Lake Ice Modelling: Predictions and Projections

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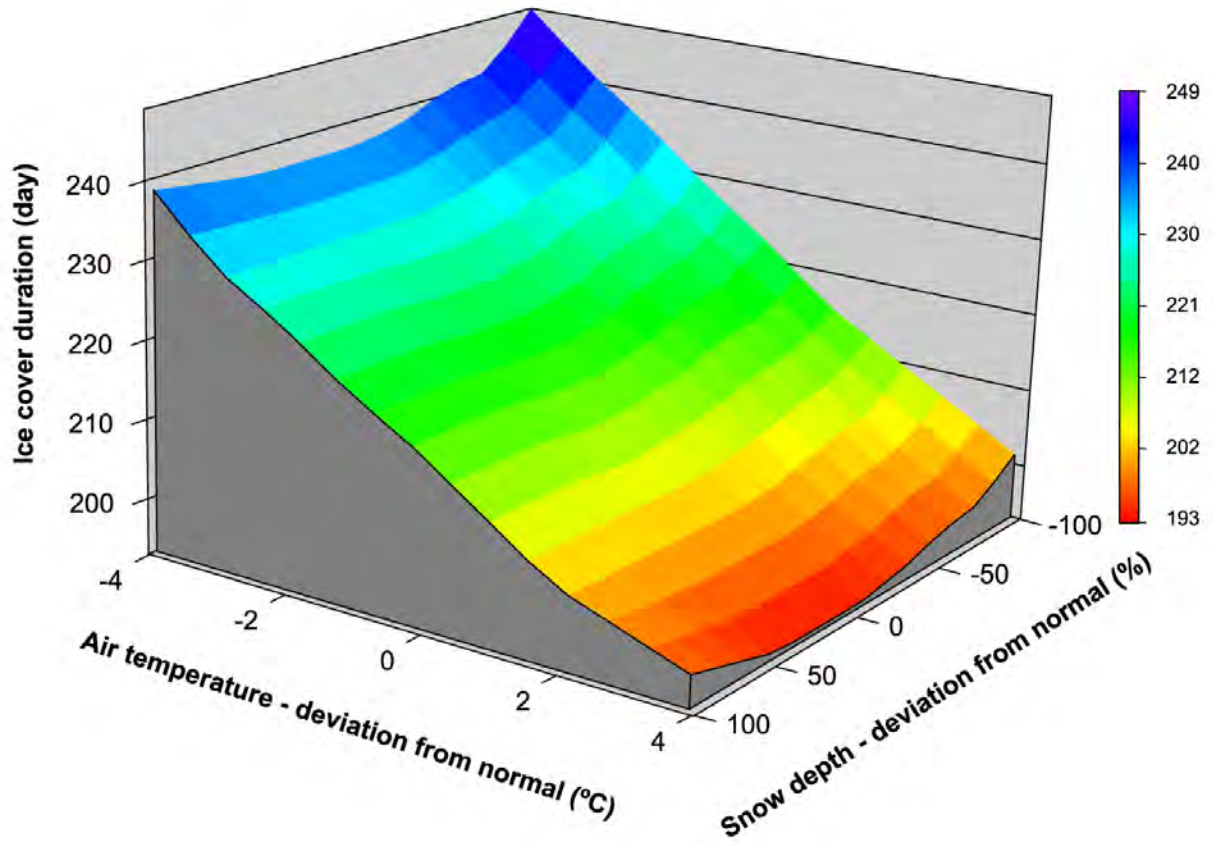
Why use lake (ice) models?

- Lake ice models are a useful complement to ground-based and satellite observations for studying the effect of climate on lake ice phenology, thickness and type.

Models allow one to:

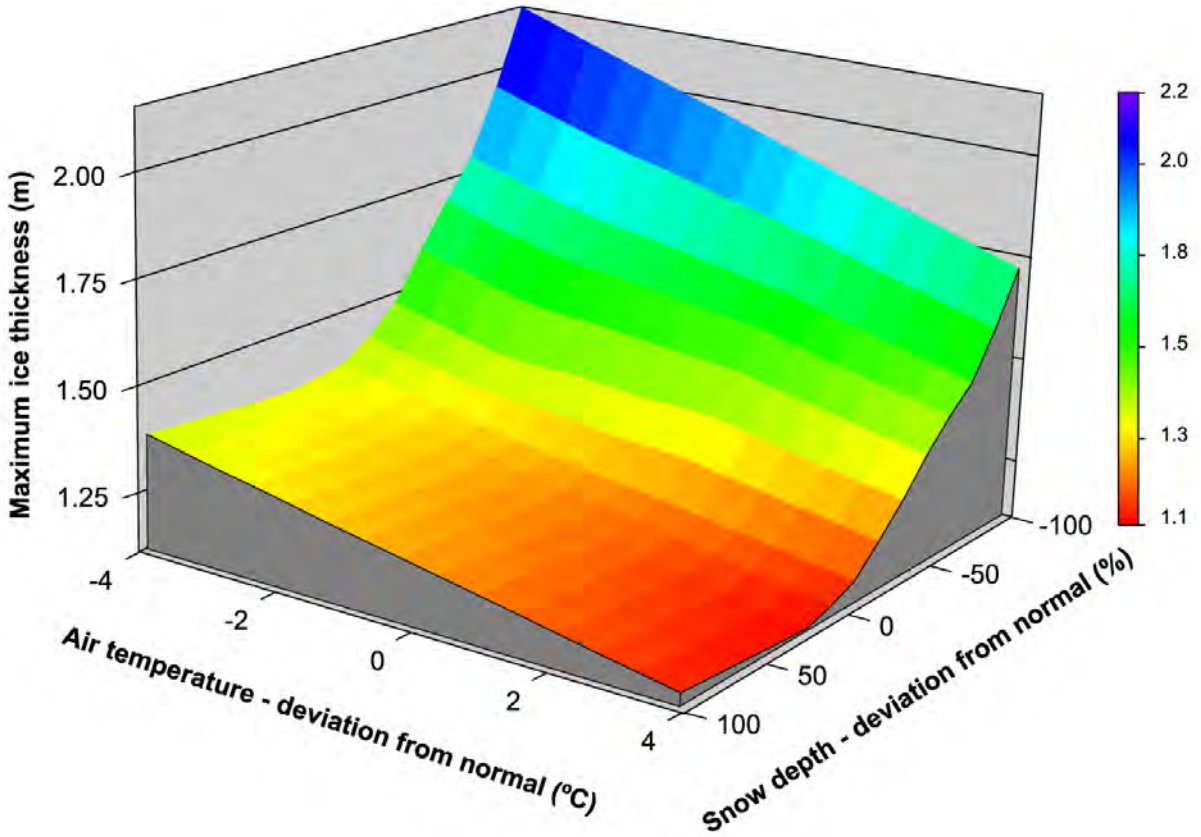
1) ascertain what climatic variables are reflected in freeze-up/break-up dates and hence how one might use freeze-up/break-up observations as an adjunct to **more conventional (e.g. air temperature and precipitation) climate monitoring** in data sparse areas;
2) understand **sources of uncertainty** or complications in interpreting freeze-up and break-up data (e.g. confounding effects of temperature and snowfall);
3) estimate the magnitude of natural variability in ice dates and thickness for use in climate change detection studies; and
4) estimate potential **impacts of changing climate (projections)** on ice dates, ice thickness and ice type (congelation ice versus snow-ice).

Impact of changes in air temperature and snow depth on ice cover duration



From 1-D thermodynamic ice model runs

Impact of changes in air temperature and snow depth on maximum ice thickness



From 1-D thermodynamic ice model runs

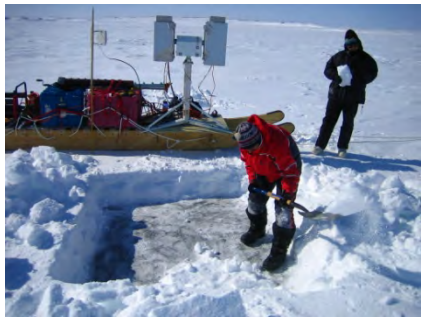
Lake ice model – CLIMo

INPUT

- Air Temperature
- Relative Humidity
- Wind Speed
- Cloud Amount
- Snow Accumulation

CLIMo

0% and 100 % snow scenarios



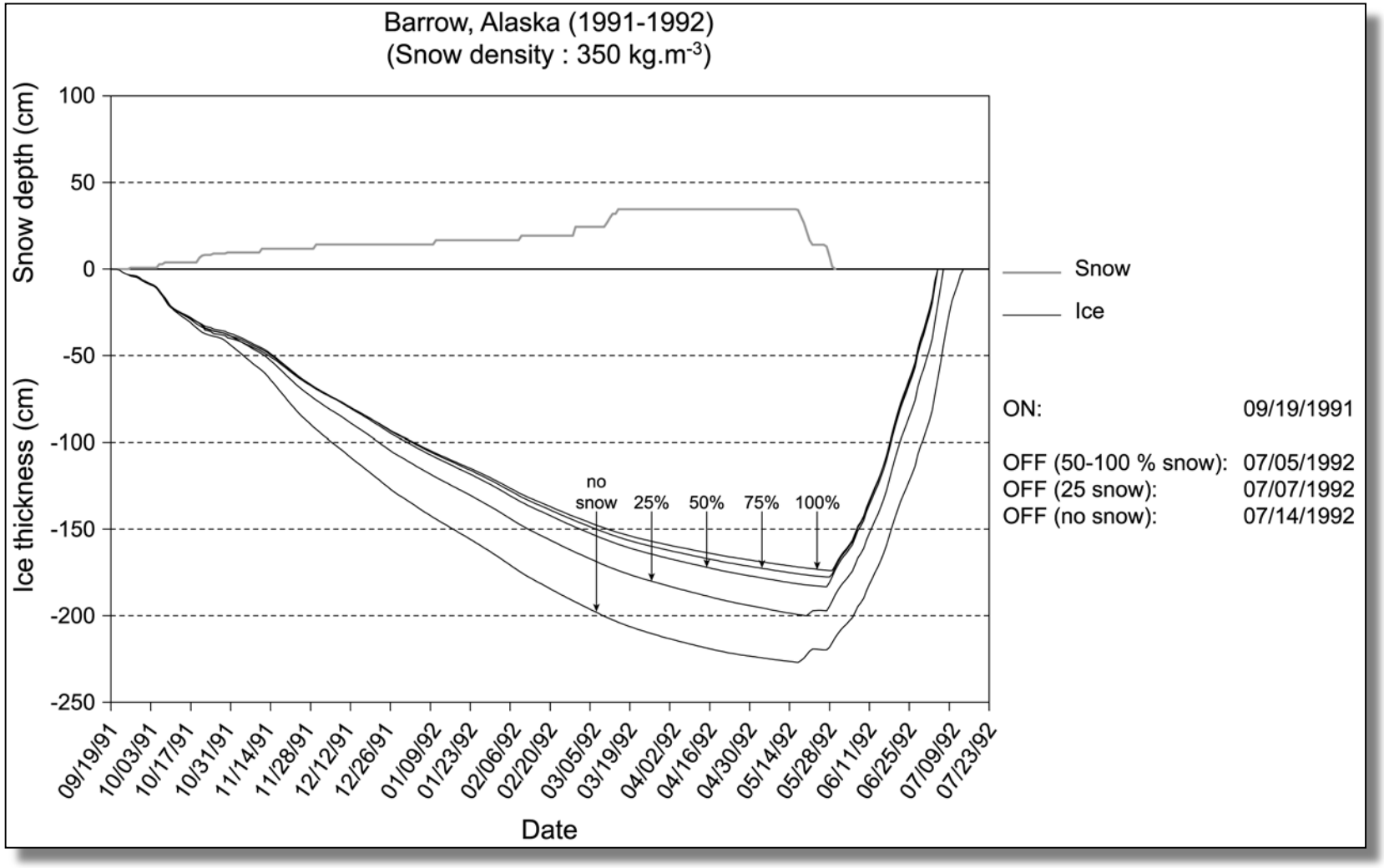
OUTPUT

- Freeze-up/Break-up dates
- On-ice Snow Depth
- Ice Thickness (Snow/Clear Ice)
- Temperature Profile (ice and water temperature during the ice-free period)
- Energy Balance Components

Duguay *et al*. (2003) and subsequent papers (adaptation of one-dimensional thermodynamic sea ice model of Flato & Brown, 1996, to lakes – with changes to snow and albedo parameterizations)

Lake ice model – CLIMo

Validation – Small, shallow, lakes (Barrow, Alaska)



Ice thickness (April 19-29, 1992)

