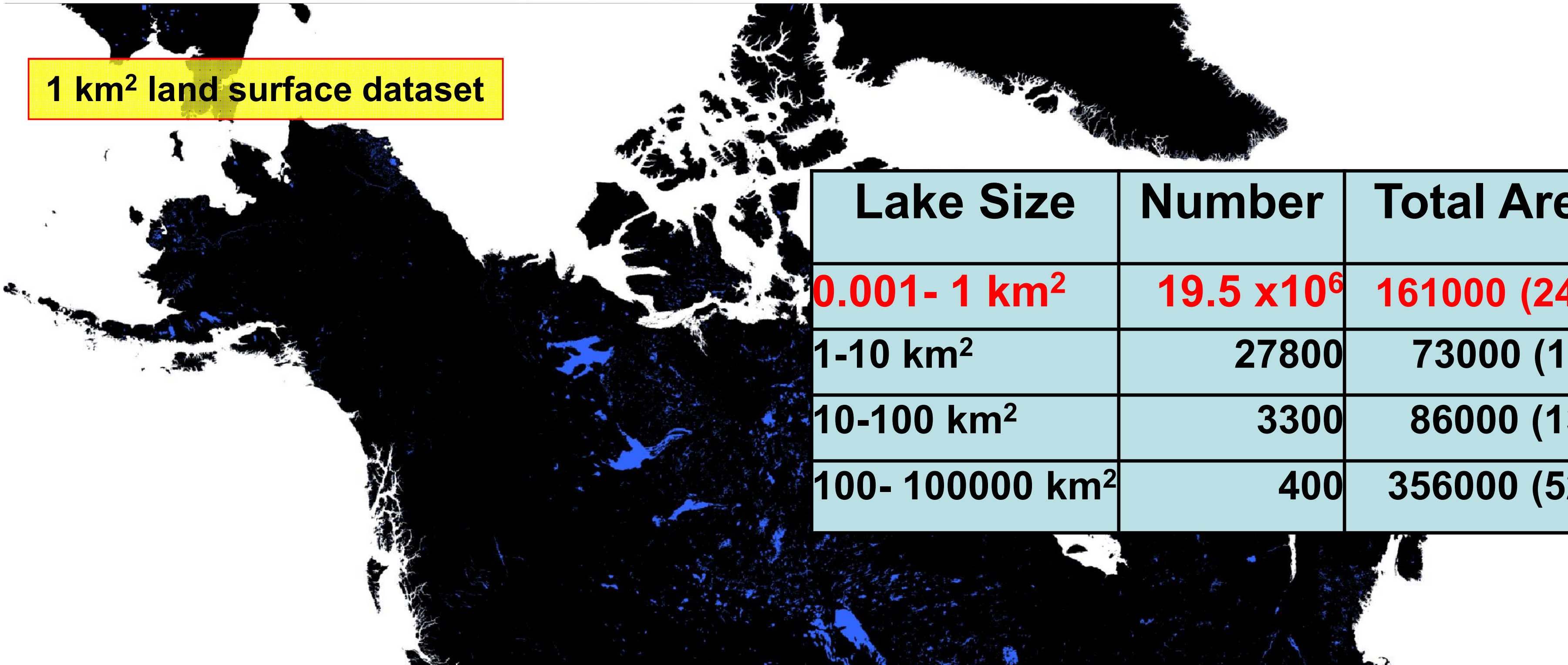
Modelling Lakes in Weather and Climate Systems

- Importance of surface water for weather and climate well established
- Canada has fallen behind some countries in terms of modelling this

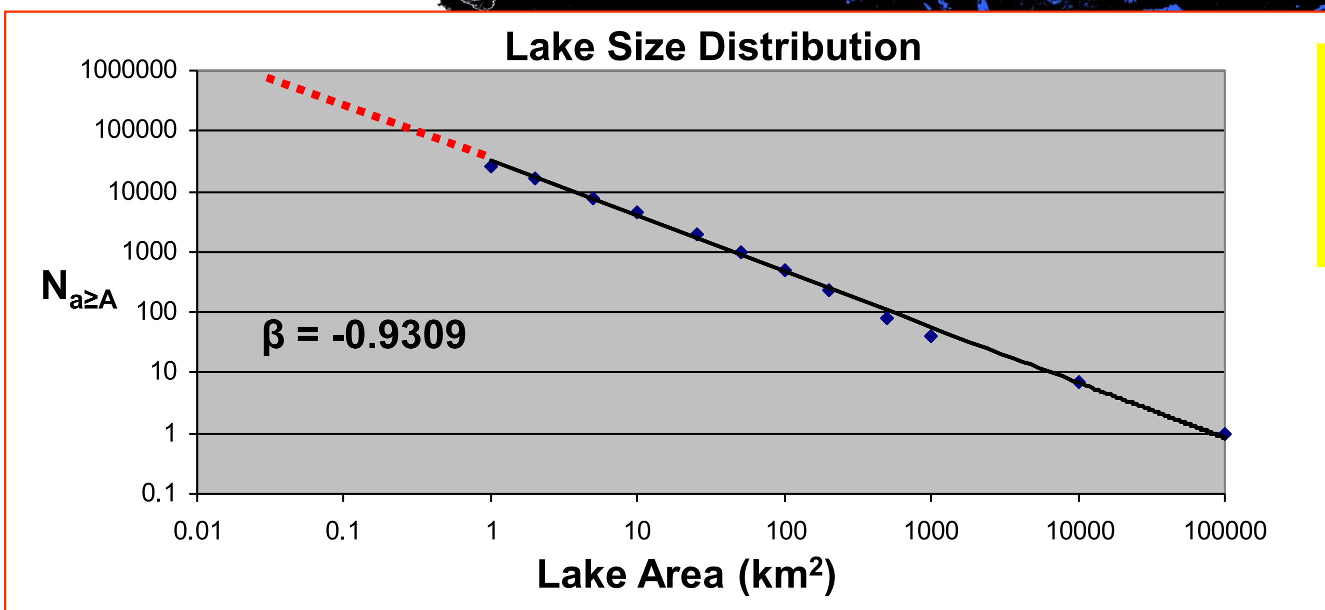
Rationale for the Canadian Small Lake Model

- Develop a single modelling system for individual lake process studies *and* regional scale hydrolimnology for use in NWP and climate prediction
- May be slightly overkill for global modelling since many included physical processes may not be relevant on global scales
- But we are a small country so there is appeal in developing deeper expertise in a smaller number of models

1 km^2 land surface dataset



Lake Size	Number	Total Area
0.001- 1 km^2	19.5 $\times 10^6$	161000 (24 %)
1-10 km^2	27800	73000 (11%)
10-100 km^2	3300	86000 (13%)
100- 100000 km^2	400	356000 (52%)

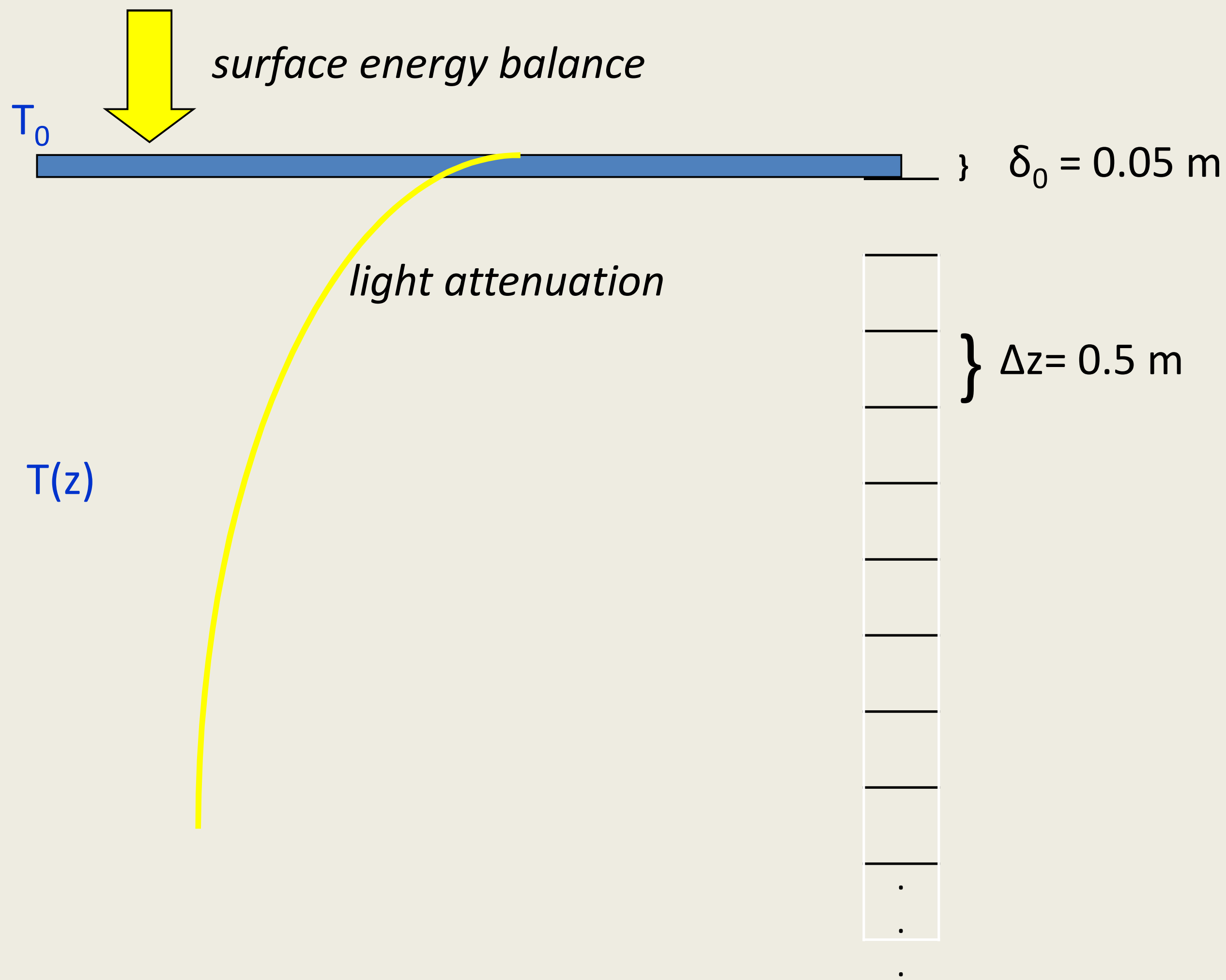


$$N_{a \geq A} = \alpha A^{\beta}$$

$$pdf(a) = \alpha \beta a^{\beta - 1}$$

Canadian Small Lake Model

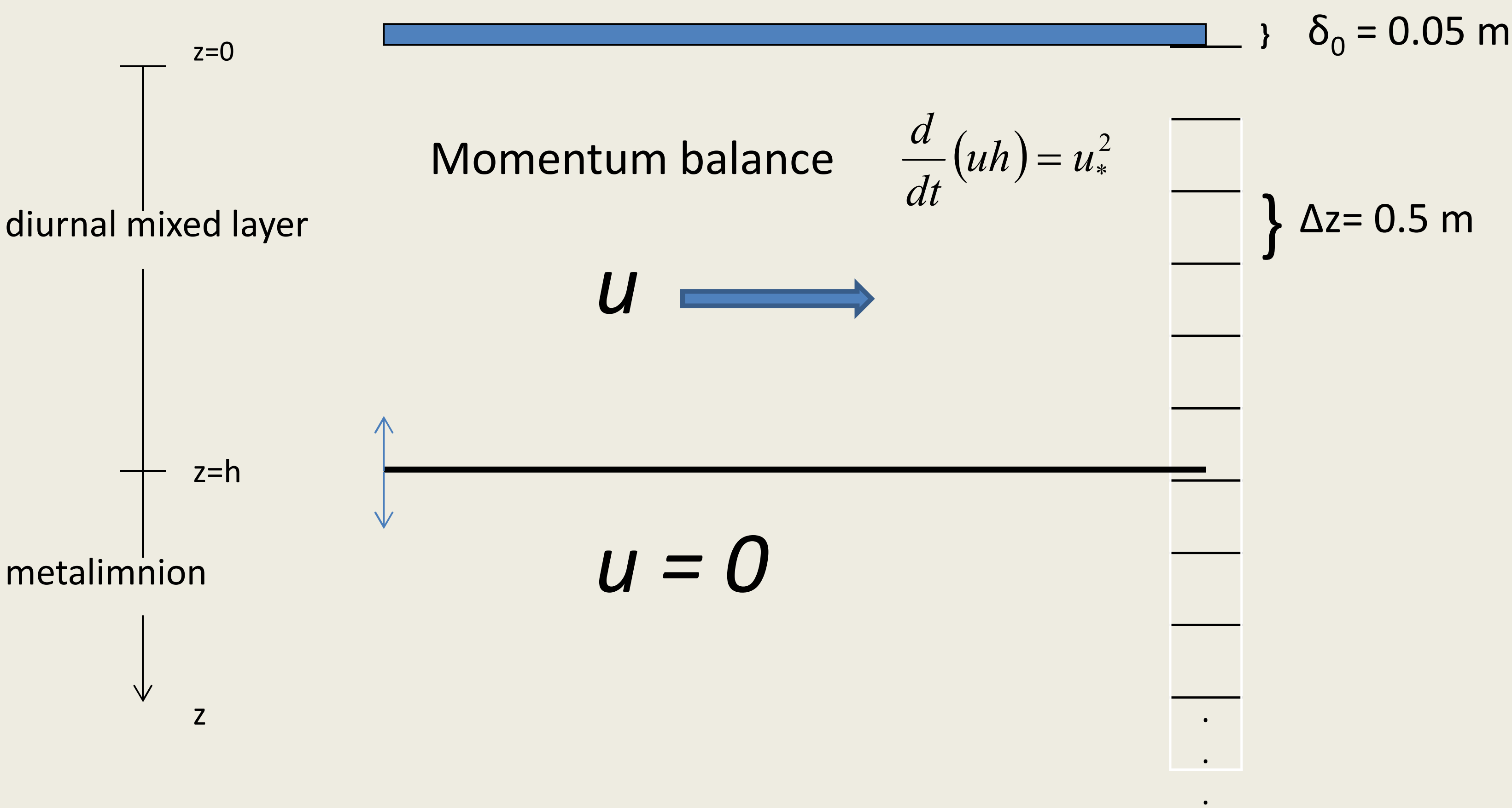
MacKay 2012, J. Hydromet.