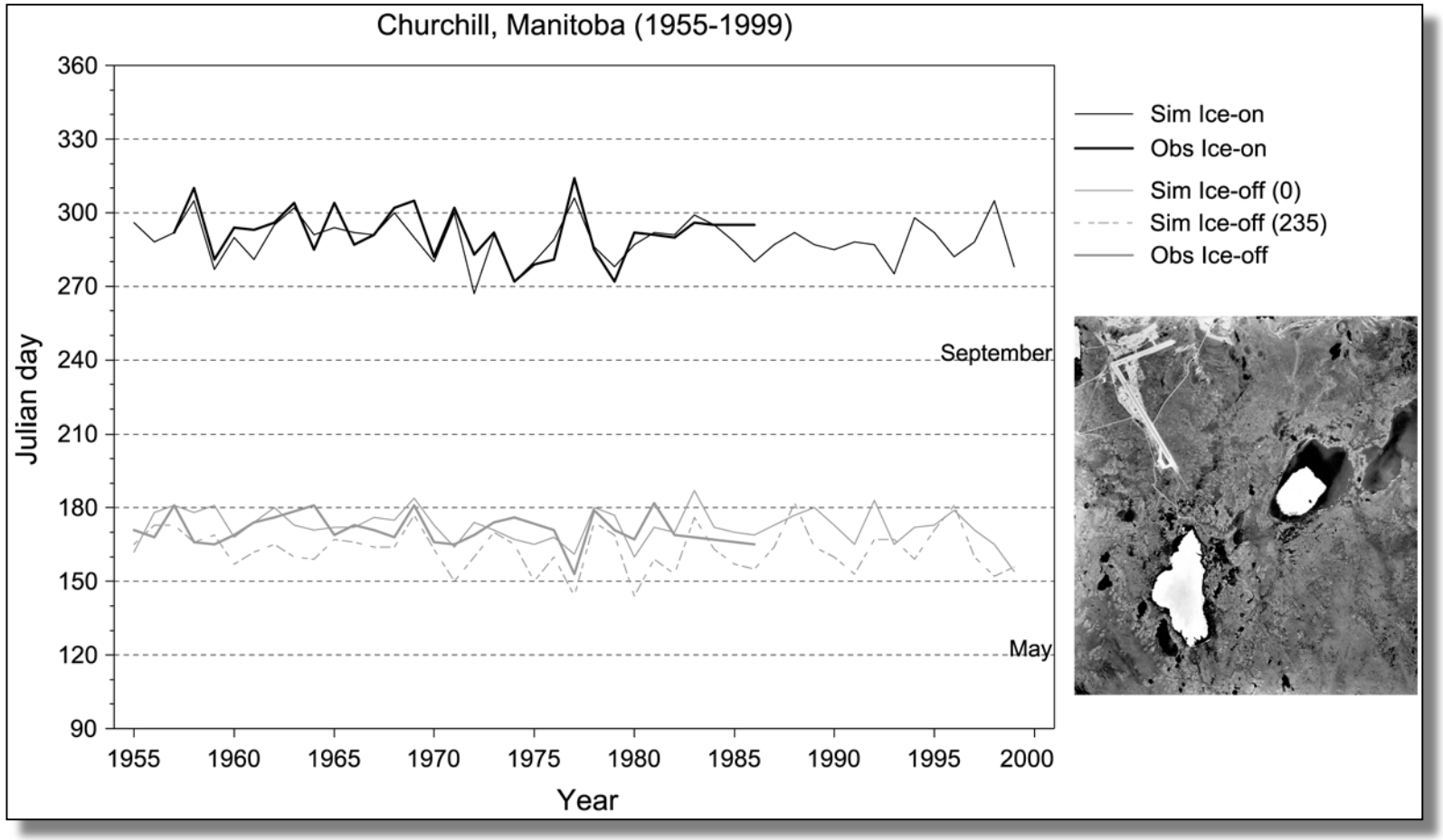
Simulated (100% snow to 0): 1.65-2.21 m

Observed: 1.59-2.16 m

(Source: Jeffries et al., 1994)

Lake ice model – CLIMo

Validation – Farnworth Lake (Churchill, Manitoba)



Simulated vs Observed (ice-on and ice-off) = 2 days

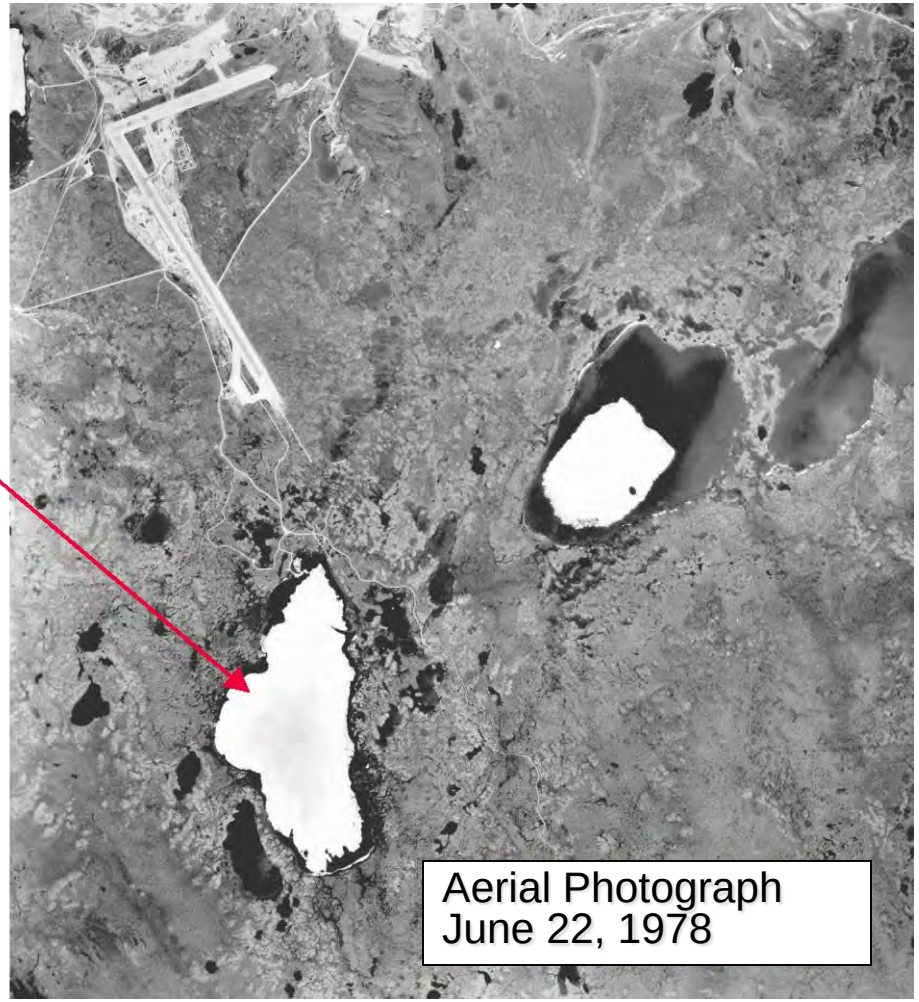
Lake ice model – CLIMo

Validation – Farnworth Lake (Churchill, Manitoba)

Ice-off date

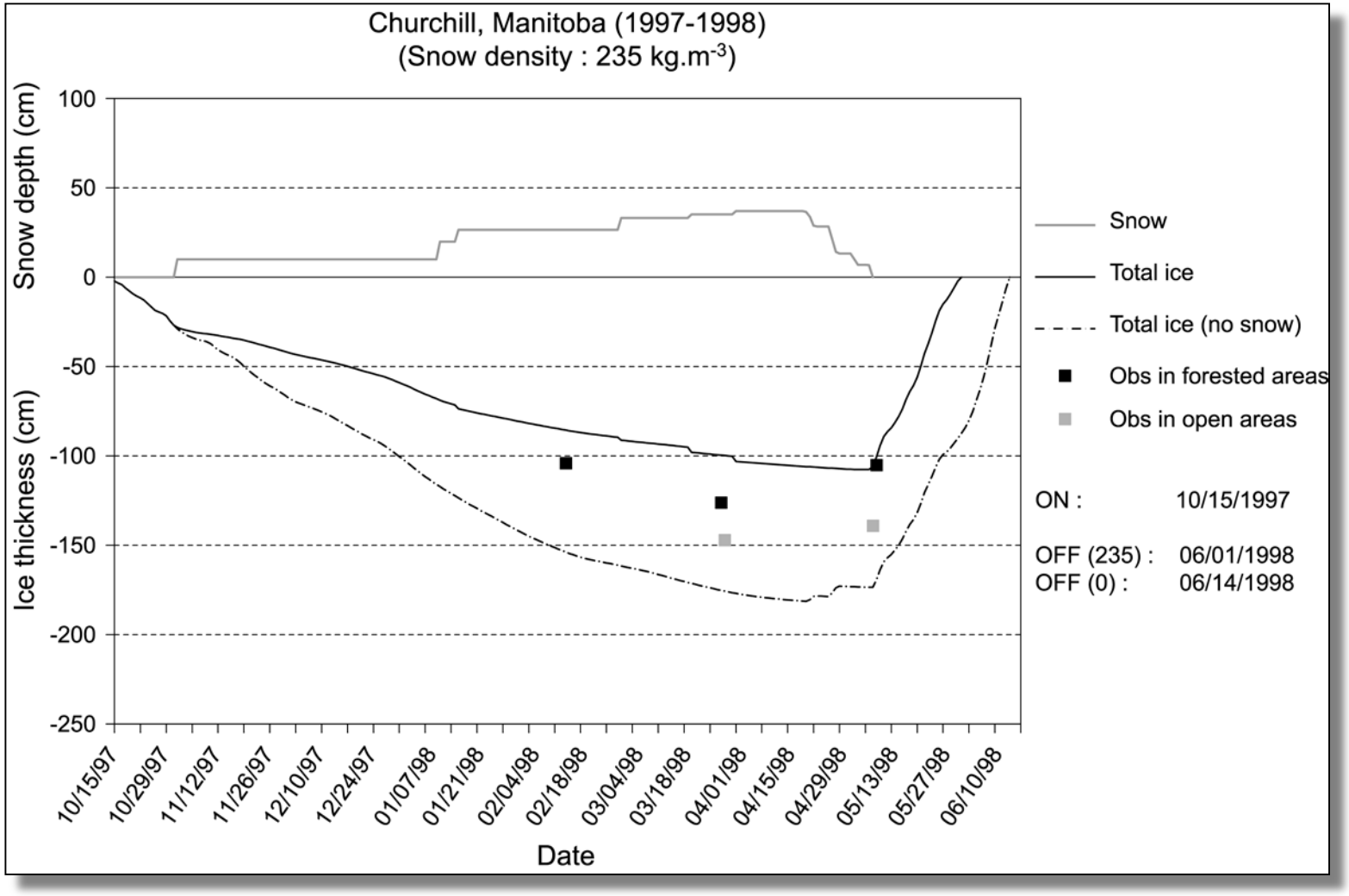
Simulated: June 23-29, 1978

Observed: June 28, 1978



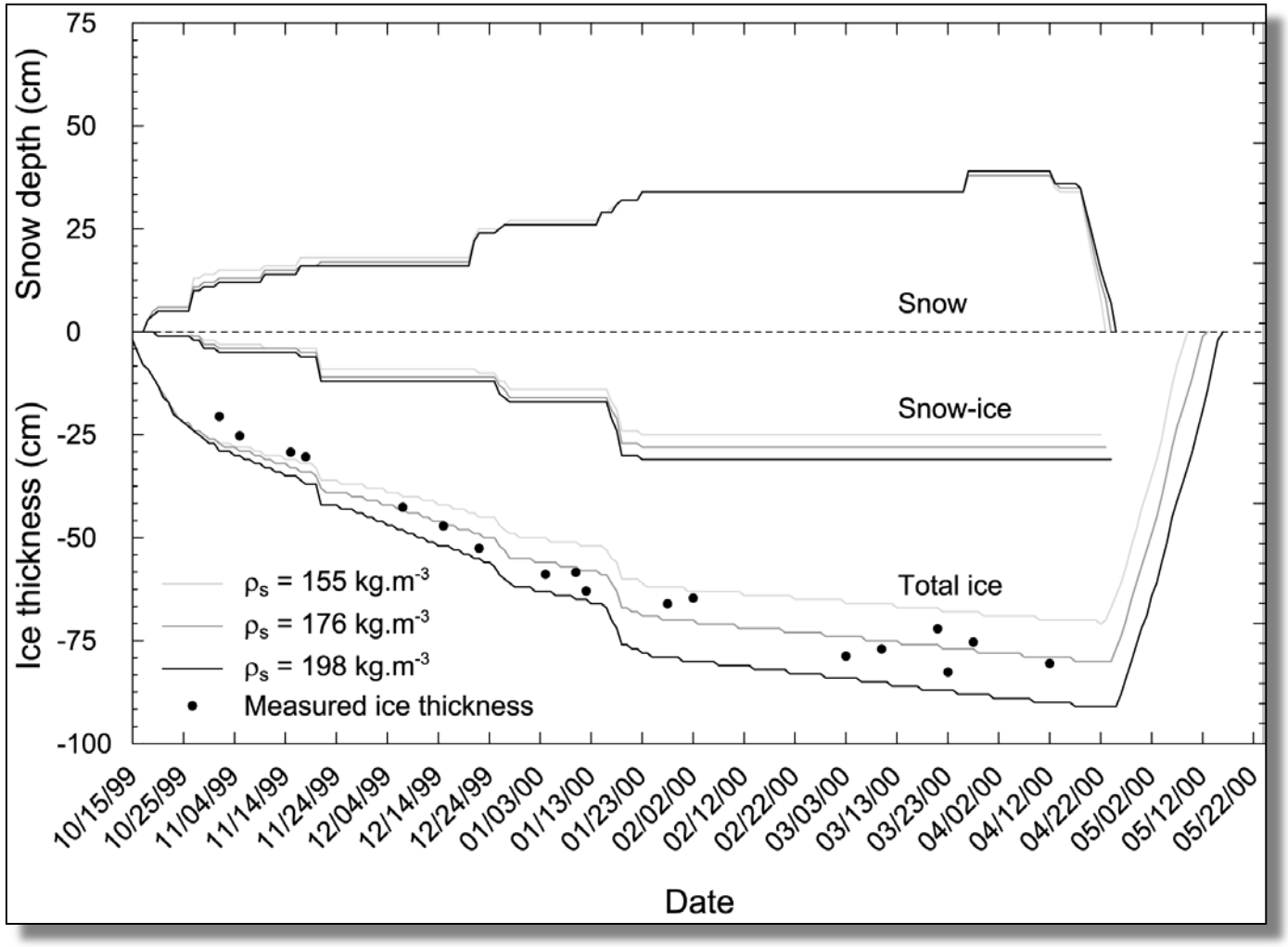
Lake ice model – CLIMo

Validation – Small, shallow, lakes (Churchill, Manitoba)