- thermal model computes surface energy balance and light attenuation through column

Canadian Small Lake Model

MacKay 2012, J. Hydromet.

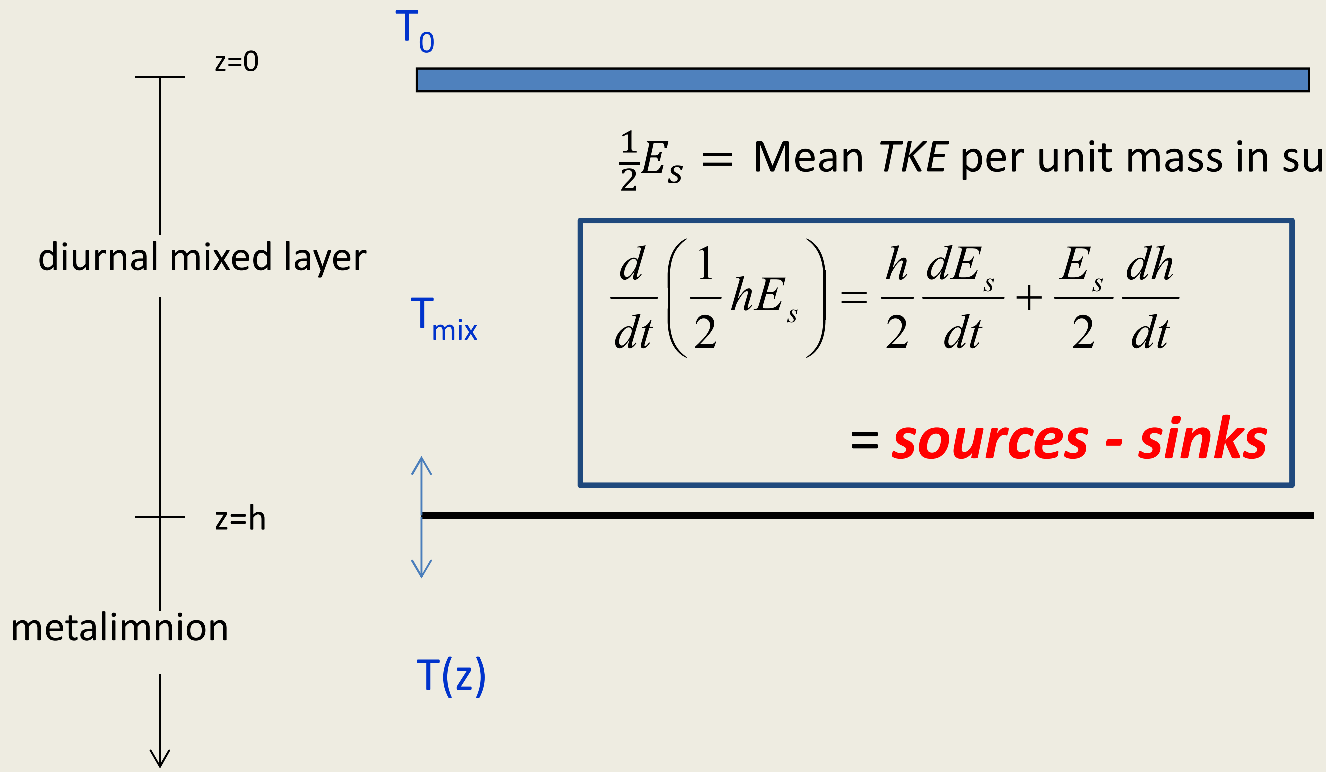


- wind stress forces current in diurnal mixed layer until ¼ period of fundamental internal seiche (Spigel and Imberger, 1980)

Canadian Small Lake Model

MacKay 2012, *J. Hydromet.*

- An integrated TKE model based on Rayner (1980), Imberger (1985) and Spigel *et al.* (1986) (following tradition of Kraus and Turner, 1967)



$\frac{1}{2}E_s$ = Mean *TKE* per unit mass in surface mixed layer

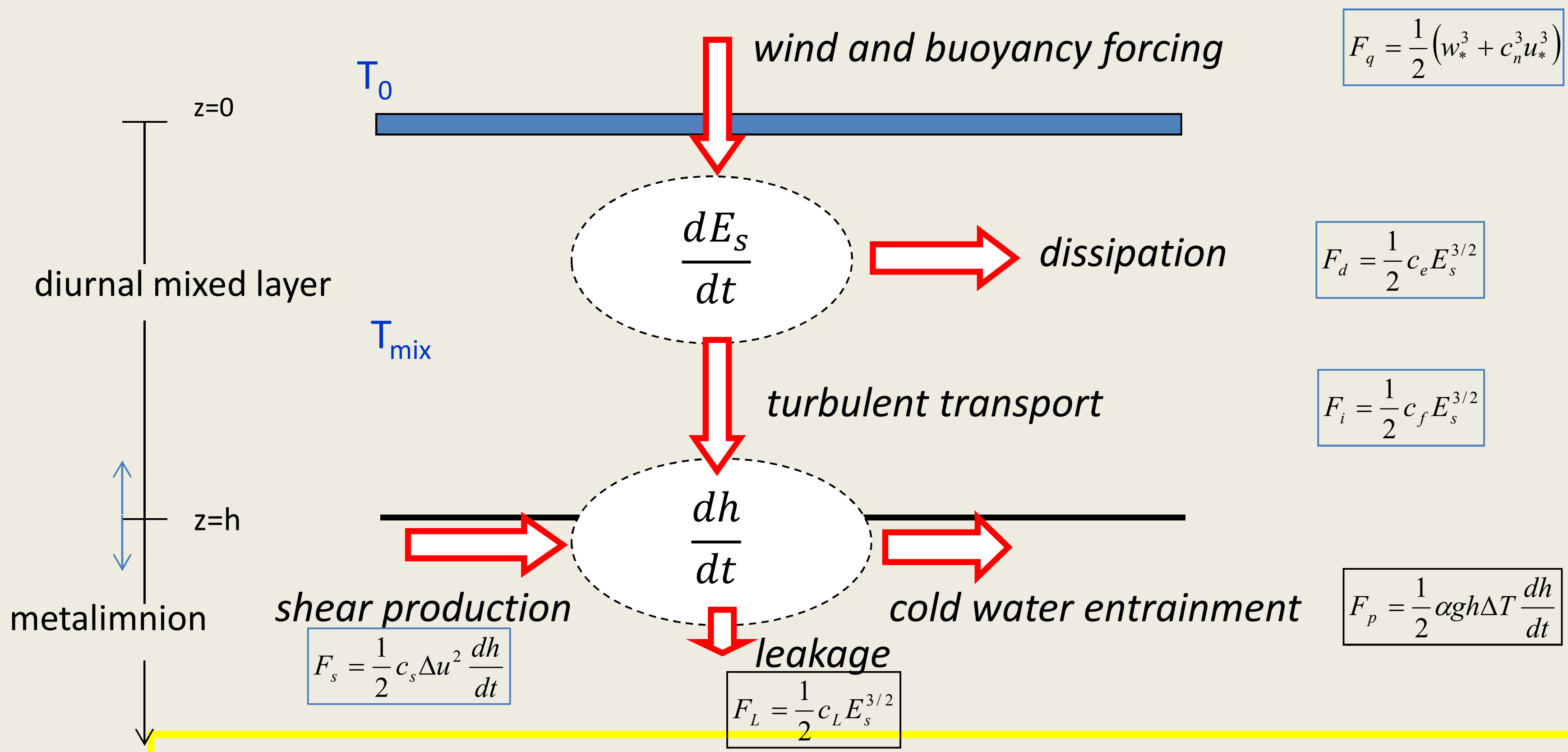
$$\frac{d}{dt}\left(\frac{1}{2}hE_s\right) = \frac{h}{2}\frac{dE_s}{dt} + \frac{E_s}{2}\frac{dh}{dt}$$

= ***sources - sinks***

Canadian Small Lake Model

MacKay 2012, J. Hydromet.

- An integrated TKE model based on Rayner (1980), Imberger (1985) and Spigel *et al.* (1986) (following tradition of Kraus and Turner, 1967)

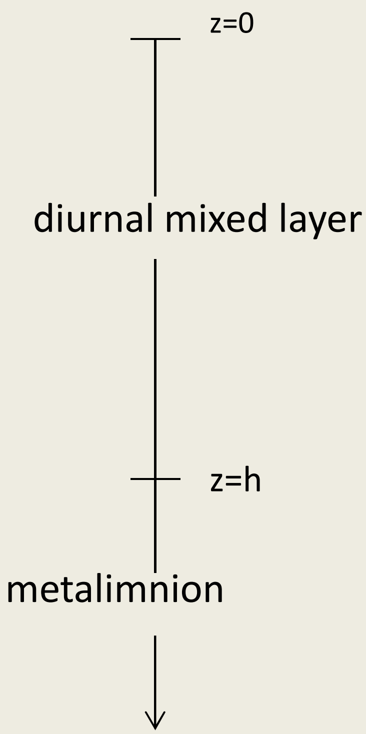


- well known sources/sinks of *turbulent kinetic energy* govern depth of mixed layer
- both surface energy balance and mixed layer depth affect surface temperature

MacKay 2012, J. Hydromet.

Canadian Small Lake Model

- An integrated TKE model based on Rayner (1980), Imberger (1985) and Spigel *et al.* (1986) (following tradition of Kraus and Turner, 1967)



Solution:

$$\frac{d}{dt}\left(uh\right) = u_*^2$$

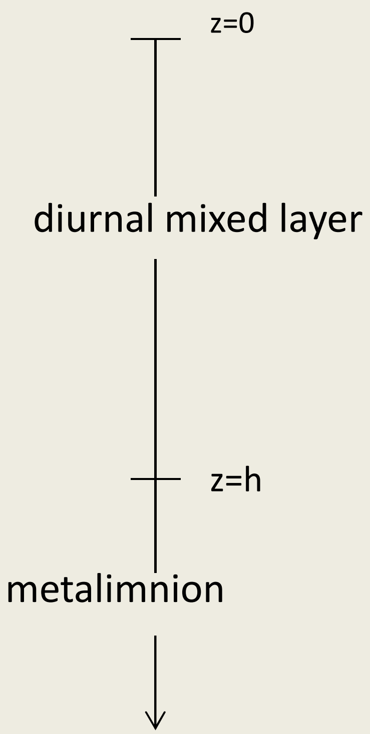
$$\frac{h}{2}\frac{dE_s}{dt} = F_q - F_d - F_i$$

$$\frac{E_s}{2}\frac{dh}{dt} = F_i + F_s - F_p - F_L$$

MacKay 2012, J. Hydromet.

Canadian Small Lake Model

- An integrated TKE model based on Rayner (1980), Imberger (1985) and Spigel *et al.* (1986) (following tradition of Kraus and Turner, 1967)



Solution:

$$\frac{du}{dt} = \frac{u_*^2}{h} - \frac{u}{h}\frac{dh}{dt}$$

$$\frac{dE_s}{dt} = \frac{1}{h}c_n^3 u_*^3 + c_B H^* - \frac{1}{h}\left(c_f + c_e\right)E_s^{3/2}$$

$$\frac{dh}{dt} = \frac{\left(c_f - c_L\right)E_s^{3/2}}{E_s - c_s u^2 + \alpha g h \Delta T}$$

(MacKay et al. 2017, J. Hydromet.)

Canadian Small Lake Model: Ice and Snow

- Snow physics from Canadian Land Surface Scheme (CLASS)

TABLE 1. Equations used for calculating snow properties, where z_s is snow depth (m), T_a is air temperature (K), and T_f is freezing temperature (K).

Snow property	Equation	Data source
Aging of snow albedo α_s	$\alpha_s(t+1) = [\alpha_s(t) - \alpha_{s,\mathrm{old}}]\exp(-0.01\Delta t/3600) + \alpha_{s,\mathrm{old}}$, where $\alpha_{s,\mathrm{old}} = 0.50$ for melting snow and 0.70 otherwise	Aguado (1985), Robinson and Kukla (1984), and Dirmhirn and Eaton (1975)
Max snow density $\rho_{s,\max}$ (kg m^{-3})	$\rho_{s,\max} = A_s - (204.70/z_s)[1.0 - \exp(-z_s/0.673)]$, where $A_s = 700.0$ for melting snow and 450.0 otherwise	Tabler et al. (1990)
Aging of snow density ρ_s (kg m^{-3})	$\rho_s(t+1) = [\rho_s(t) - \rho_{s,\max}]\exp(-0.01\Delta t/3600) + \rho_{s,\max}$	Longley (1960) and Gold (1958)
Density of fresh snow $\rho_{s,i}$ (kg m^{-3})	$\rho_{s,i} = 67.92 + 51.25\exp[(T_a - T_f)/2.59]$ for $T_a < T_f$ and $\rho_{s,i} = 119.17 + 20.0(T_a - T_f)$ for $T_a \geq T_f$	Hedstrom and Pomeroy (1998) and Pomeroy and Gray (1995)
Thermal conductivity λ_s (W m^{-1} K^{-1})	$\lambda_s = 3.233 \times 10^{-6}\rho_s^2 - 1.01 \times 10^{-3}\rho_s + 0.138$ for $\rho_s \geq 156.0$ and $\lambda_s = 0.234 \times 10^{-3}\rho_s + 0.023$ for $\rho_s < 156.0$	Sturm et al. (1997)
Transmissivity τ_s	$\tau_s = \exp(-25.0z_s)$	Grenfell and Maykut (1977) and Thomas (1963)

(MacKay et al. 2017, J. Hydromet.)

Canadian Small Lake Model: Ice and Snow

- Snow-ice scheme described in MacKay *et al.* (2017)

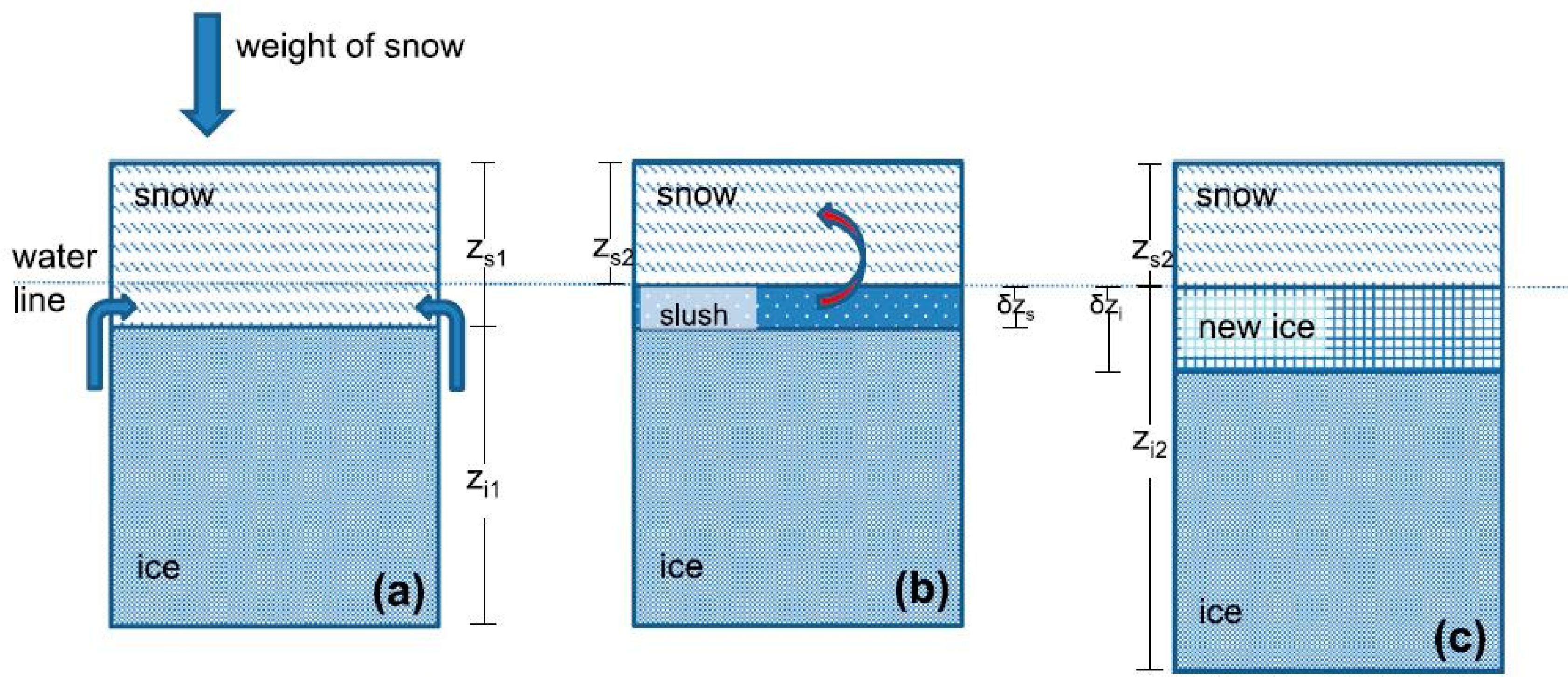
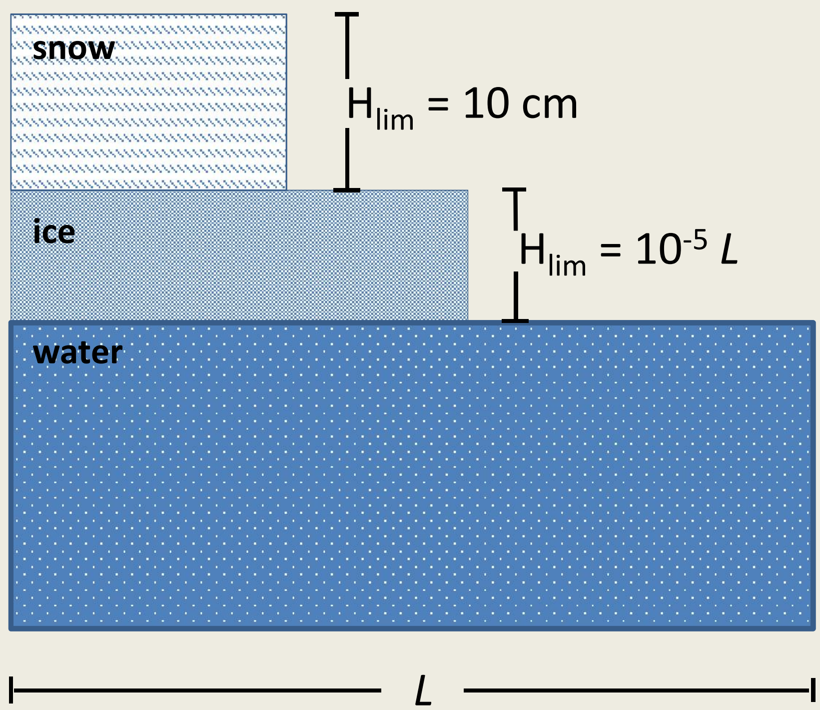


FIG. A1. The process of snow-ice formation in the CSLM: (a) ice cannot support the weight of overlying snow so that water floods a thin layer of snow to form slush, (b) slush layer freezes releasing latent heat into the overlying snow layer, and (c) new snow-ice is thicker than slush layer due to thermal expansion.

(MacKay et al. 2017, J. Hydromet.)

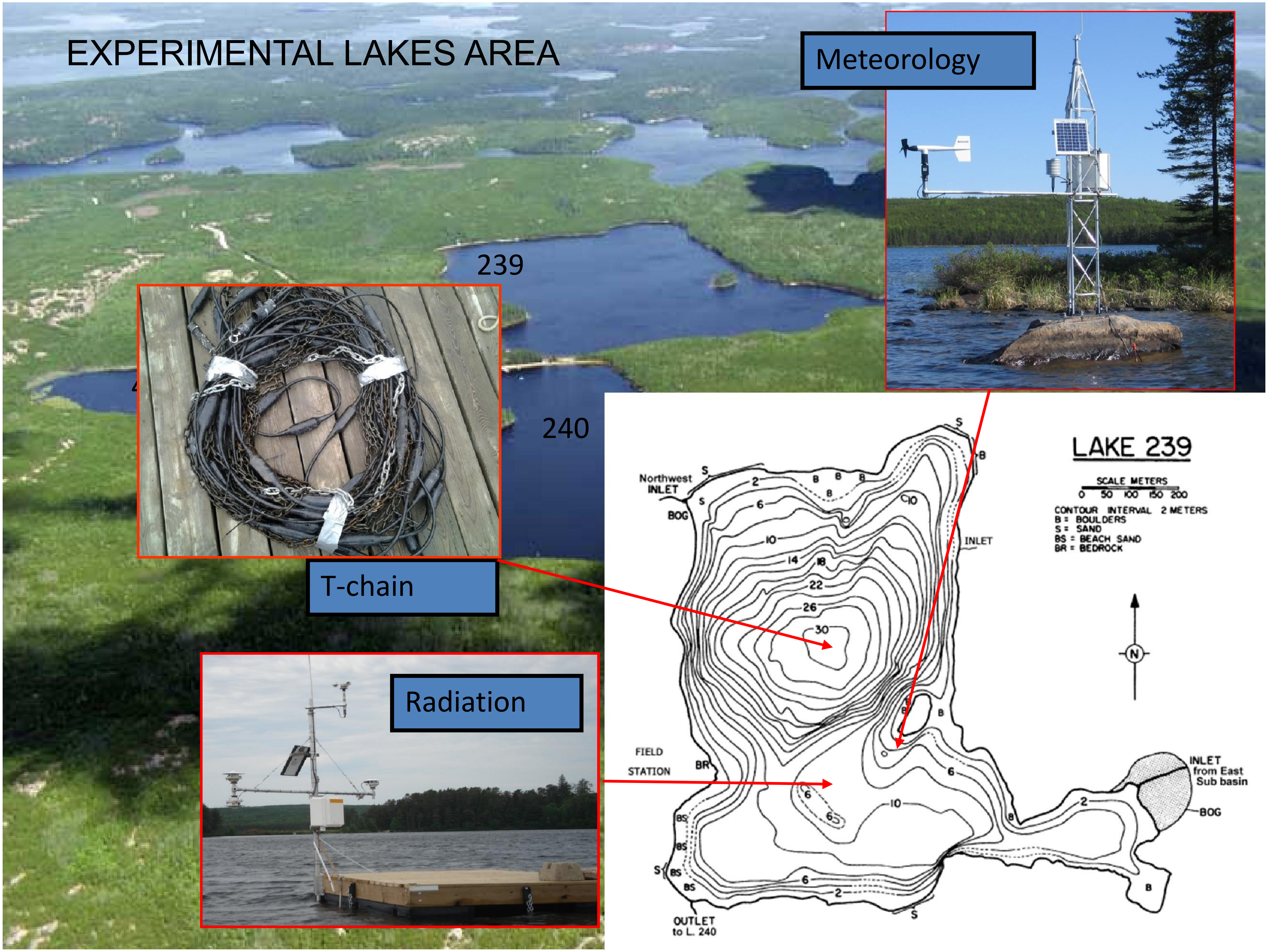
Canadian Small Lake Model: Ice and Snow

- Both patchy snow cover and fractional ice cover permitted



(Verseghy, 2016)

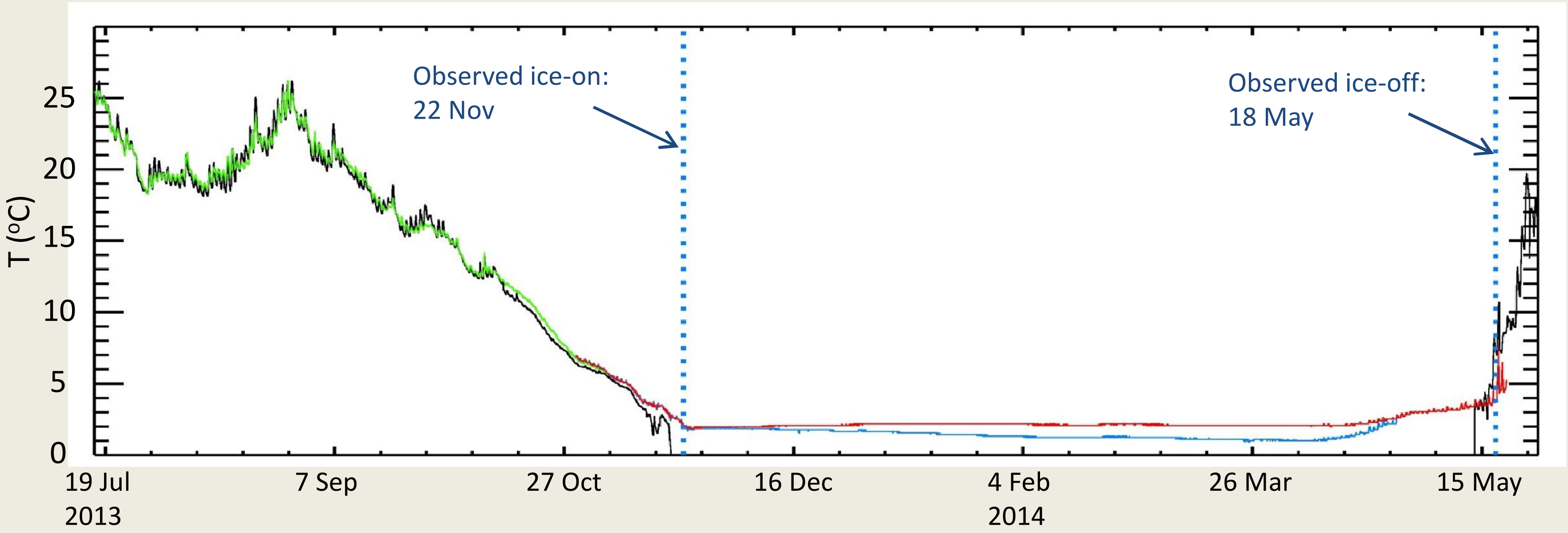
(Leppäranta and Wang, 2008)


EXPERIMENTAL LAKES AREA
239
240
Meteorology
T-chain
Radiation
LAKE 239
SCALE METERS
0 50 100 150 200
CONTOUR INTERVAL 2 METERS
B = BOULDERS
S = SAND
BS = BEACH SAND
BR = BEDROCK
Northwest INLET
BOG
INLET
FIELD STATION
OUTLET to L. 240
INLET from East Sub basin
BOG
N