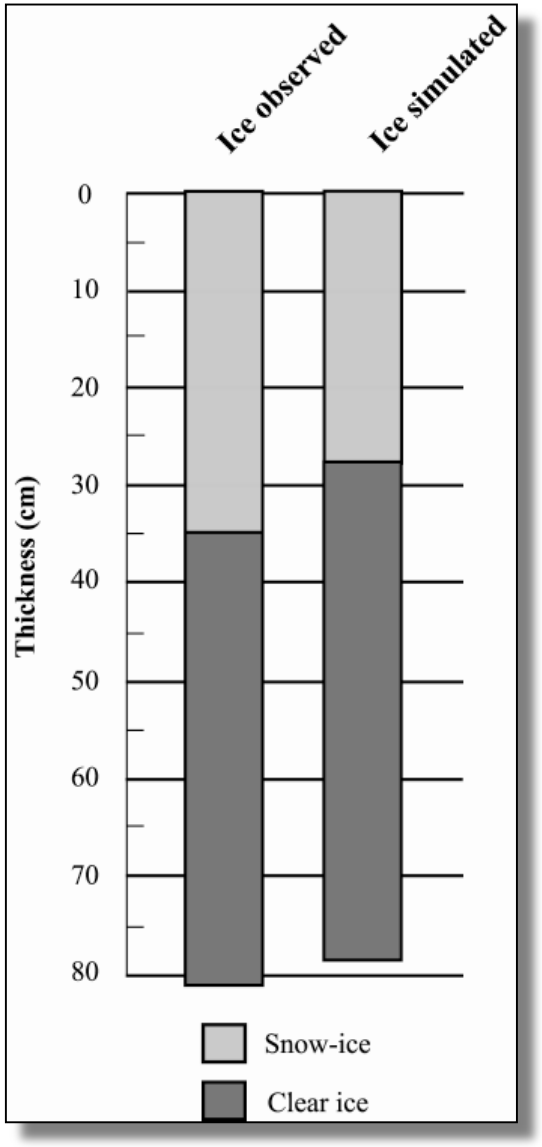
Lake ice model – CLIMo

Validation – Small, shallow, lakes/ponds (Poker Flat, Alaska)



Lake ice model – CLIMo

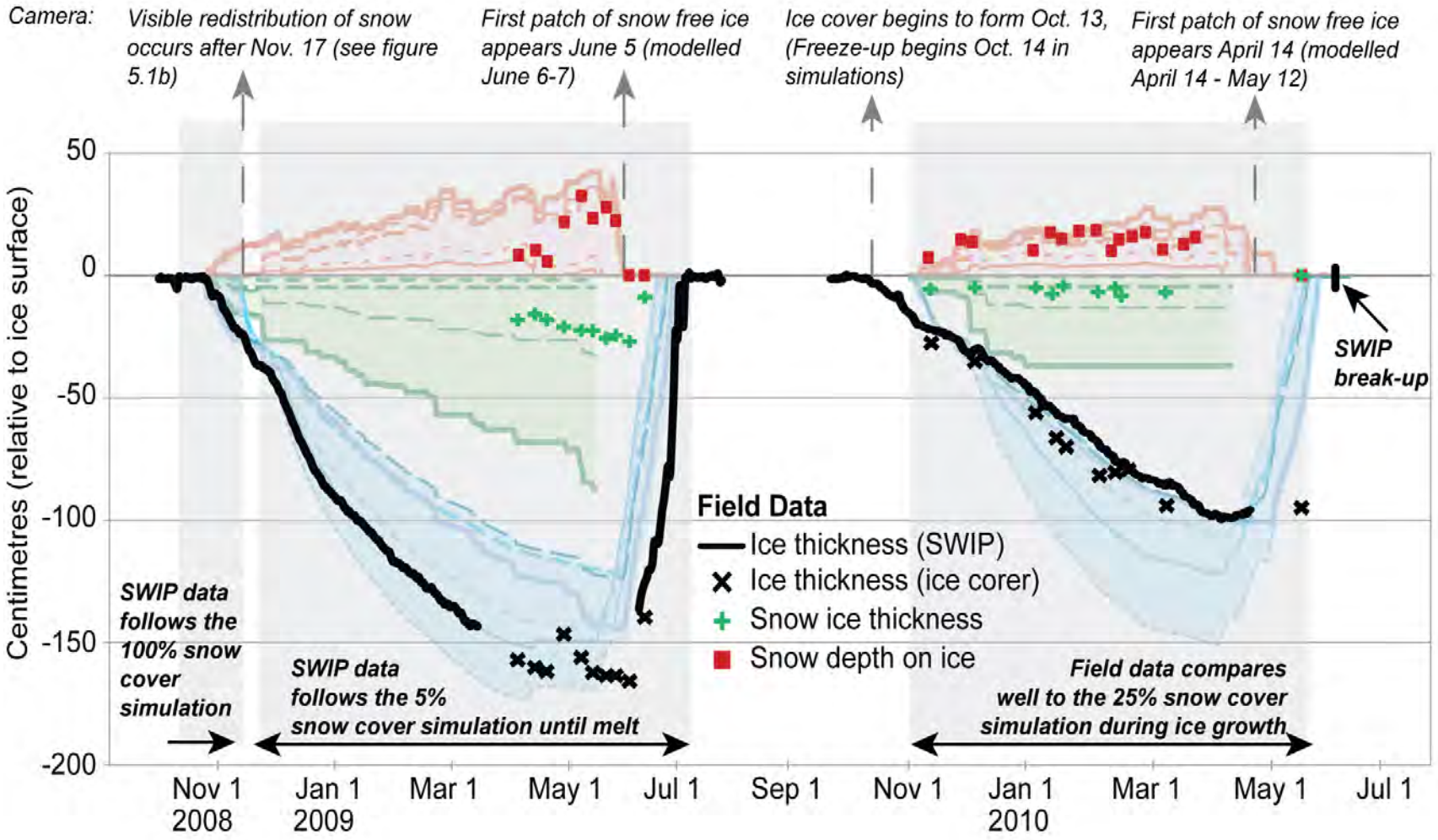
Validation – Small, shallow, lakes/ponds (Poker Flat, Alaska)



- Underestimation of snow-ice formation

Lake ice model – CLIMo

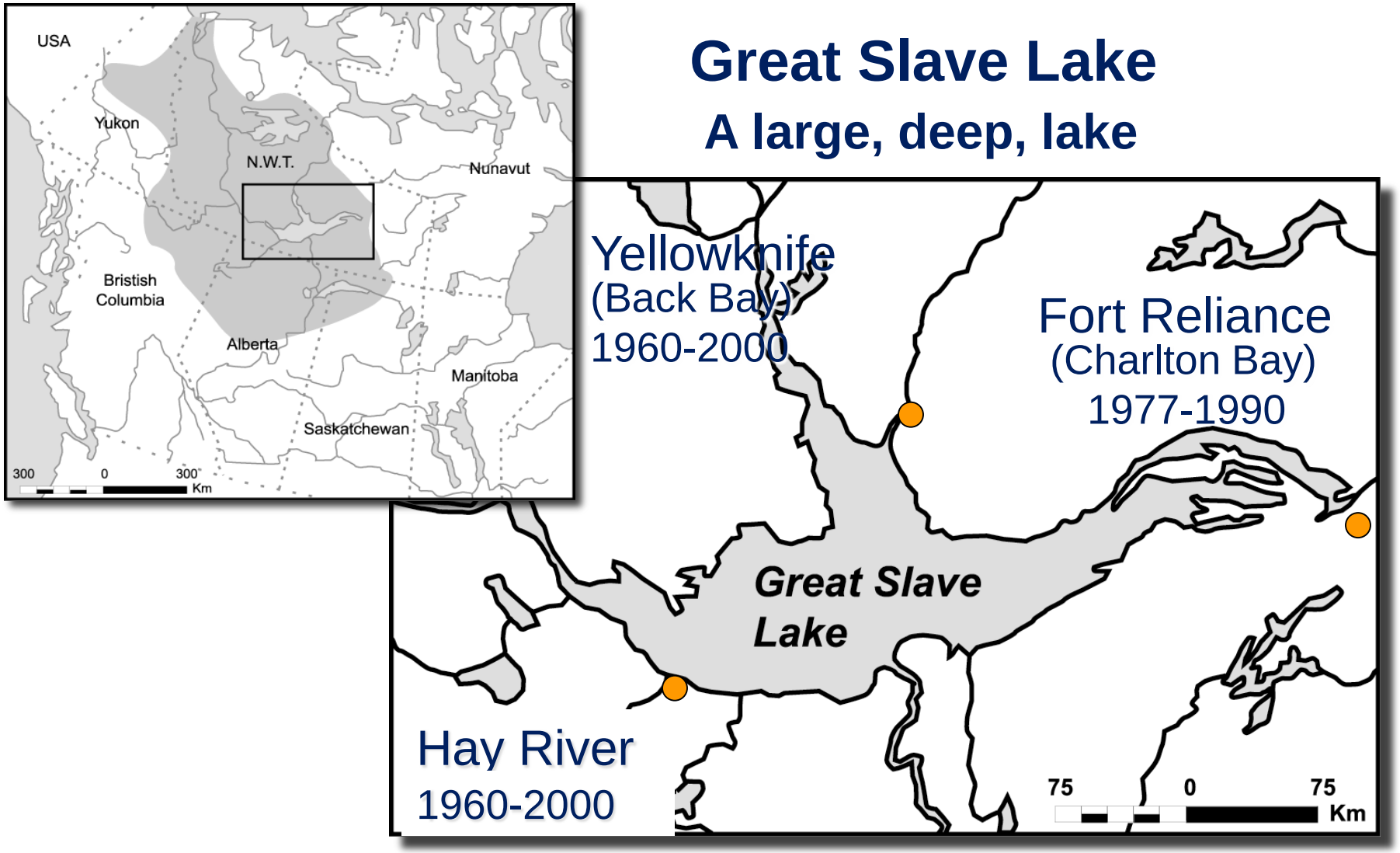
Validation – Malcolm Ramsay Lake (Churchill, Manitoba)



Brown and Duguay (2011)

Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)



Lake ice model – CLIMo

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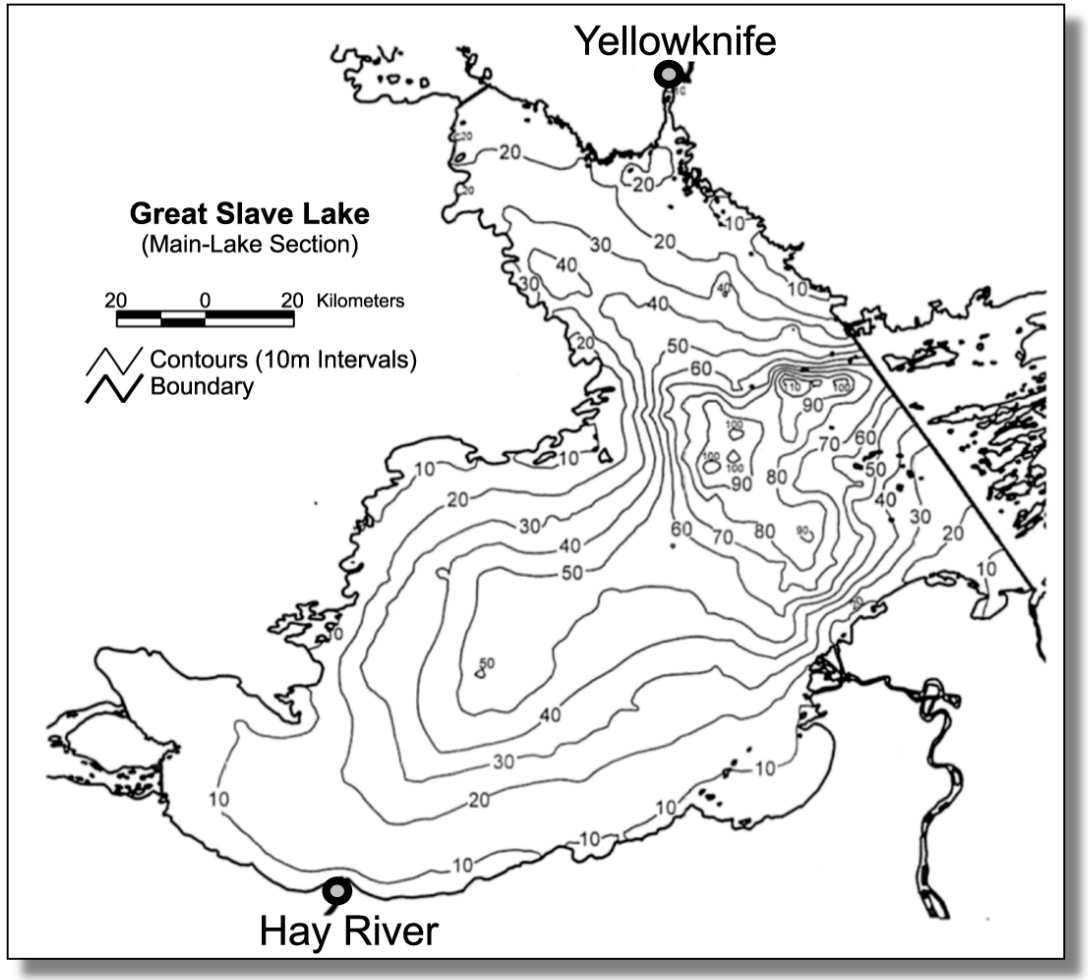
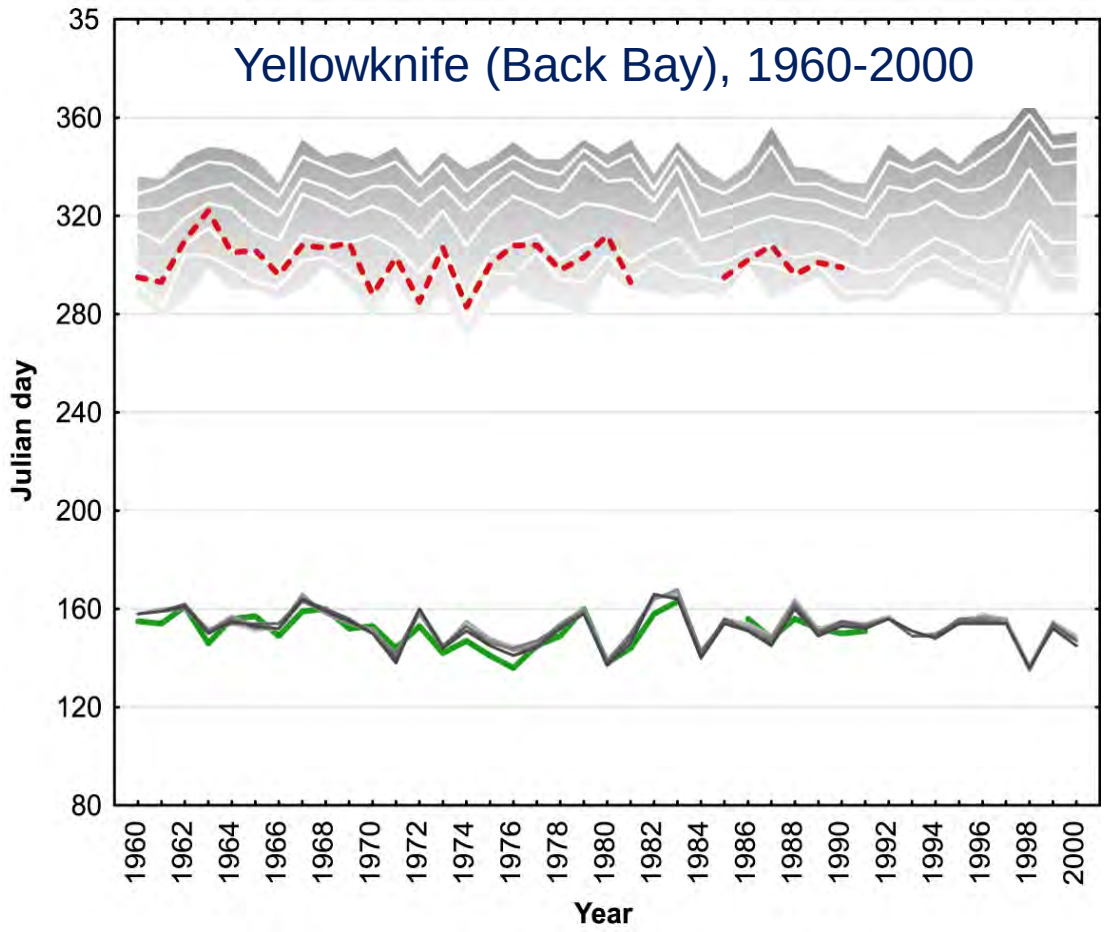
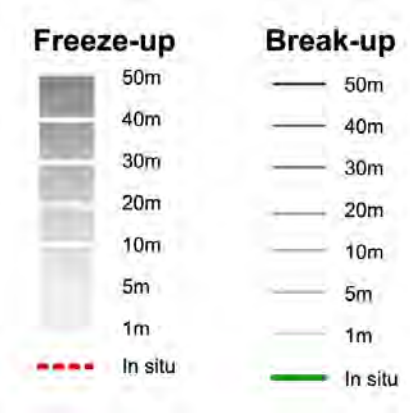


Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)





Freeze-up

I_a	0.996
RMSE	6
MBE	6

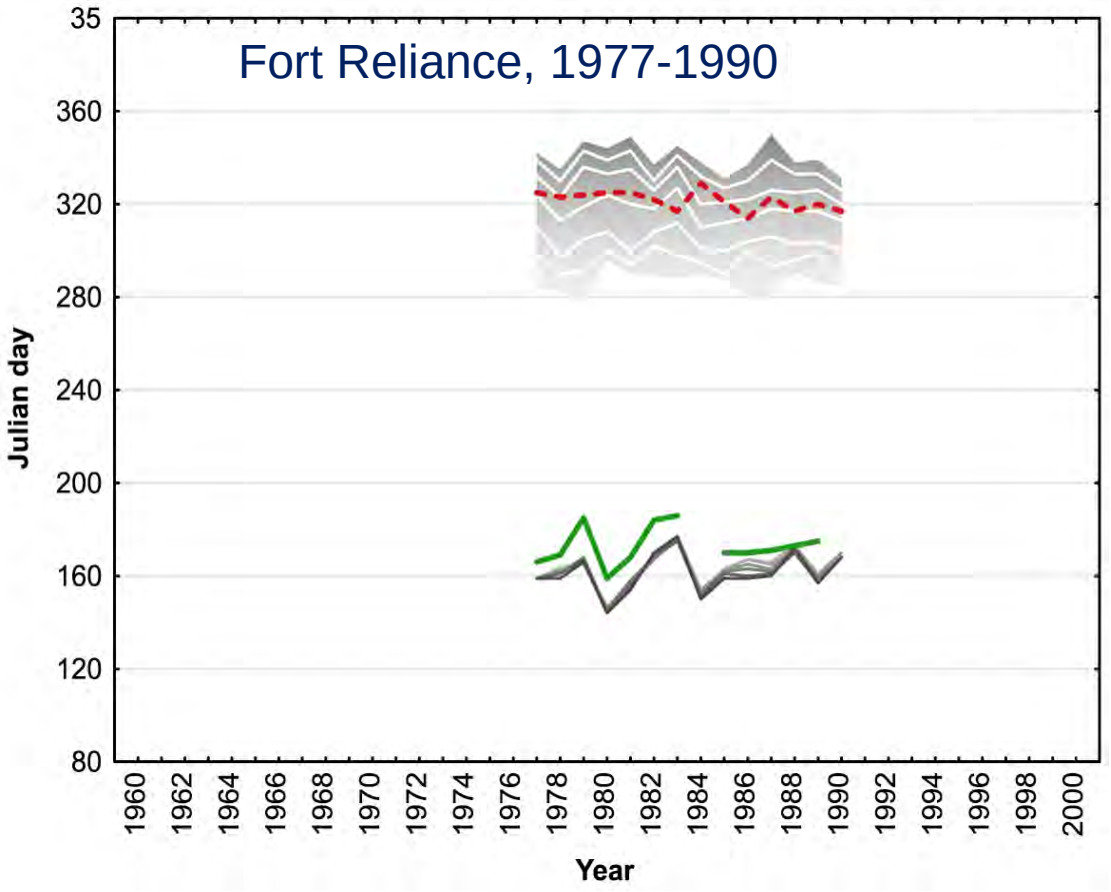
Break-up

I_a	0.901
RMSE	4
MBE	4

I_a: relative index of agreement, RMSE: root mean square error (day), MBE: mean bias error (day)

Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)



Freeze-up

I_a	0.891
RMSE	4
MBE	3

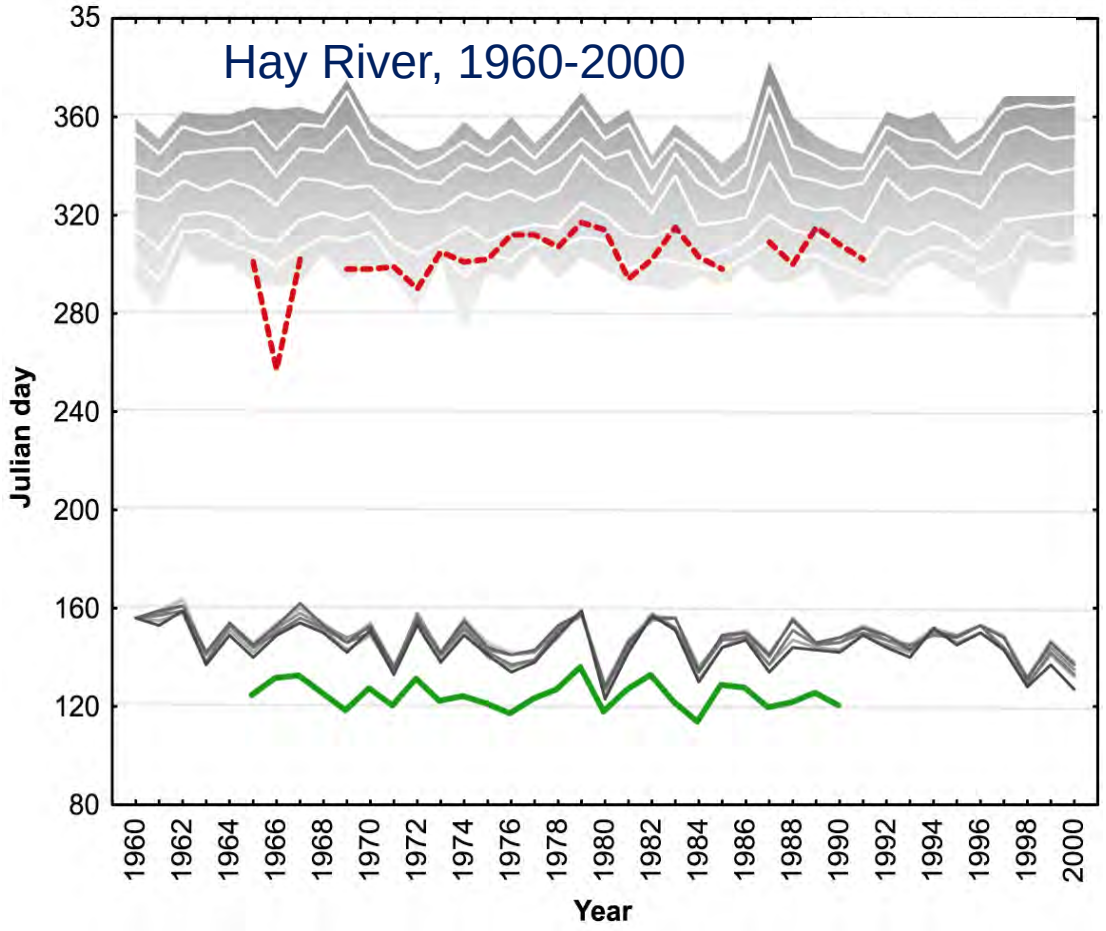
Break-up

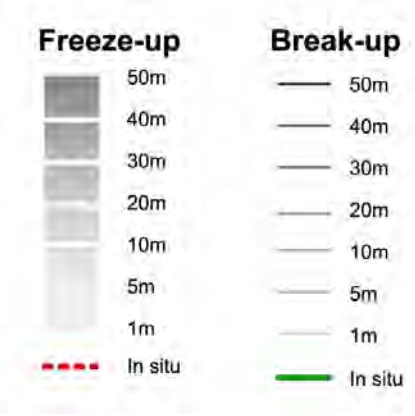
I_a	0.998
RMSE	11
MBE	-10

I_a: relative index of agreement, RMSE: root mean square error (day), MBE: mean bias error (day)

Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)





Freeze-up

I_a	0.516
RMSE	6
MBE	5

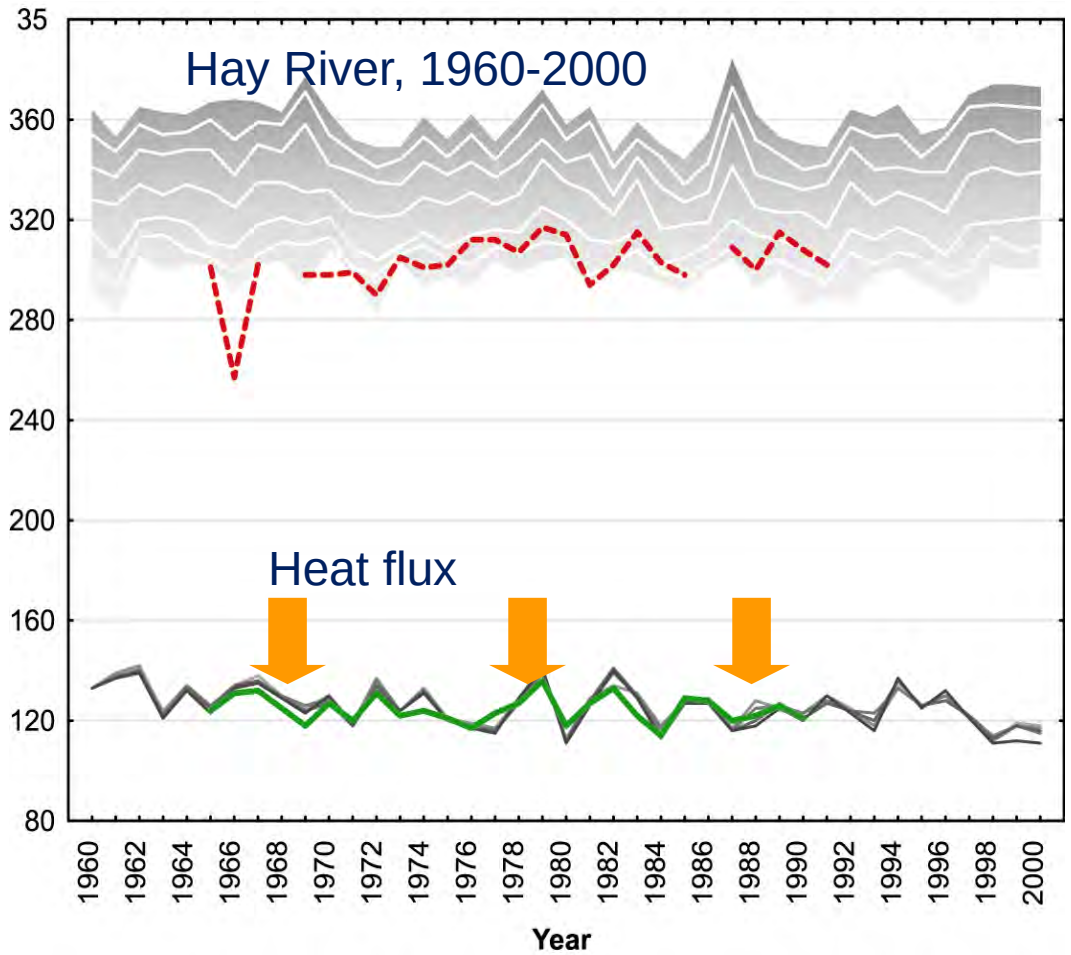
Break-up

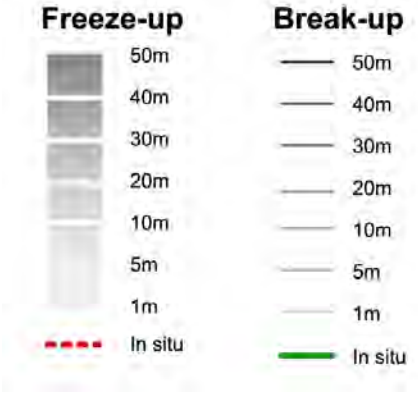
I_a	0.903
RMSE	23
MBE	23

I_a: relative index of agreement, RMSE: root mean square error (day), MBE: mean bias error (day)

Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)





Freeze-up

I_a	0.505
RMSE	6
MBE	5

Break-up

I_a	0.999
RMSE	6
MBE	-4

I_a: relative index of agreement, RMSE: root mean square error (day), MBE: mean bias error (day)

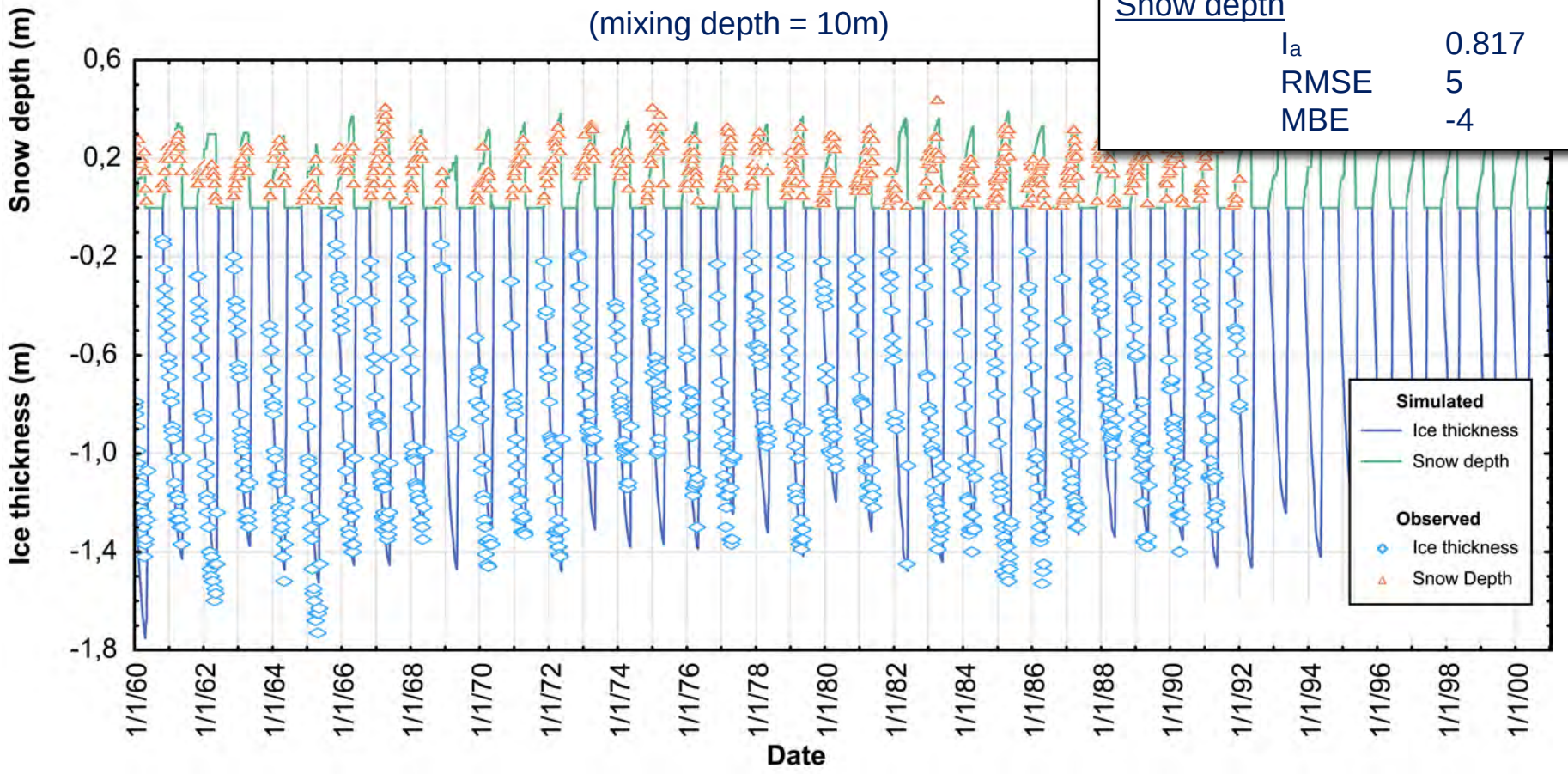
Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)

Yellowknife (Back Bay), 1960-2000

(mixing depth = 10m)

Ice thickness		
	I_a	0.943
	RMSE	9
	MBE	6
Snow depth		
	I_a	0.817
	RMSE	5
	MBE	-4



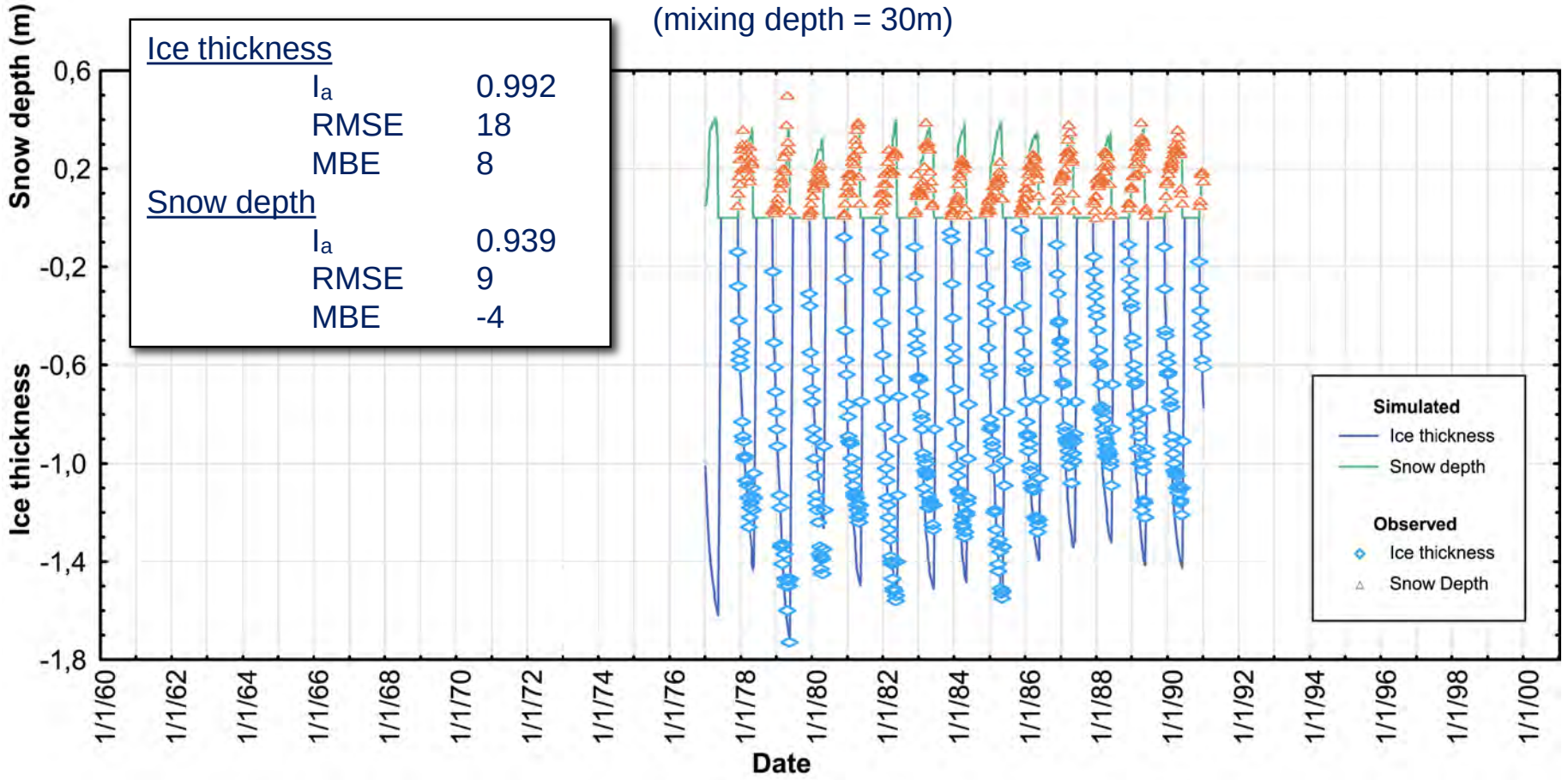
I_a: relative index of agreement, RMSE: root mean square error (cm), MBE: mean bias error (cm)

Lake ice model – CLIMo

Validation – Great Slave Lake (NWT)

Fort Reliance, 1977-1990

(mixing depth = 30m)



I_a: relative index of agreement, RMSE: root mean square error (cm), MBE: mean bias error (cm)

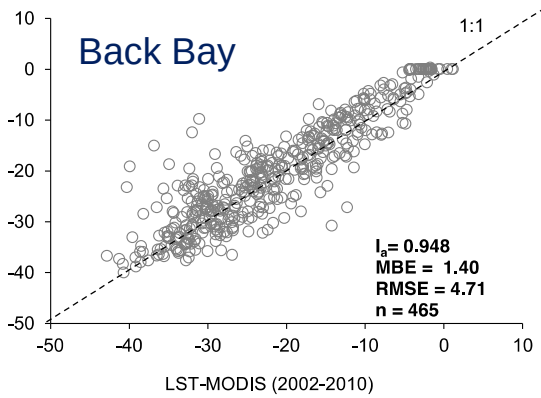
Lake (ice) models – CLIMo vs FLake

Great Slave Lake (NWT)

Snow/ice surface temperature

CLIMo

Back Bay

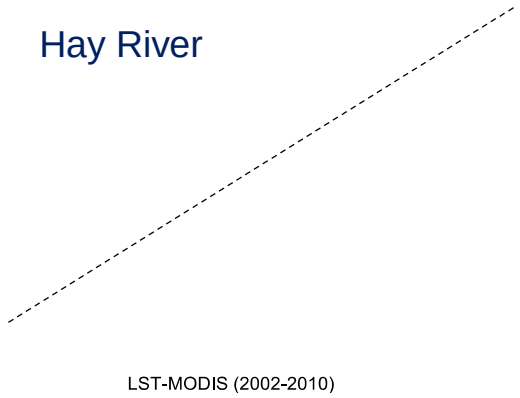


Hay River

FLake*

Back Bay

Hay River



MODIS LST
vs
1-D lake models

Comparison for 2 sites at Great Slave Lake

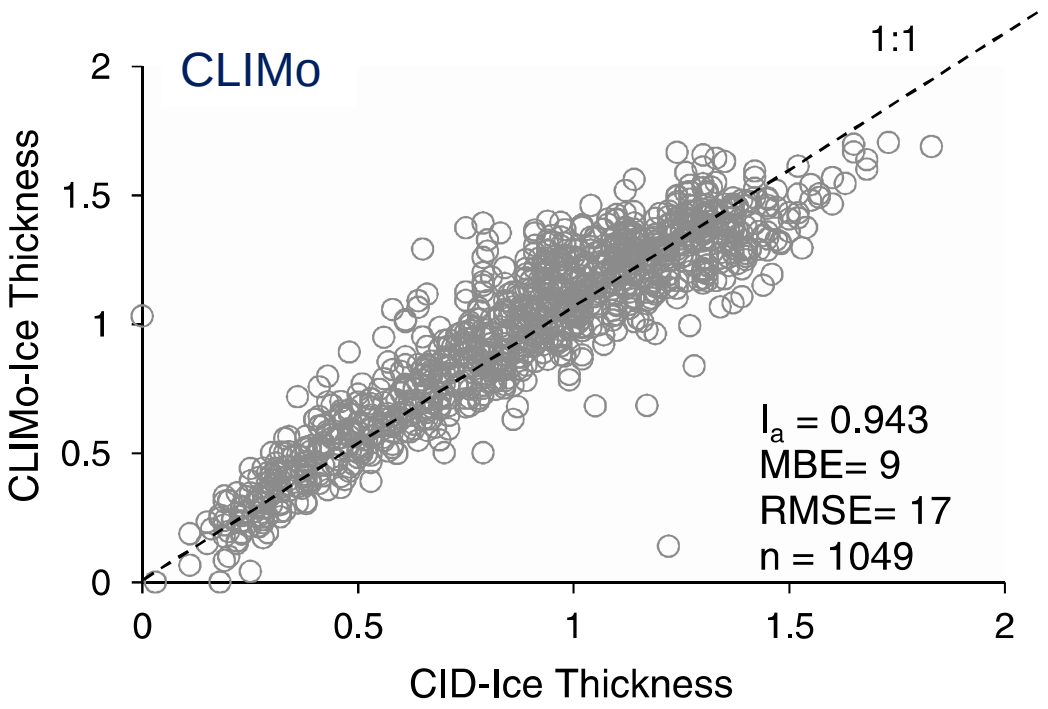
* FLake used as lake parameterization scheme in NWP and RCM