Lake 239: 17 July 2013 – 27 May 2014

Winter period discussed in MacKay et al. 2017

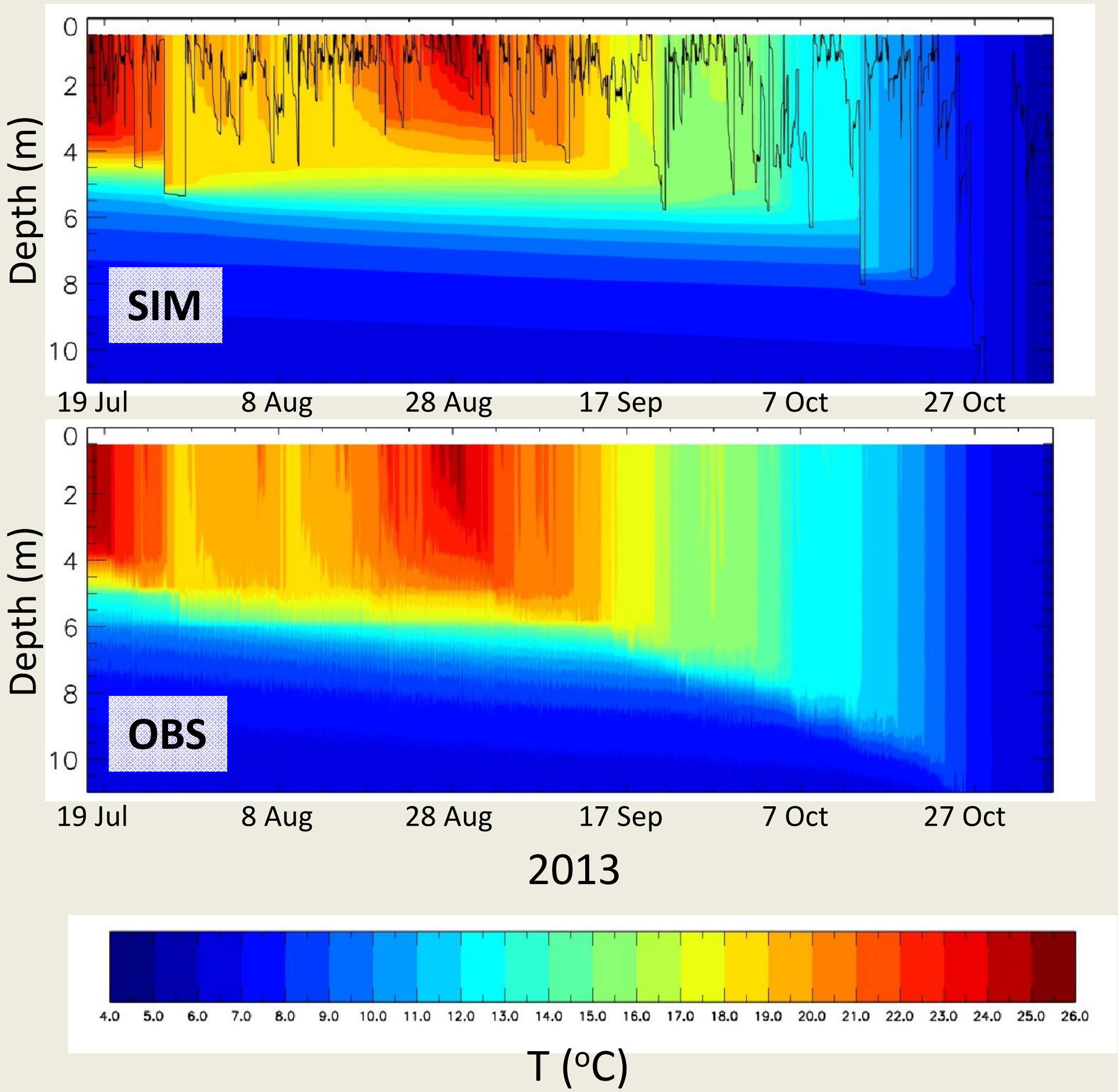
__Surface Simulation__



Summertime Processes

Lake 239: 17 July – 5 Nov, 2013

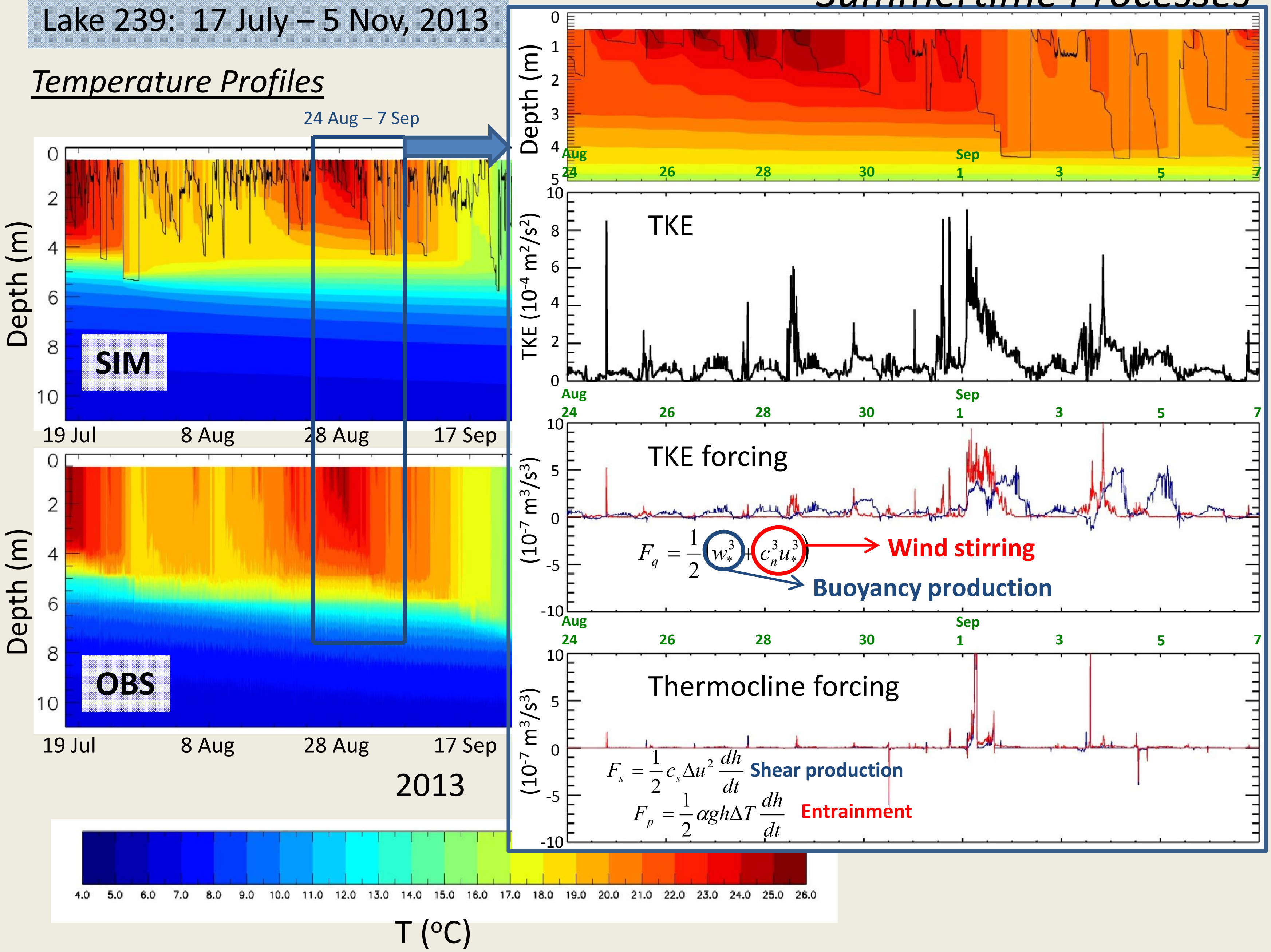
Temperature Profiles



Summertime Processes

Lake 239: 17 July – 5 Nov, 2013

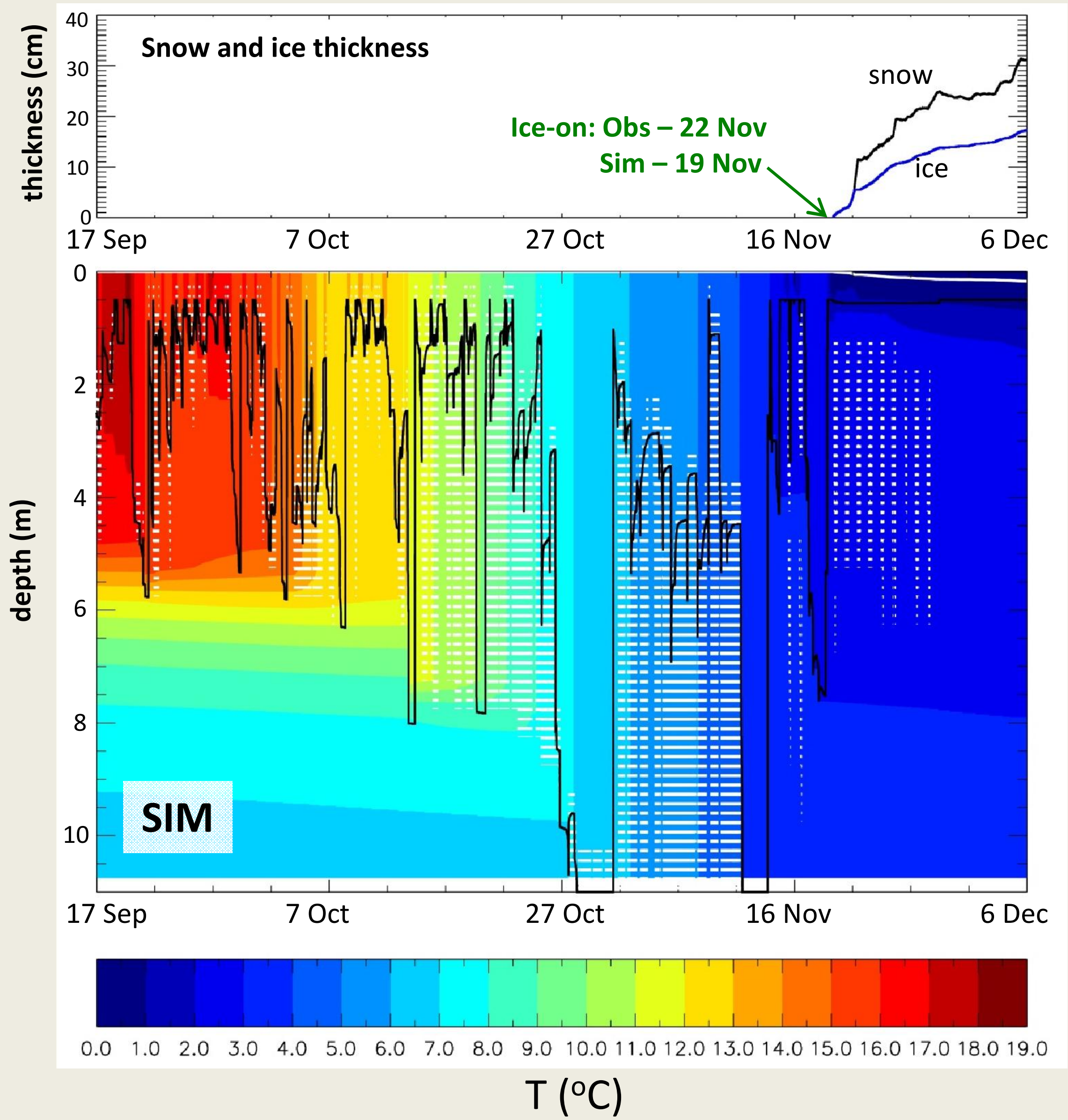
Temperature Profiles



MacKay et al. 2017

Lake 239: 17 Sep – 6 Dec, 2013

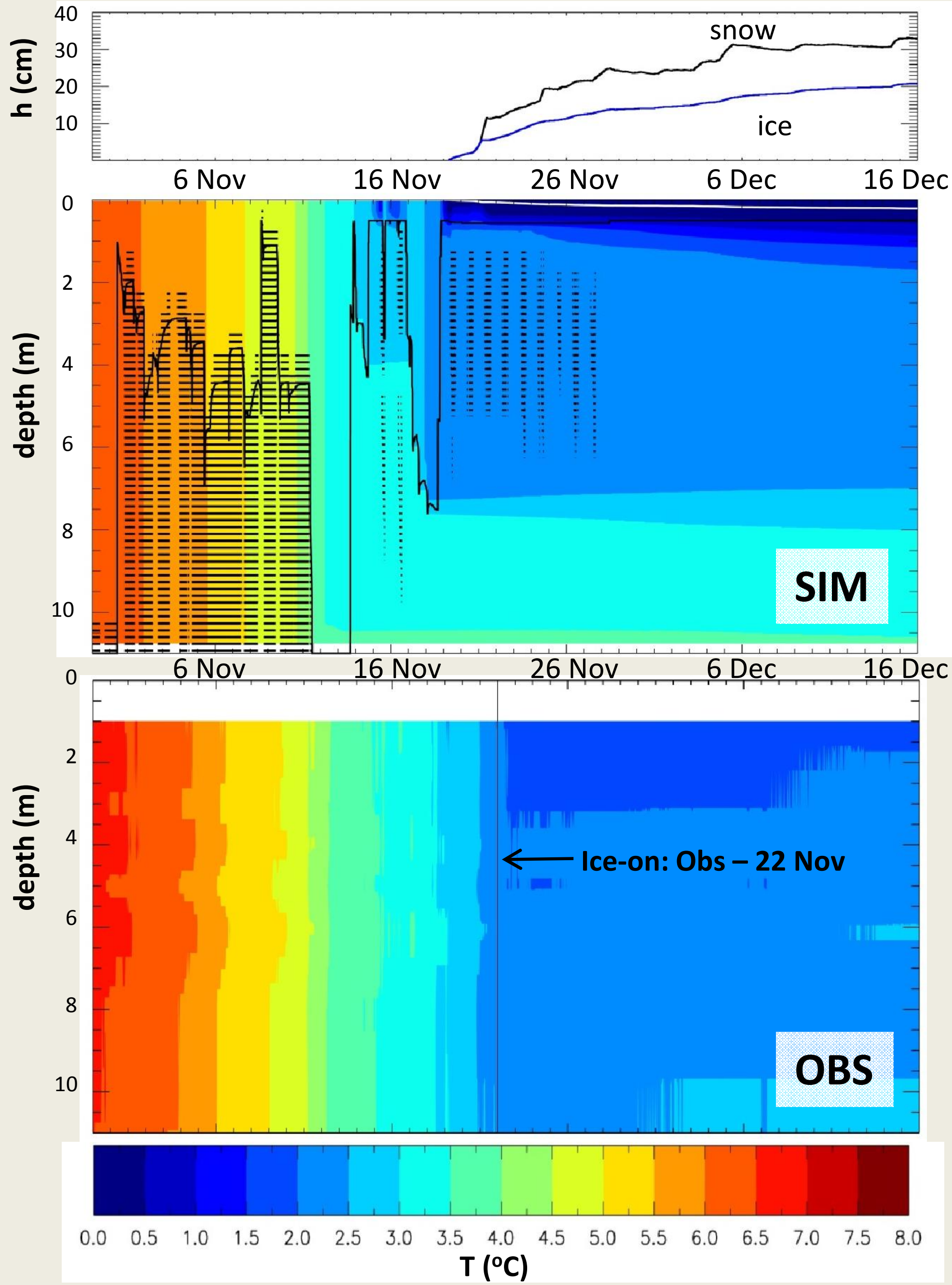
Autumn Processes



MacKay et al. 2017

Lake 239: 30 Oct – 16 Dec, 2013

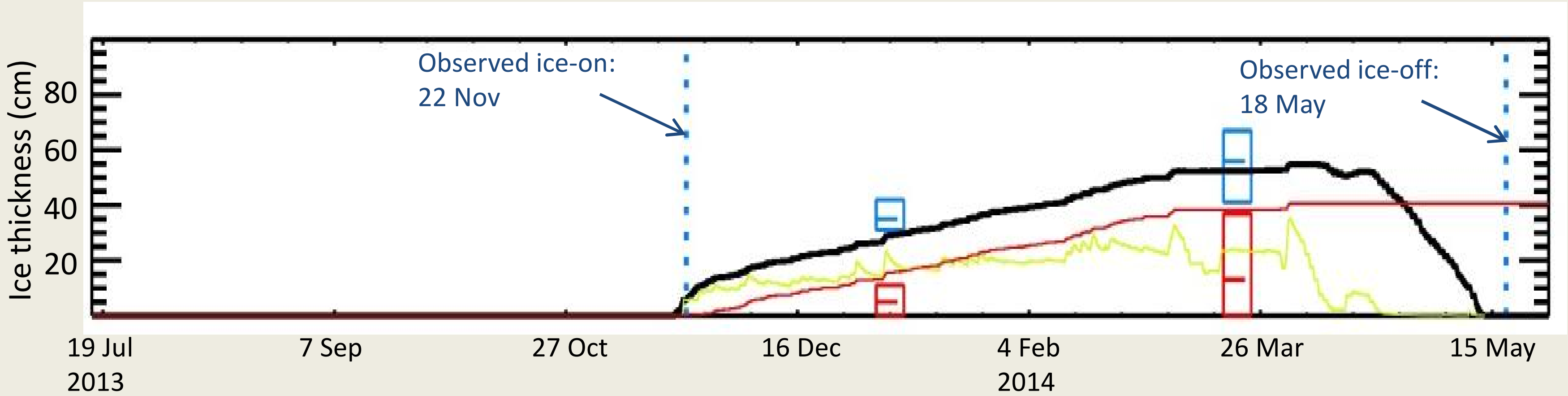
Autumn Processes



MacKay et al. 2017

Lake 239: 19 Jul, 2013 – 27 May, 2014

Winter Processes



MacKay et al. 2017

Lake 239: 16 Nov, 2013 – 20 May, 2014

Winter Processes

<u>Δ heat content (10 m column)</u>

26 Nov – 6 Mar (100 days)

SIM: -1.027×10^{7} Jm^{-2}

OBS: $+1.435 \times 10^{7}$ Jm^{-2}

bias: -2.462×10^{7} Jm^{-2}

≈ -2.8 Wm^{-2}

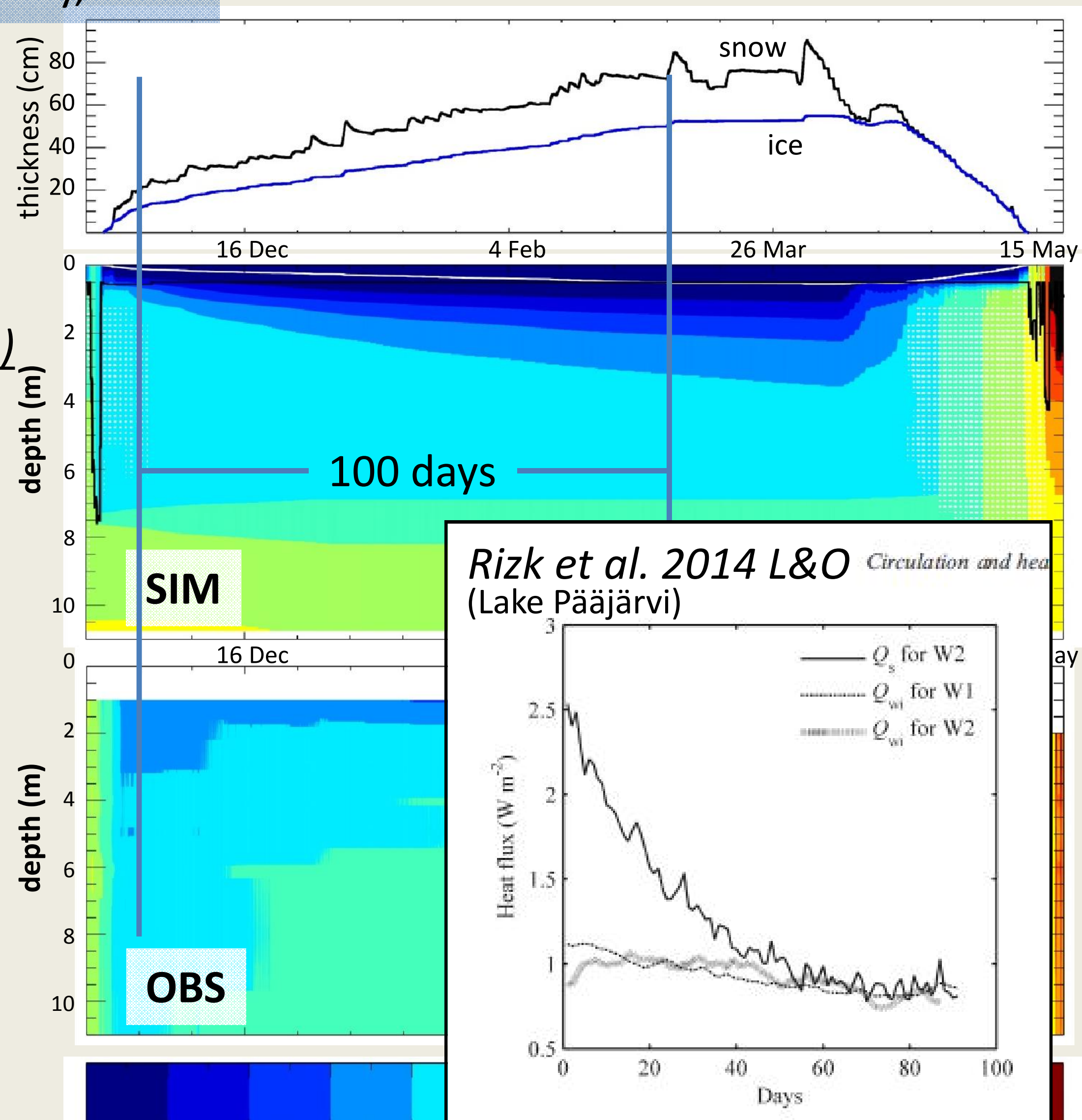


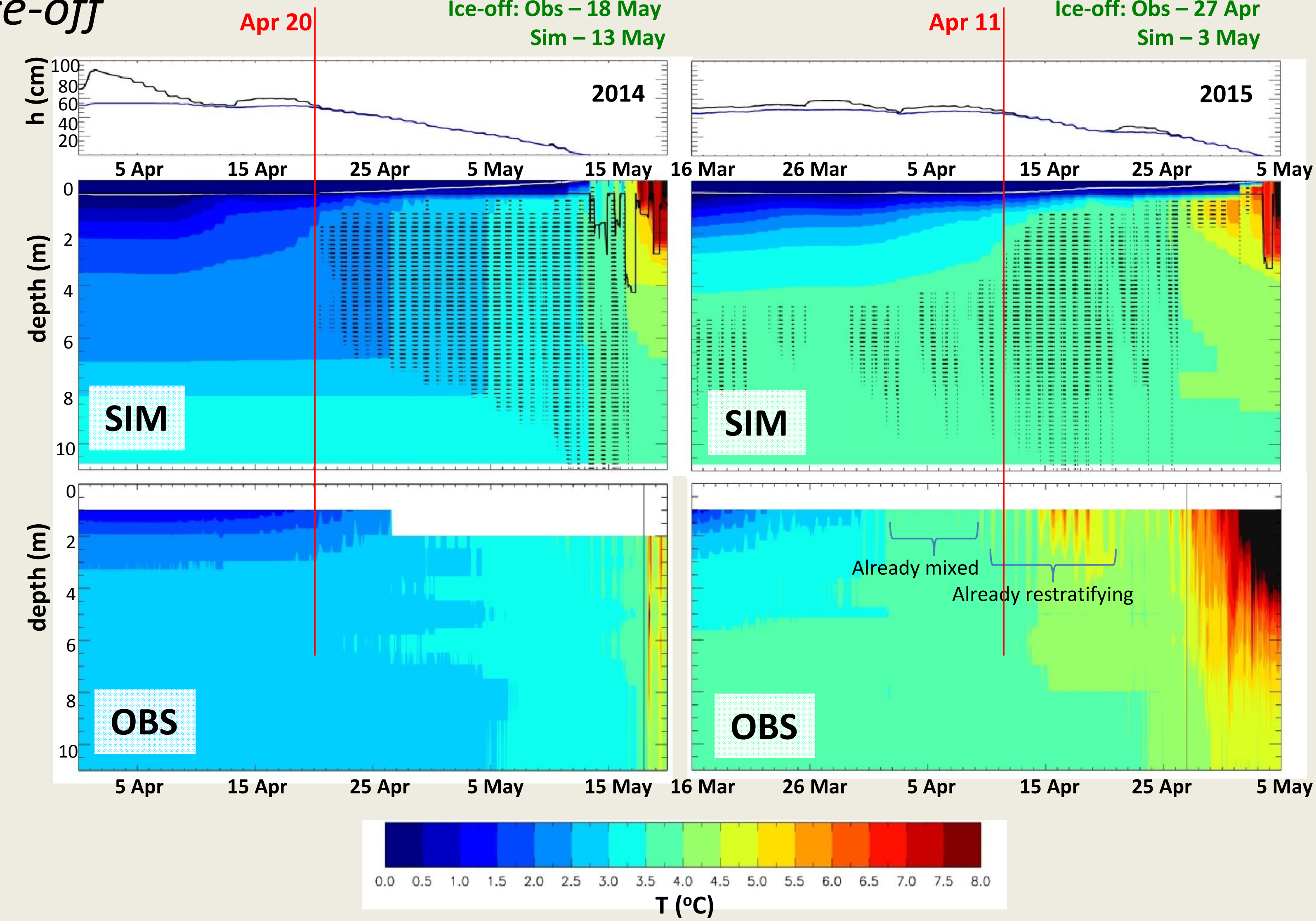
Fig. 8. Time series of the vertical heat flux from the sediment Q_s (W m^{-2}; solid line) near W2Ch3 and the estimated vertical heat fluxes through the water–ice interface Q_{wi} (W m^{-2}), spatially averaged for all TCs during W1 (dotted line) and W2 (thick grey line). The data were time-averaged over 24 h steps.

MacKay et al. 2017

Lake 239: 31 Mar – 20 May, 2014

Lake 239: 16 Mar – 5 May, 2015

Ice-off



Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

- CSLM run on a 0.25° horizontal resolution grid over western Canada.
- Atmospheric forcing: ERA-Interim reanalysis downscaled with Canadian Regional Climate Model (CRCM5).
- 1990 – 2011 simulation.