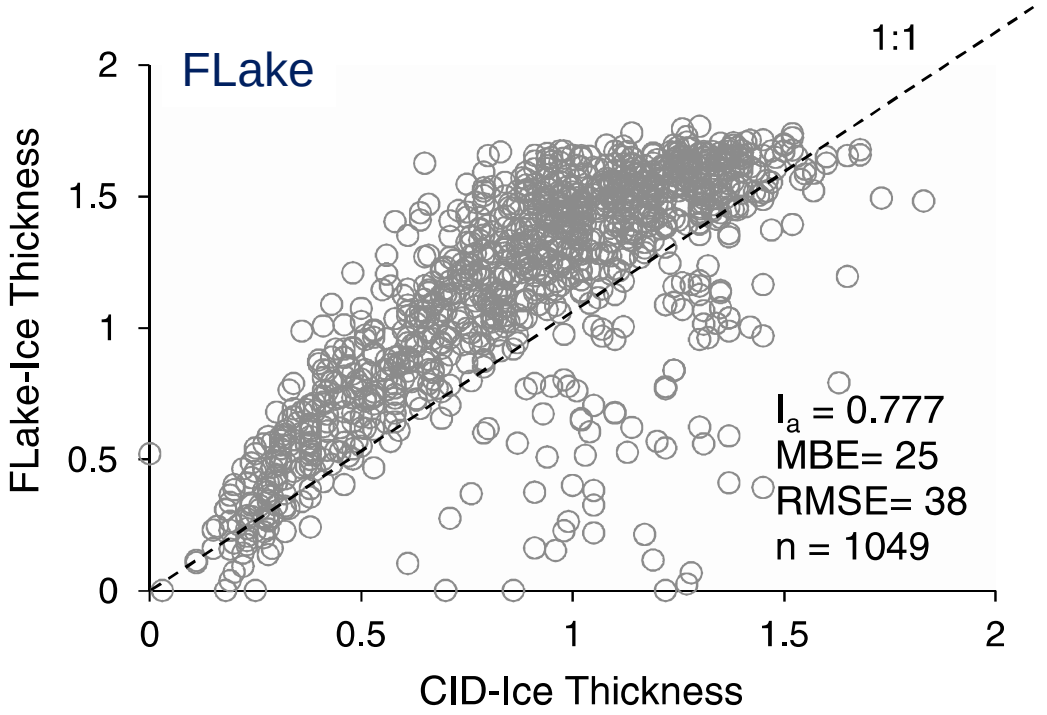
Kheyrollah Pour *et al.* (2012)

Lake (ice) models – CLIMo vs FLake

Great Slave Lake (NWT)

Ice thickness



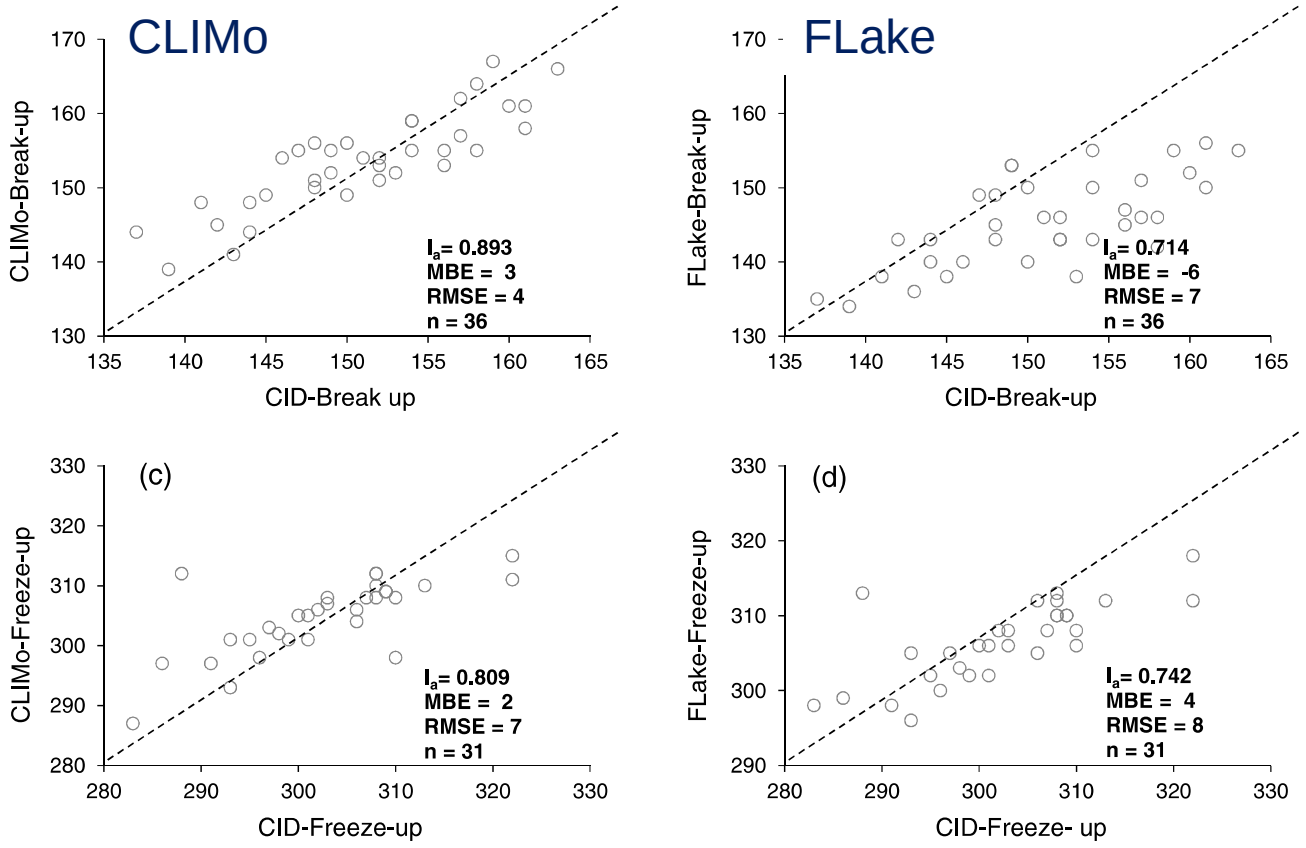


Kheyrollah Pour *et al.* (2012)

Lake (ice) models – CLIMo vs FLake

Great Slave Lake (NWT)

Break-up/Freeze-up

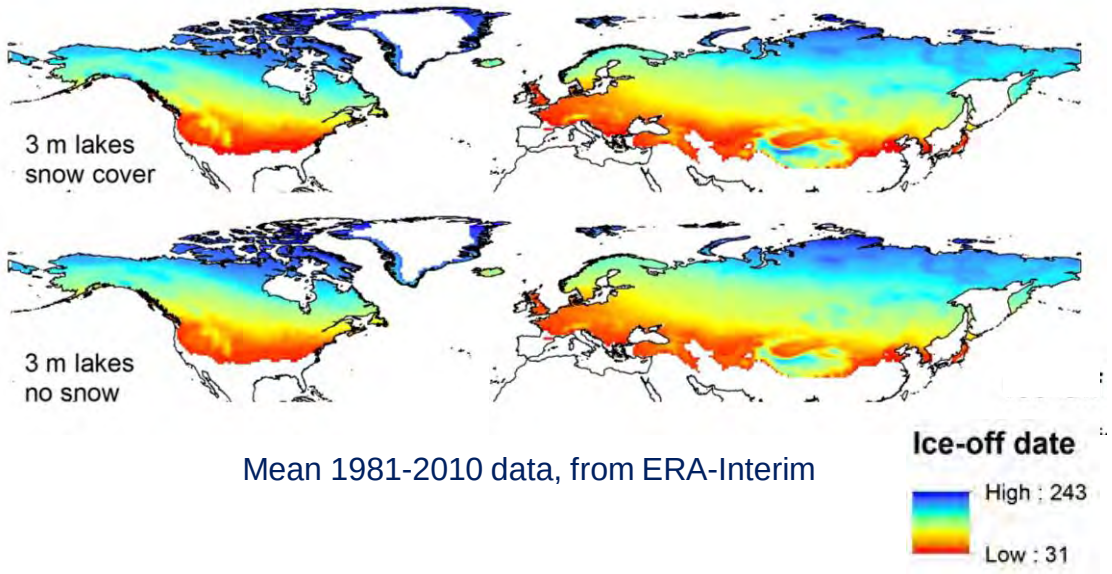


	CLIMo	FLake
Ice thickness		
I_a	0.943	0.777
MBE (cm)	9	25
RMSE (cm)	17	38
Break-up		
I_a	0.893	0.714
MBE (days)	3	–6
RMSE (days)	4	7
Freeze-up		
I_a	0.809	0.742
MBE (days)	2	3
RMSE (days)	7	7

Kheyrollah Pour *et al.* (2012)

Northern Hemisphere Lake Ice Modelling

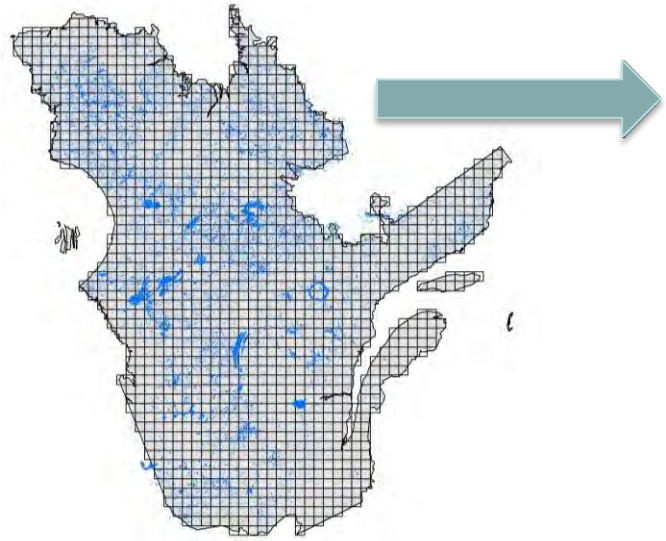
- Lake ice modelling (CLIMo) at the hemispheric scale
  - No longer have a local climate station for one lake with a known depth
  - Use gridded climate data from reanalysis data, or RCMs / GCMs and a set of hypothetical lake depths



Mean 1981-2010 data, from ERA-Interim

Courtesy: Laura Brown

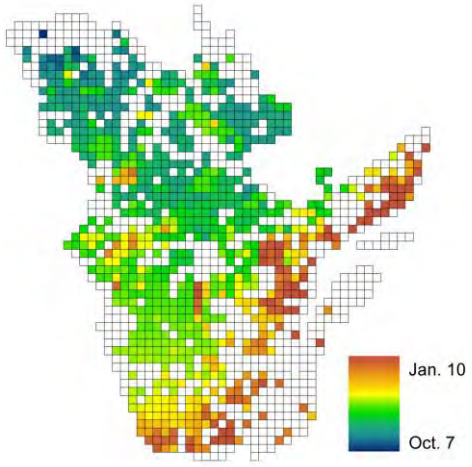
Hypothetical Lakes?

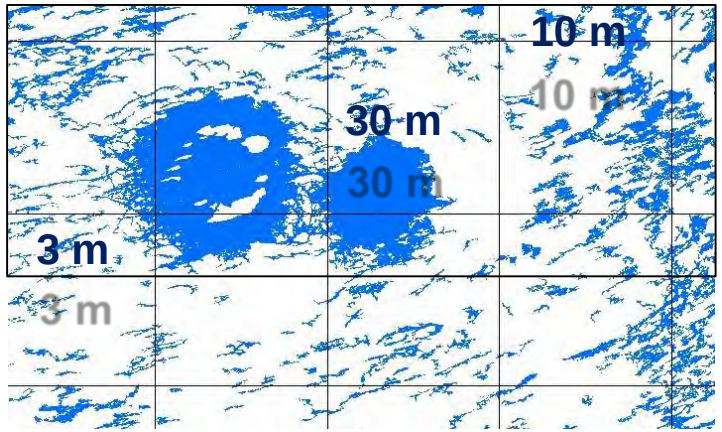


1 set of climate data for each grid cell

↓

1 output of the lake ice model





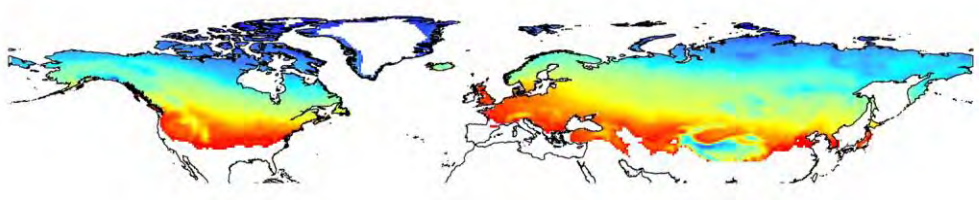
Sub-grid cell lakes

When lake depths are unknown, the best solution is to run multiple simulations to cover representative depths of lakes that *MIGHT* be in that grid cell:

- **3 m – shallow**
- **10 m – medium, or near shore of large lakes**
- **30 m – larger deeper lakes**