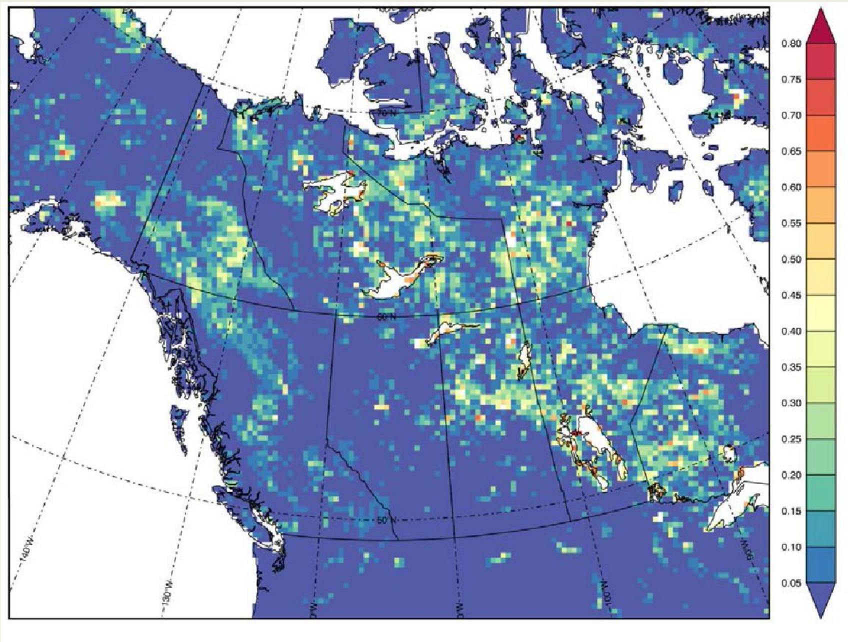


Fig. 2. *Fractional coverage of subgrid-scale lakes on the model domain.*

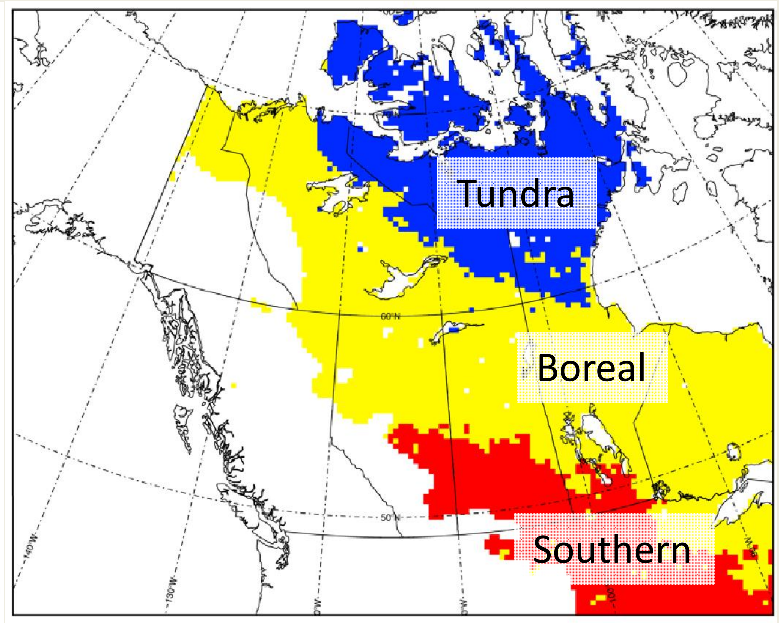


Fig. 6. *Locations of tundra, boreal, and southern ecozones used for averaging of surface fields.*

Verseghy and MacKay, 2017

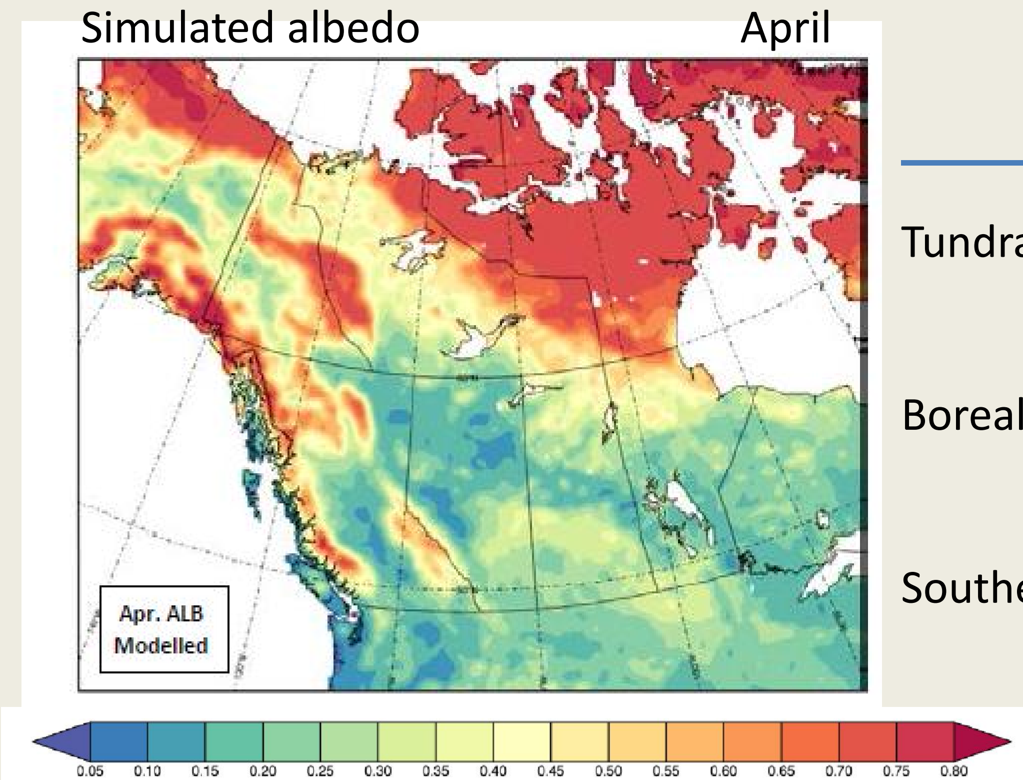
Regional Scale Simulations: Uncoupled Runs

- Shortwave extinction: 0.5 m^{-1} (also 2.0 m^{-1})
- Lake depth: Kourzeneva, 2010 or default 10.0 m (also 5.0 m, 50.0 m)
- Initial conditions: 4 ^{o}C (isothermal); 1 year spinup.
- Simulated precipitation scaled by monthly gridded observed product (CANGRD) – details in Verseghy and MacKay, 2017
- Validation data: ARC-Lake (temperature, ice cover)
  MODIS (surface albedo)

Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Albedo (2000 – 2010)

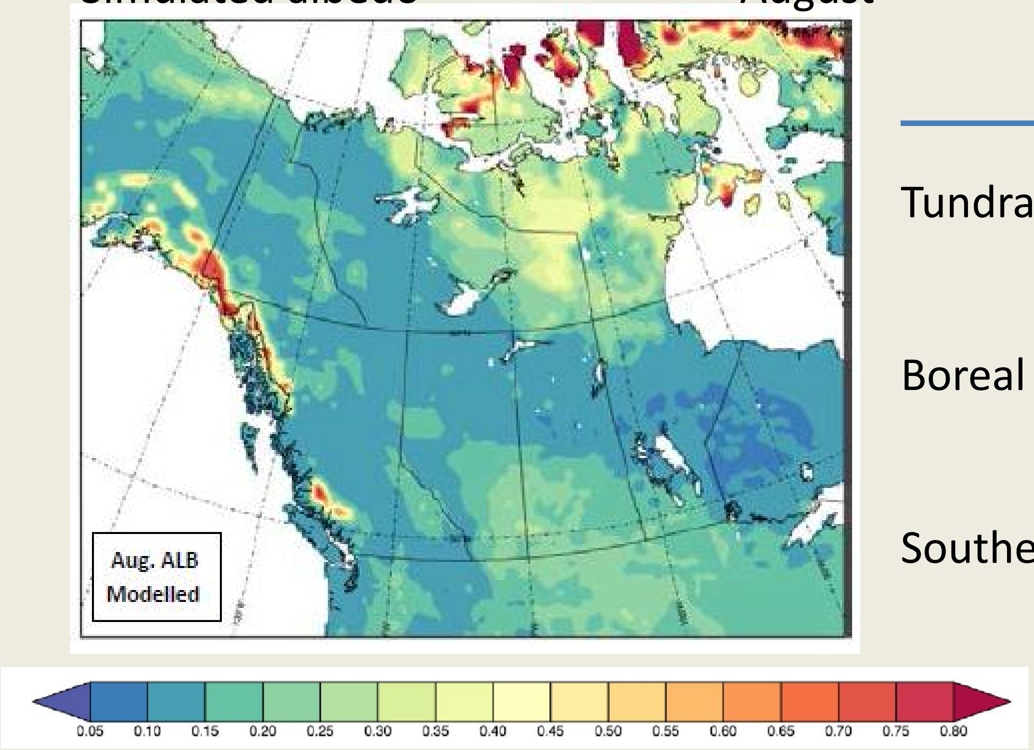


	BIAS No Lakes	Lakes
Tundra	-0.06	-0.05
Boreal	-0.06	-0.03
Southern	+0.08	+0.08

Regional Scale Simulations: Uncoupled Runs

Albedo (2000 – 2010)

Simulated albedo August



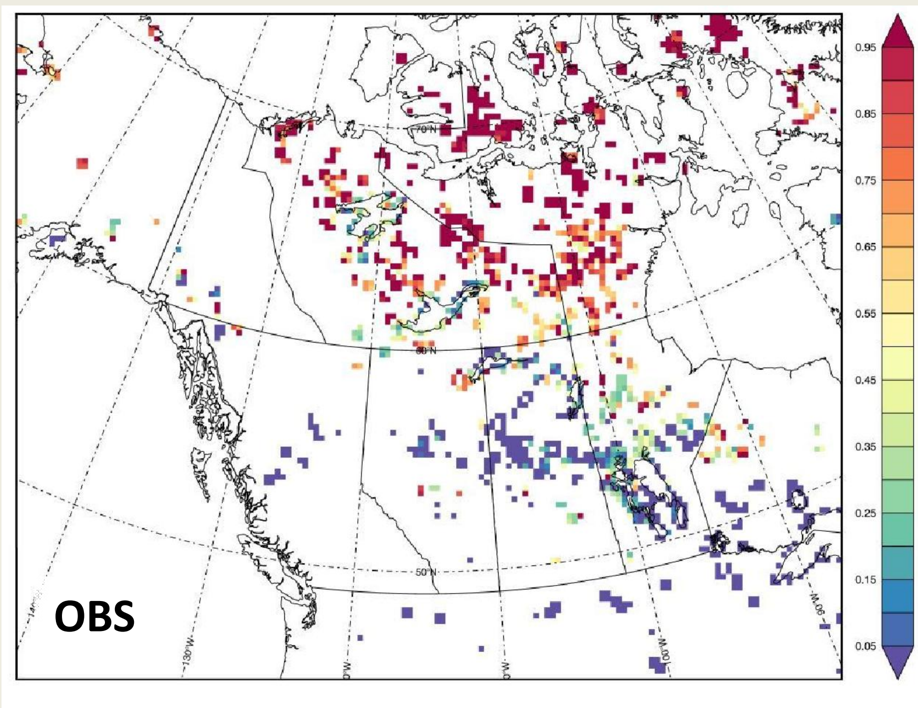
	BIAS No Lakes	Lakes
Tundra	+0.16	+0.14
Boreal	+0.03	+0.02
Southern	+0.02	+0.02

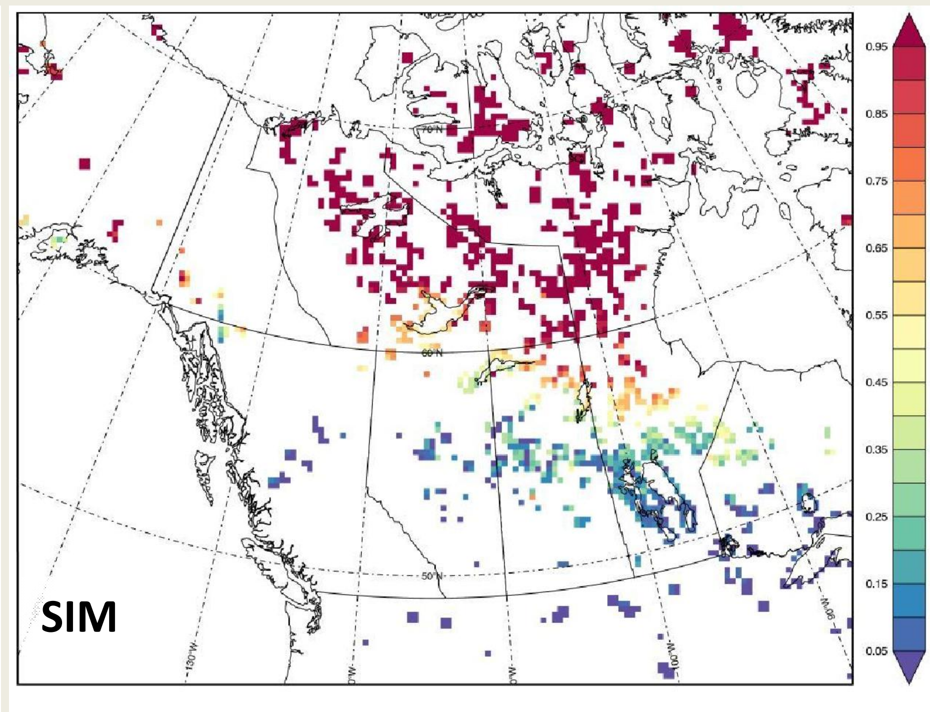
Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Ice Cover (1995 – 2011)

October



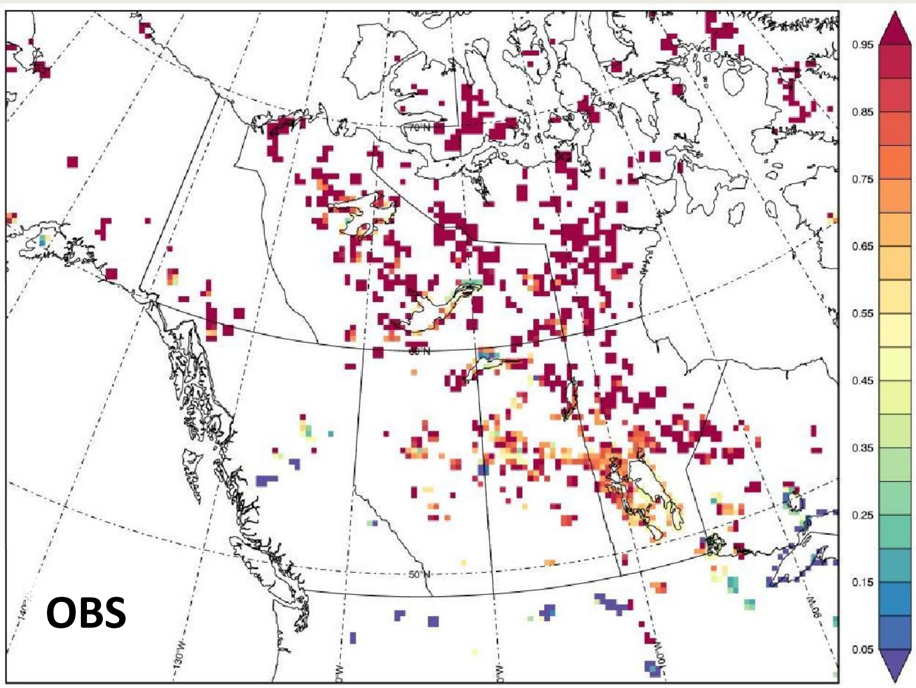


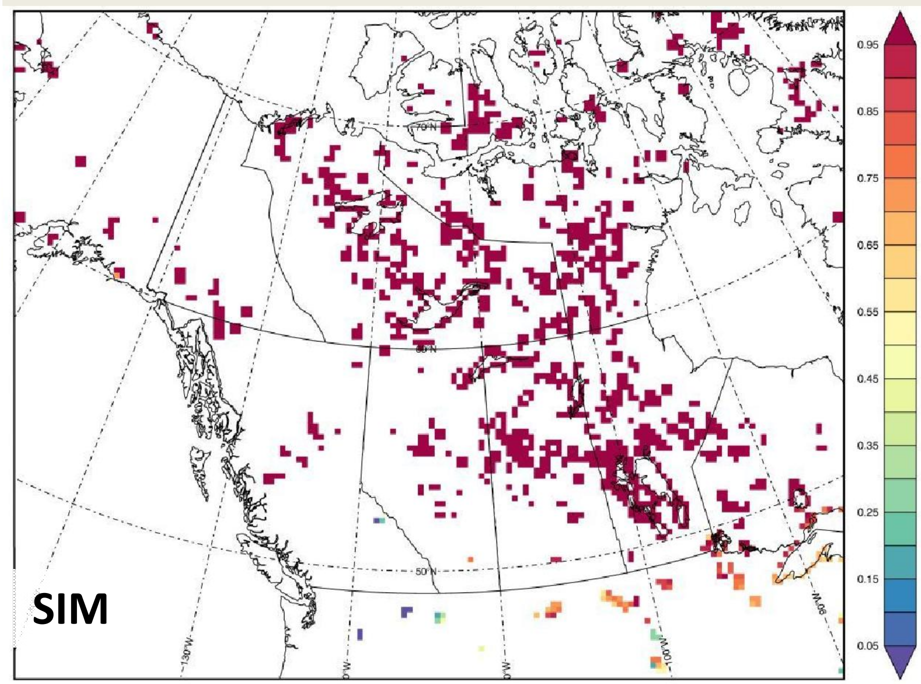
Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Ice Cover (1995 – 2011)

November

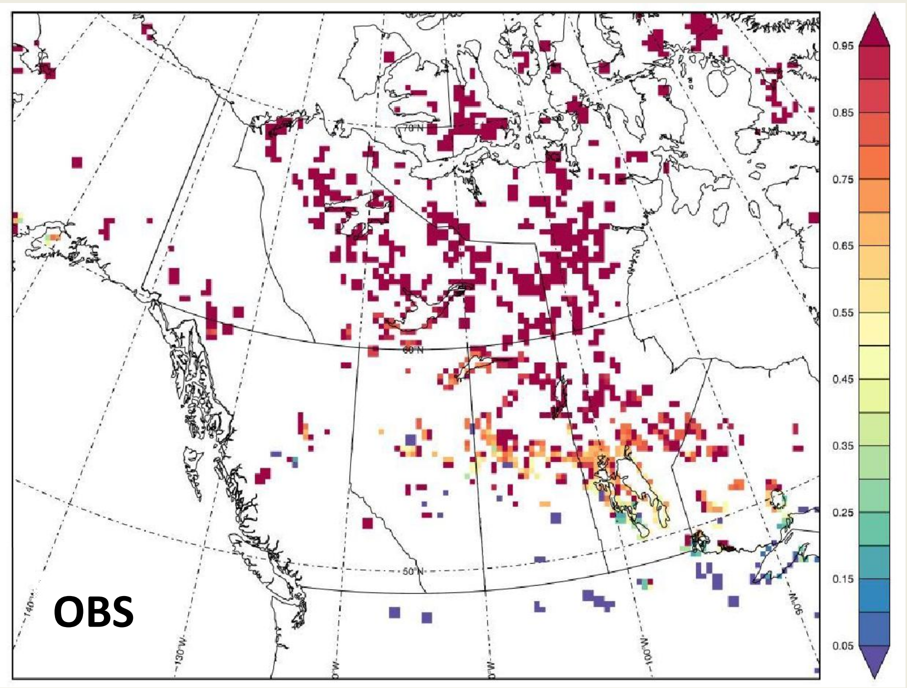


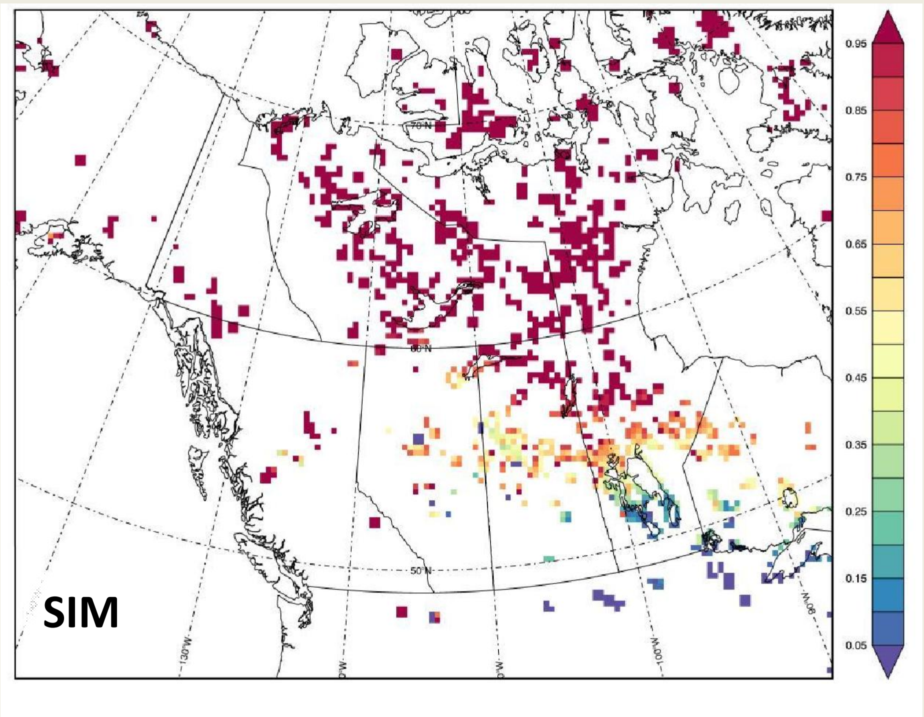


Regional Scale Simulations: Uncoupled Runs

Ice Cover *(1995 – 2011)*

May



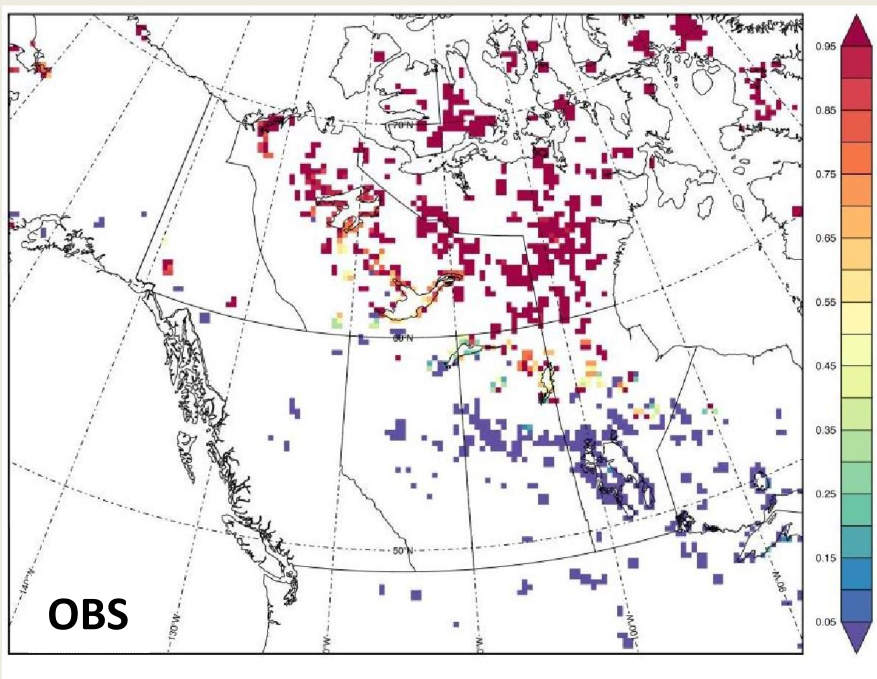


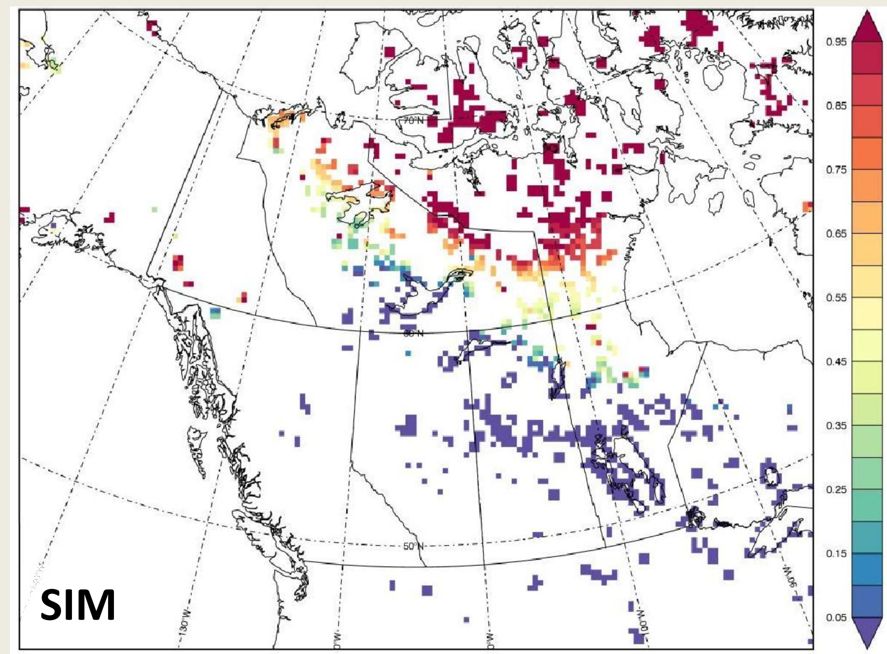
Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Ice Cover (1995 – 2011)

June





Regional Scale Simulations: Uncoupled Runs

Ice Cover (1995 – 2011)

Table 1: Summary statistics for modelled vs. observed sub-grid lake fractional ice cover for the months of May, June, October and November.