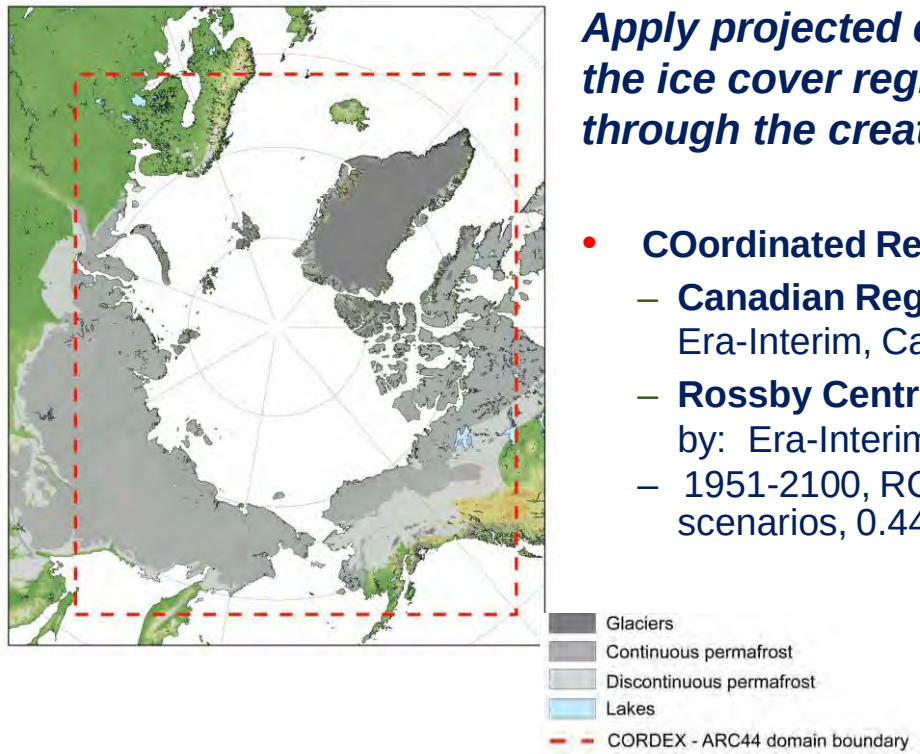
Courtesy: Laura Brown

Input Data – Predictions and Projections



Establish lake ice conditions under historical and contemporary climate conditions

- **ERA-Interim (1979 - 2011)**
- **ERA-40 (1958 - 2001)**
  - ECMWF, Northern Hemisphere domain
  - 0.75° resolution (ERA-40 resampled)
  - Reconstructed ERA-interim snow data: Brown and Derksen, 2013

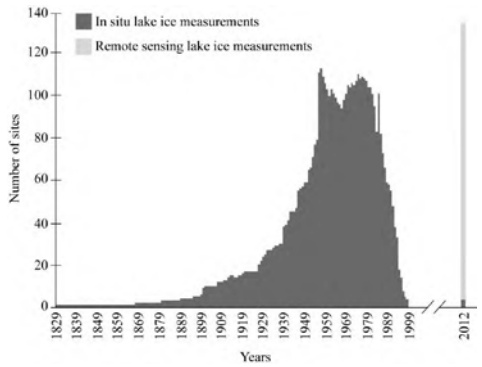


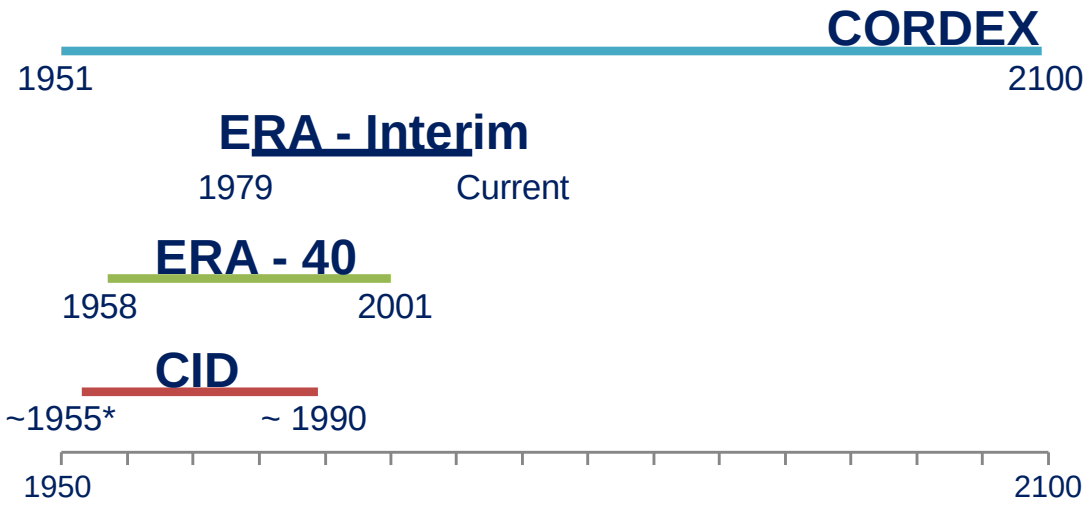
Apply projected climate data to investigate potential changes in the ice cover regimes between 1981-2010 and 2071-2100, through the creation of a small ensemble data set

- **COordinated Regional climate Downscaling EXperiment (CORDEX)**
  - **Canadian Regional Climate Model - CanRCM4 (CCCma)** (driven by: Era-Interim, CanESM2)
  - **Rossby Centre Regional Atmospheric Model – RCA4 (SMHI)** (driven by: Era-Interim, CanESM2, EC-Earth, NorESM1-M, MPI- ESM-LR)
  - 1951-2100, RCP 4.5 (CanRCM4), RCP 8.5 (RCA4, CanRCM4) GHG scenarios, 0.44° (ca. 50 km)

Courtesy: Laura Brown

Model Input and Validation Data





- **Canadian Ice Database (CID) (Lenormand *et al*., 2002)** — In Situ Validation Data
  - National historical database of in situ ice cover (lake ice, river ice, landfast sea ice) from 1822, for 757 sites across Canada (259 Lakes)
- **Canadian Ice Service (CIS)**
  - Snow depth on ice and ice thickness measurements from available lakes
- **CLIMo ice cover simulations driven by Climate Station Data (MSC)**
  - Daily station data (National Climate Data and Information Archive)
  - Canadian Snow CD: station snow depths, extracted station density from gridded density data
  - Homogenized Surface Air Temperature Data where available

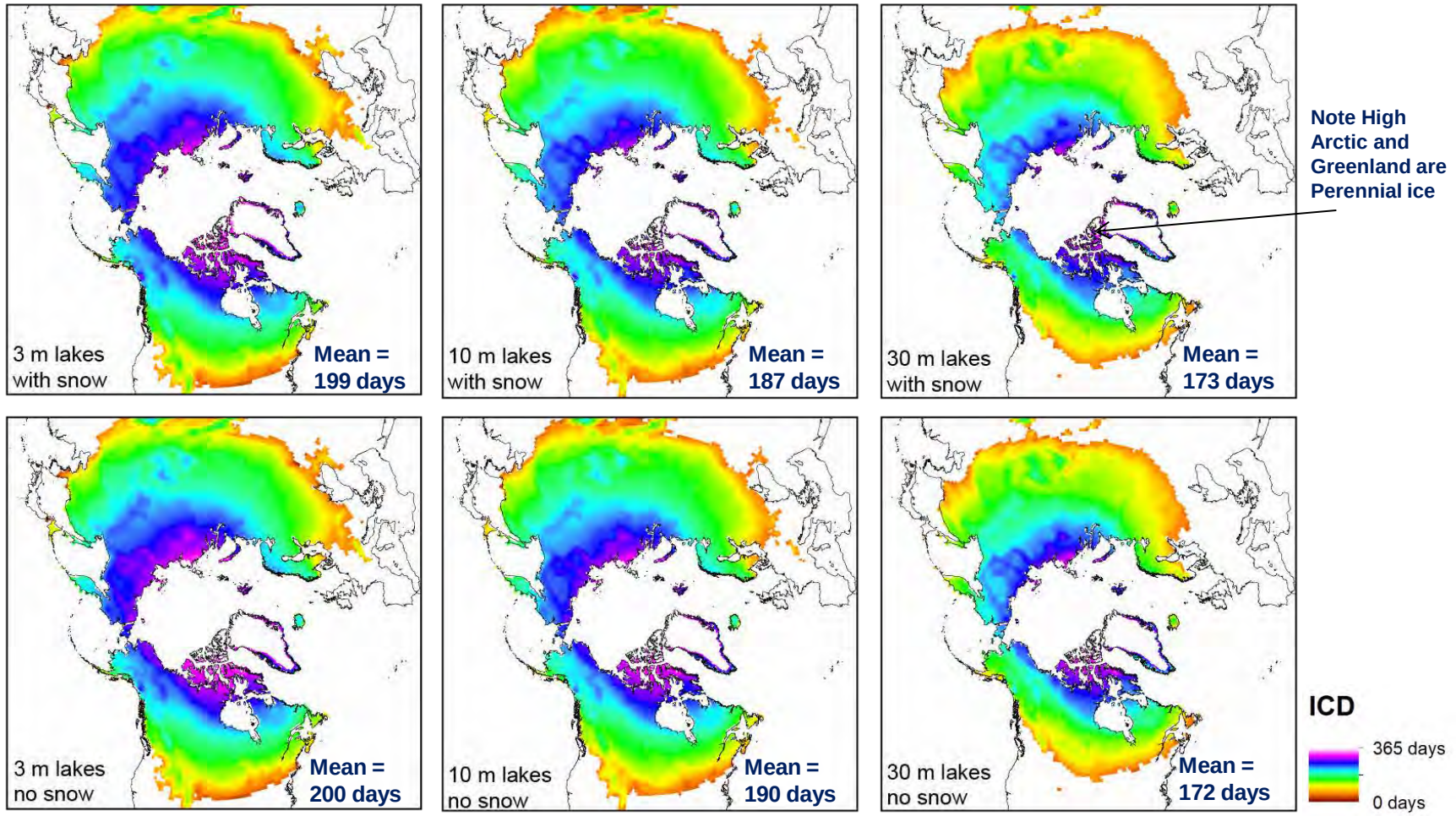
Courtesy: Laura Brown

- **CLIMo ice cover simulations driven by ERA-40 & ERA-Interim** — Modelled Validation Data

Lake Ice Under Contemporary Climate Conditions (ERA-Interim based results)

Contemporary Climate (1981-2010)

Mean ice cover duration (based on Era-Interim, 0.75)

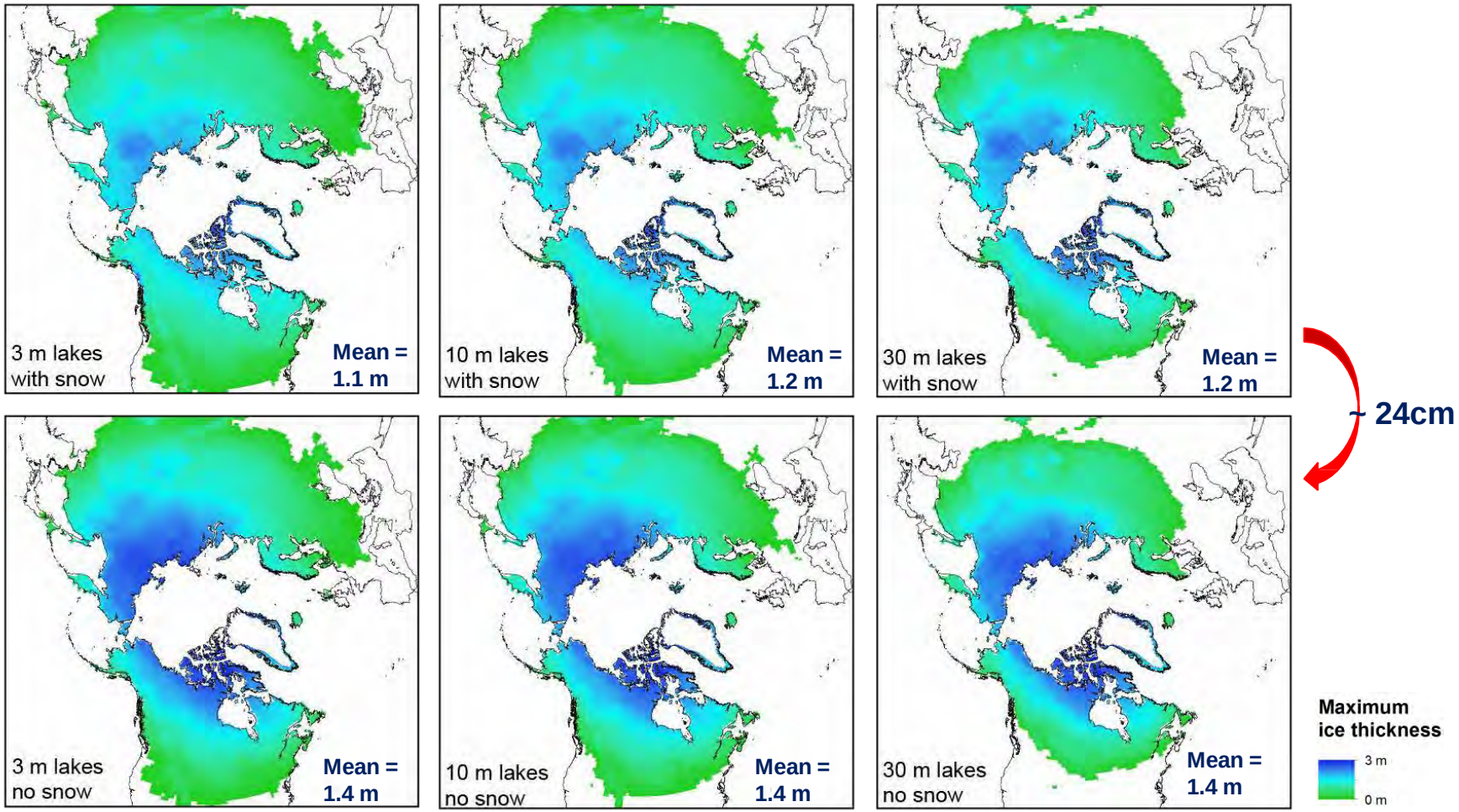


- Snow cover reduced mean duration slightly (more so in the Arctic)
- Depth affects ice duration due to delayed freeze-up with deeper lakes
- Depth affects the lower latitudinal extent of ice cover

Courtesy: Laura Brown

Contemporary Climate (1981-2010)

Mean maximum thickness (based on Era-Interim, 0.75)



- Ranges from 6 cm in the lower latitudes to 2.9 m in the highest latitudes
- Effects of snow cover more pronounced for thickness, especially in Arctic regions
- Effect of lake depth on thickness minimal