Ice melts too soon
Consistent with warm simulated air temp bias

	MBE	*RMSE*	r^2
May	-0.03	0.14	0.78
June	-0.11	0.24	0.79
October	0.18	0.30	0.67
November	0.14	0.27	0.26

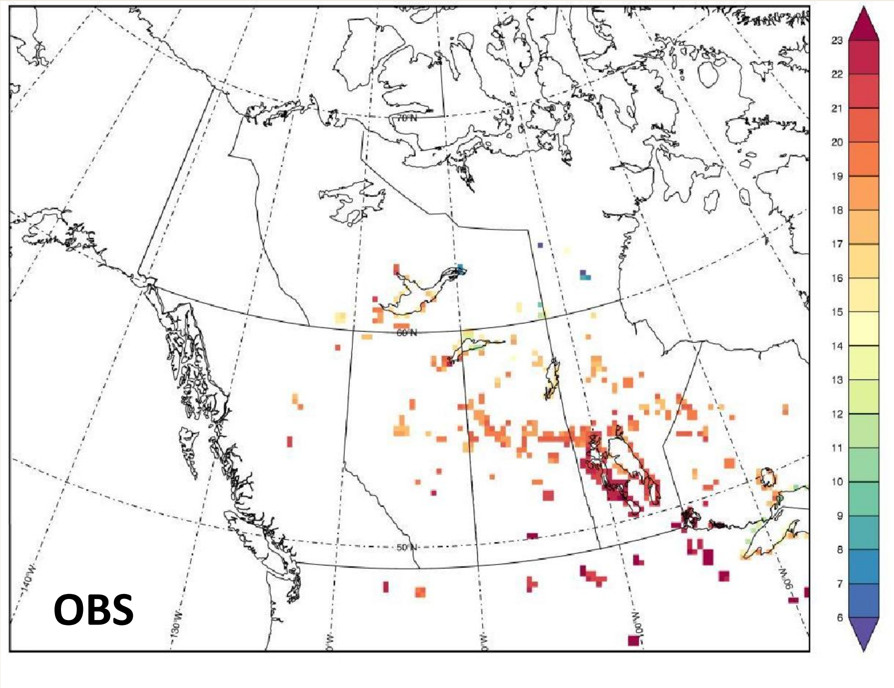
Ice forms too soon
Consistent with cold simulated air temp bias

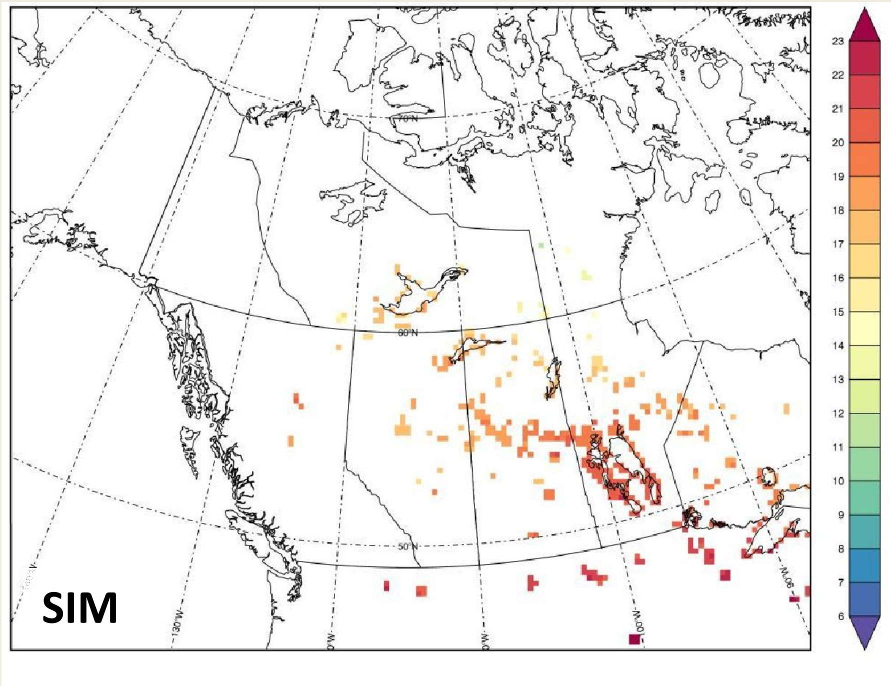
Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Surface Temperature   *(1995 – 2011)*

July



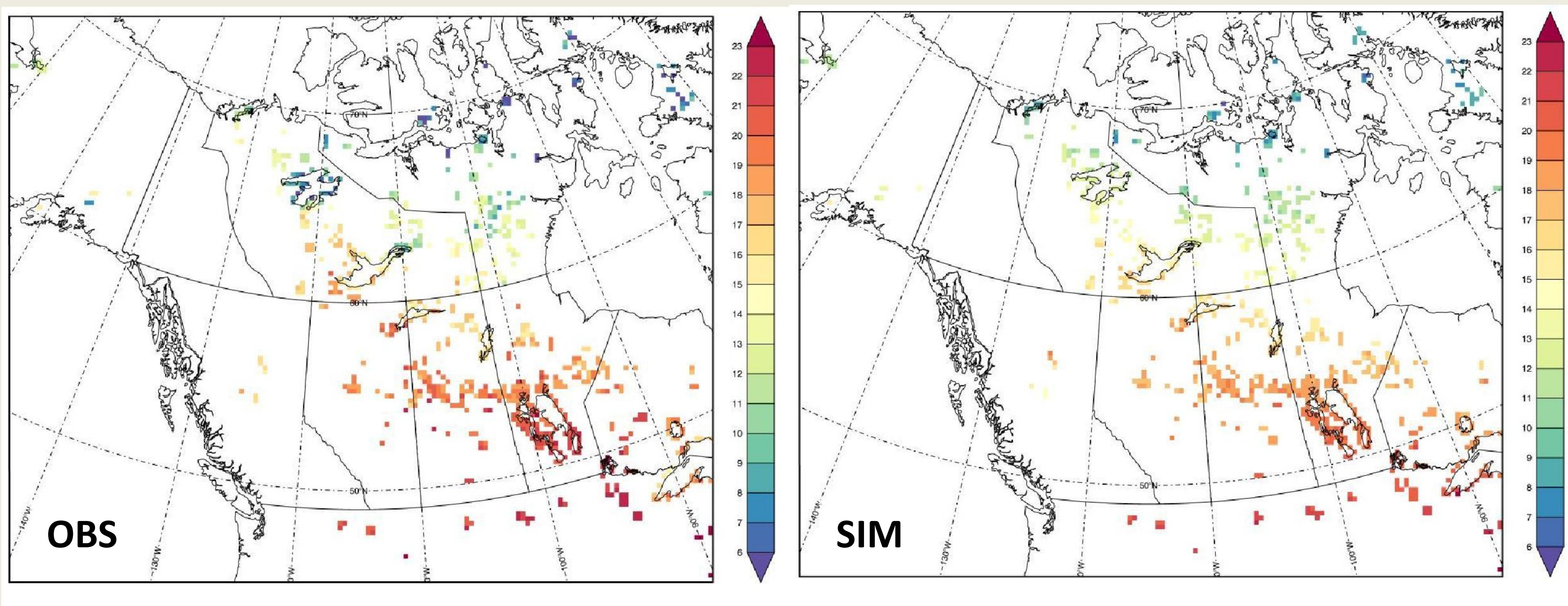


Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Surface Temperature (1995 – 2011)

August

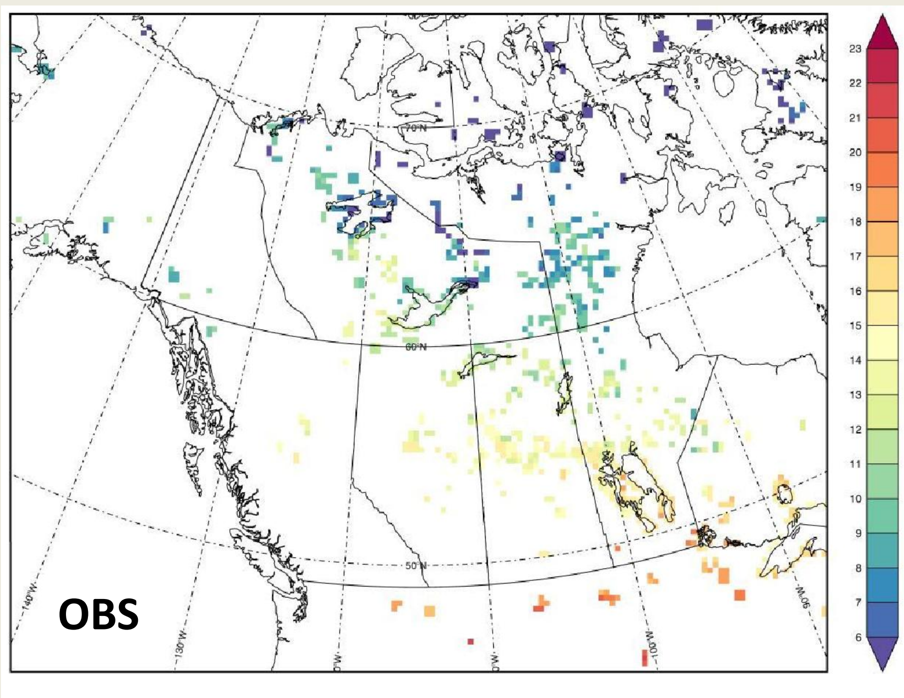


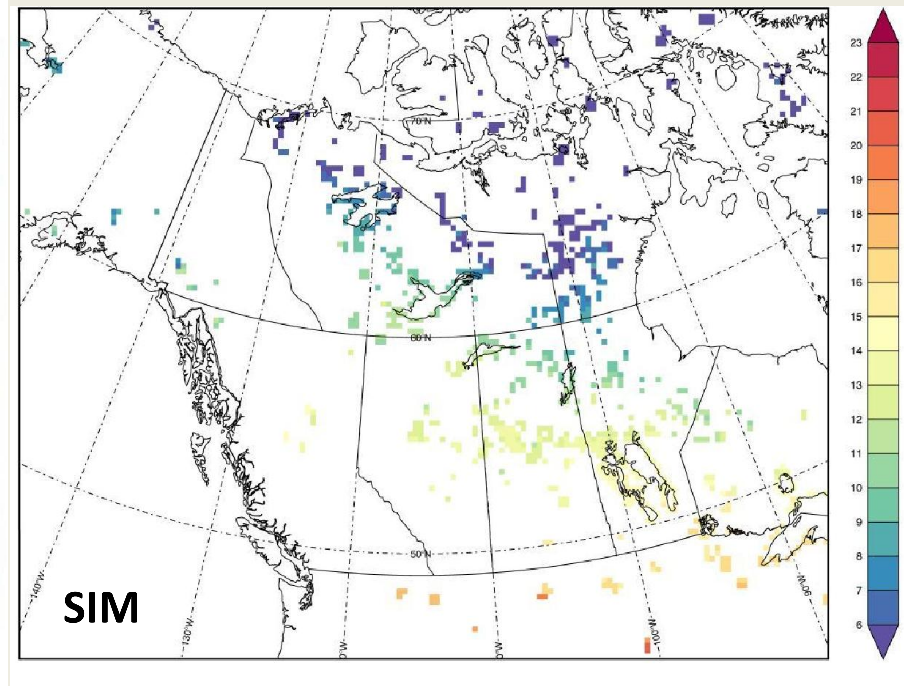
Verseghy and MacKay, 2017

Regional Scale Simulations: Uncoupled Runs

Surface Temperature *(1995 – 2011)*

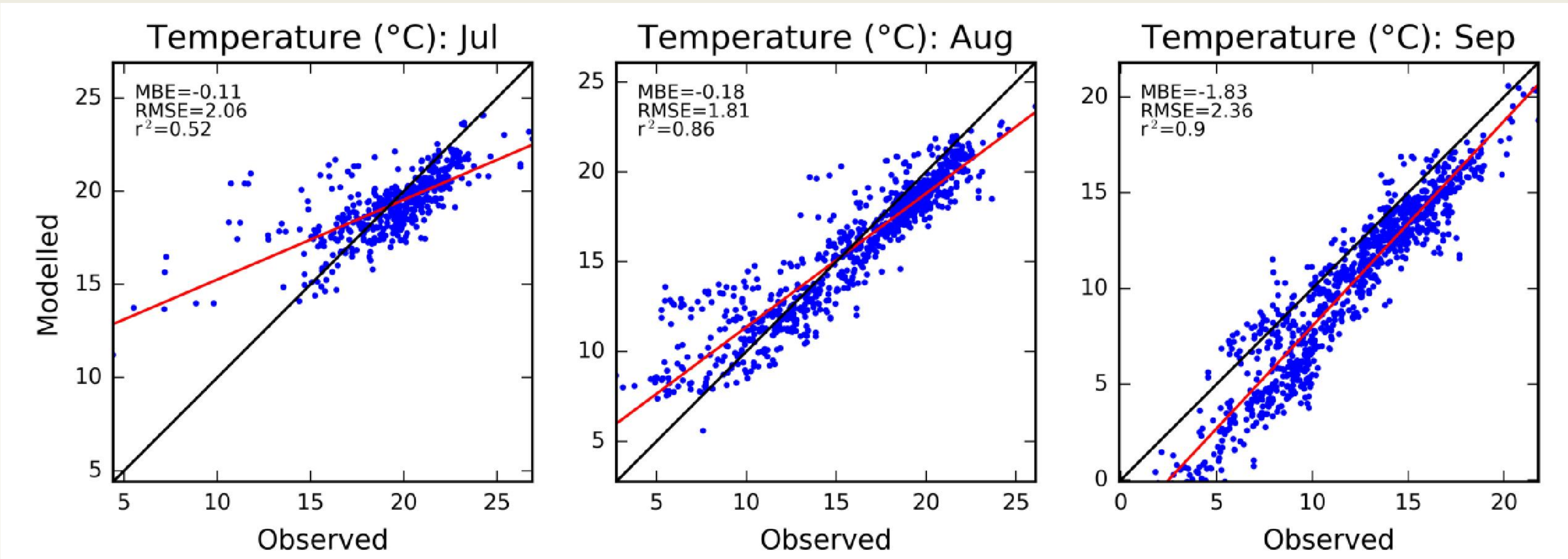
September





Regional Scale Simulations: Uncoupled Runs

Surface Temperature (1995 – 2011)



CONCLUSIONS

The Canadian Small Lake Model

We have developed a stand-alone 1-D thermodynamic lake model incorporating:

- an integrated TKE surface (diurnal) mixed layer model
- the complete snow physics package from the Canadian Land Surface Scheme
- ice physics that include snow-ice production and fractional ice cover

Performance in standalone and uncoupled regional scale tests suggest that this model is suitable for inclusion in NWP and climate prediction systems

- Model code has been implemented into the Canadian Earth System Model (CanESM) in preparation for CMIP6
- Model code is currently being implemented into the Canadian forecasting system GEM, as well as the Canadian Land Data Assimilation System CaLDAS.