Courtesy: Laura Brown

Future of Lake Ice

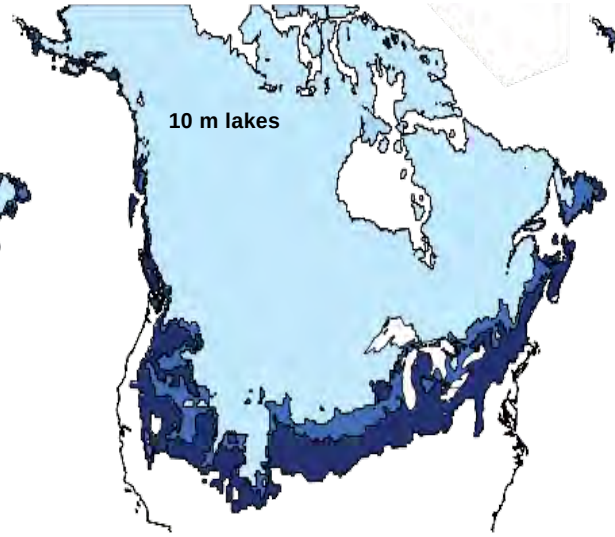
Change in Southern Extent of Lake Ice Formation

1981 - 2010 extent: 16.6 x106 km²

2071 - 2100 (mean):

7% reduction *(RCP 4.5)*

15% reduction *(RCP 8.5)*

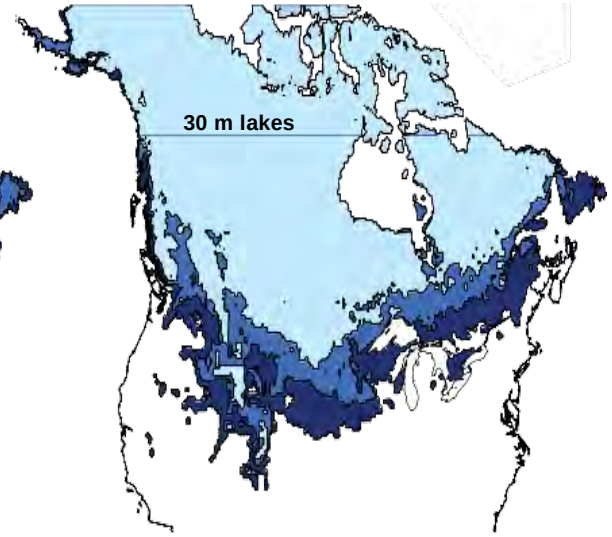


1981 - 2010 extent: 16.0 x106 km²

2071 - 2100 (mean):

11% reduction *(RCP 4.5)*

17% reduction *(RCP 8.5)*



1981 - 2010 extent: 13.8 x106 km²

2071 - 2100 (mean):

12% reduction *(RCP 4.5)*

22% reduction *(RCP 8.5)*

1981 - 2010 mean extent

2071 - 2100 mean extent (RCP 4.5)

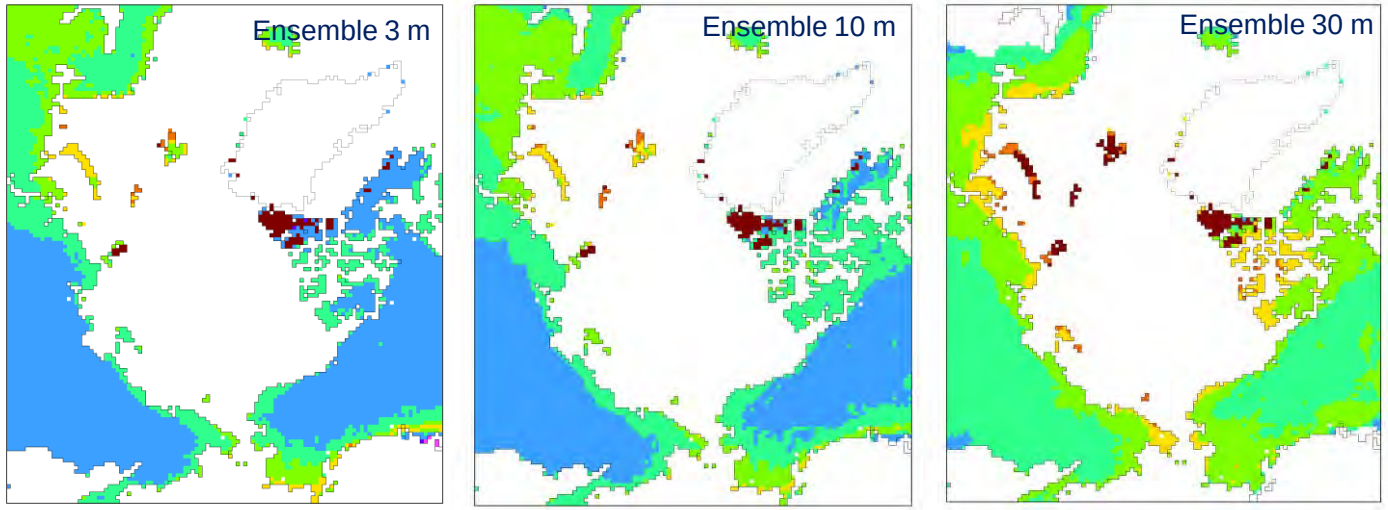
2071 - 2100 mean extent (RCP 8.5)

- **Greatest reduction of lake ice coverage projected for deeper lakes**

Brown and Duguay (2015)

Change in Break/Freeze-up dates

Change from 1981-2010 mean to 2071-2100 mean

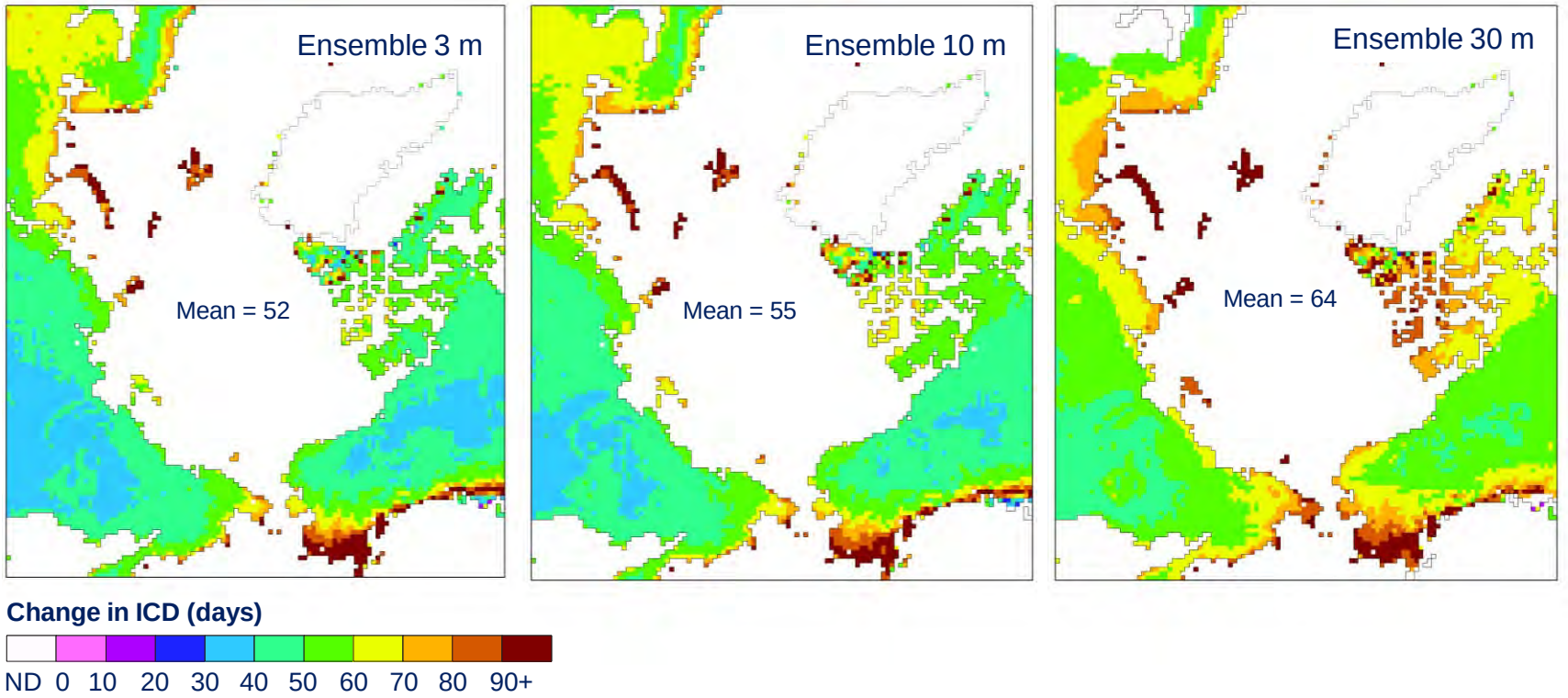


- BU changes range from 20 – 40 days earlier, more in the coastal regions (60+)
- FU changes less than BU: shallower lakes 10 - 40 days later, deeper lakes: 20 - 50 days later
- *Loss of perennial ice indicated by 60+ category days later FU*

Courtesy: Laura Brown

Change in ice cover duration

Change from 1981-2010 mean to 2071-2100 mean

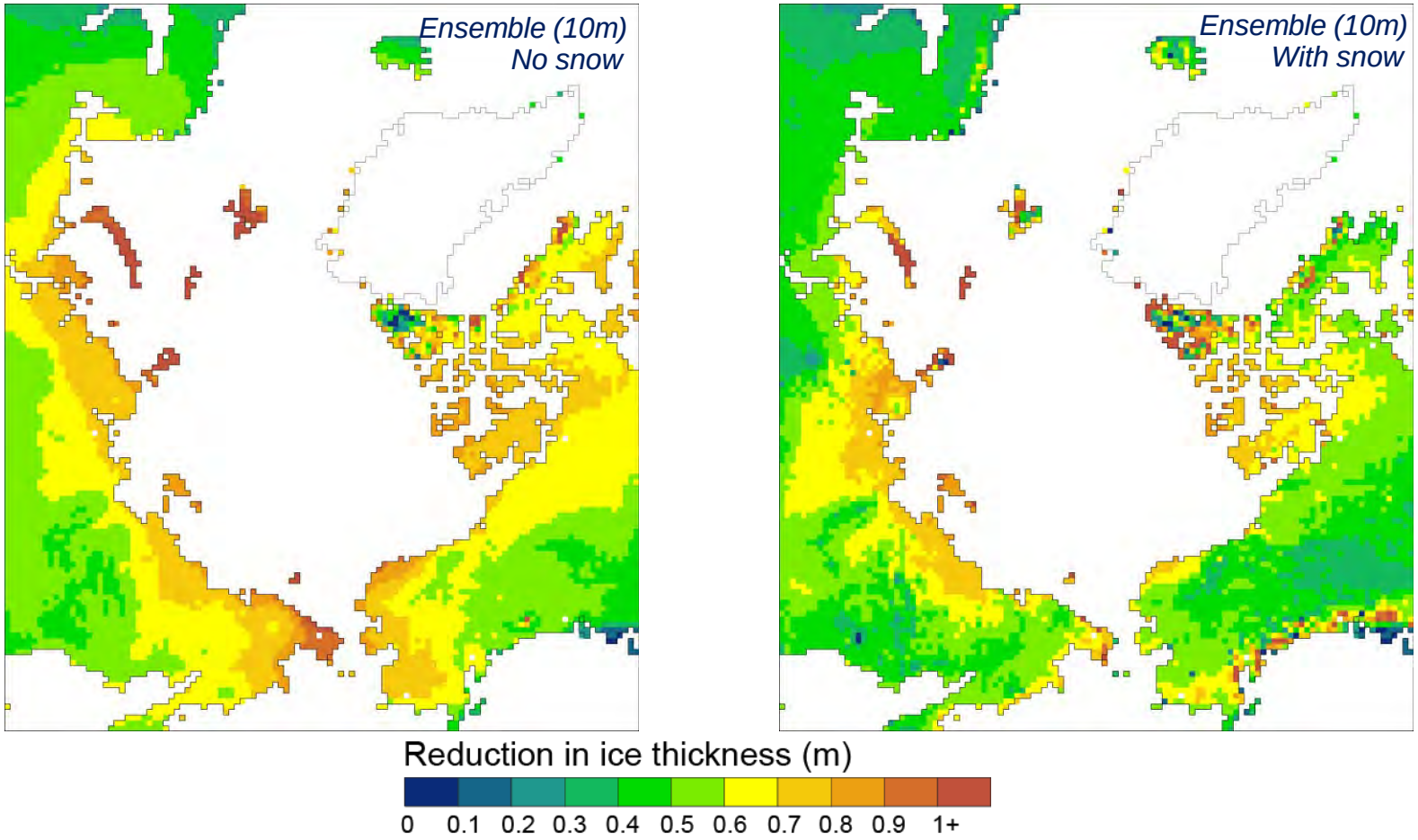


- Scandinavia: 50 – 90 days shorter ice duration, with no ice cover remaining on deeper lakes in parts of Scandinavia
- Siberia & Alaska/Canada: 30 – 60 days shorter (40 - 70 for deeper lakes)
- Coastal and High Arctic regions show the most change, up to 150 days (Alaska)

Courtesy: Laura Brown

Change in Mean Maximum Thickness

Change from 1981-2010 mean to 2071-2100 mean



- Scandinavia: 0.3 m – 0.7 m less (0.3 m – 0.5 m less with snow)
- Alaska/Canada/Siberia: 0.4 m – >1.0 m less (0.3 m – 0.9 m less with snow)
- Greater change in ice thickness for snow-free lakes (0.6 m vs 0.53 m)
- Slightly greater change in deeper lakes (~ 4 cm more ice reduction)

Courtesy: Laura Brown


Questions?