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Improvement of Lake Ice Thickness Retrieval From MODIS Satellite Data Using a Thermodynamic Model

Homa Kheyrollah Pour, C.R. Duguay, K.A. Scott, K.-K. Kang
University of Waterloo, Canada

UNIVERSITY OF WATERLOO

MEOPAR

Photo credit: Claude Duguay

Role of lake ice in regional weather and climate

Lake surface properties such as **water temperature** and **ice cover** are two important parameters when considering lake-atmosphere interactions

α = albedo

I_0 = penetration radiation through ice

F_r=downward shortwave radiation

F_l^{up}=upward longwave radiation

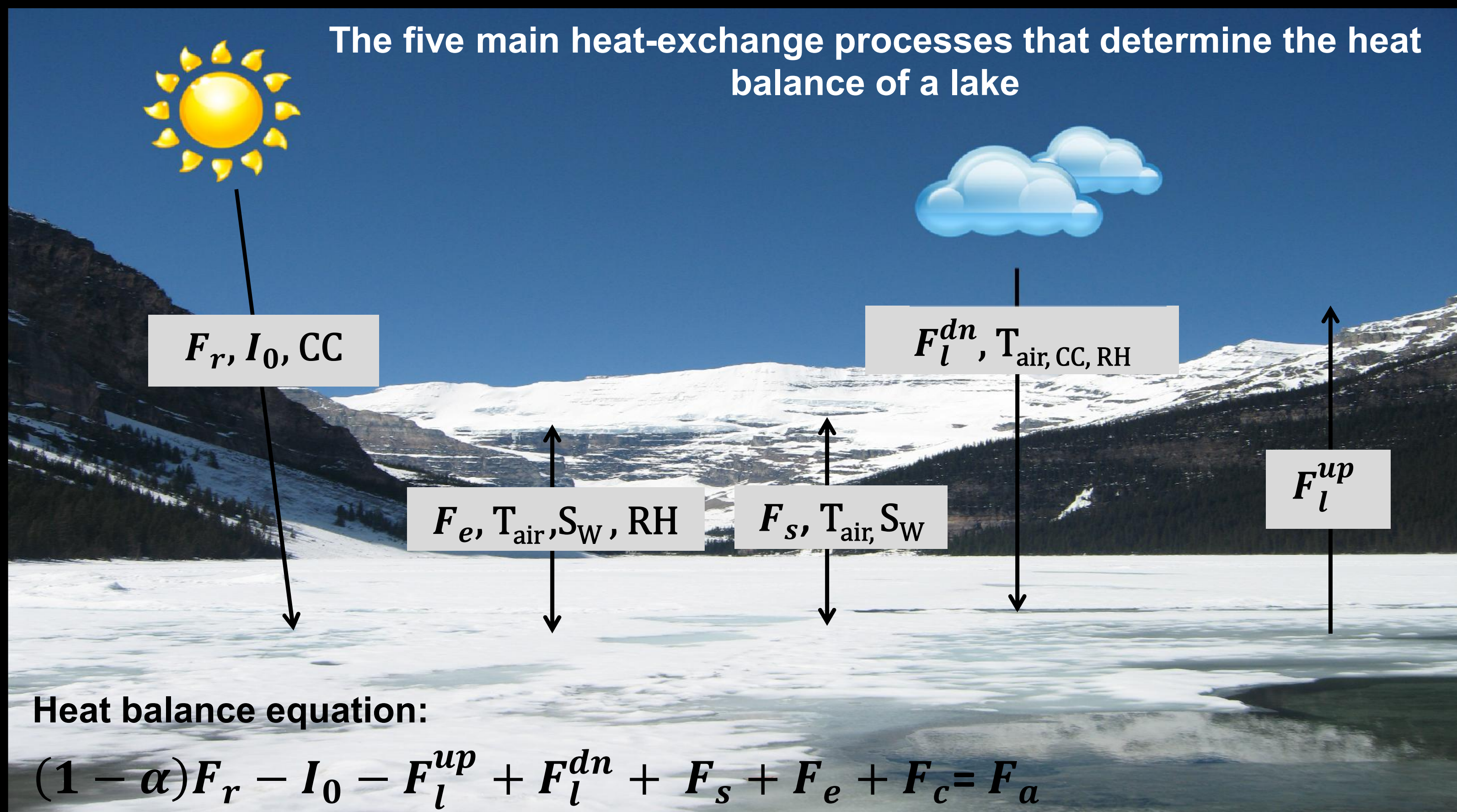
F_l^{dn}=downward longwave radiation

F_s=sensible Heat Flux

F_e=latent heat flux

F_c=conductive heat flux

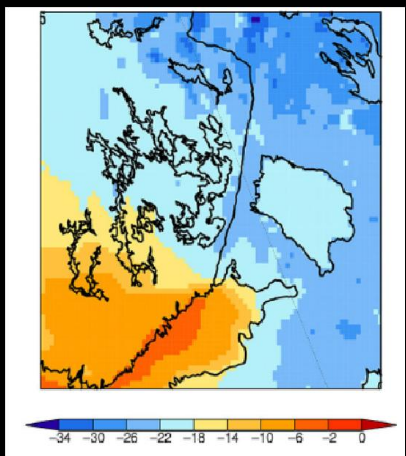
F_a=residual heat flux (F_a assumed to be zero)



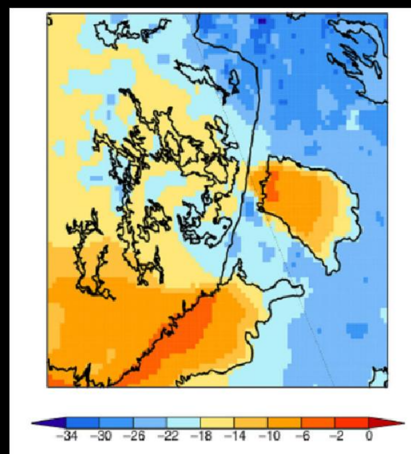
Importance of ice cover monitoring
Assimilate lake surface temperature in HIRLAM forecasting model

without LWST data

with LWST data



Simulated 2m air temperature



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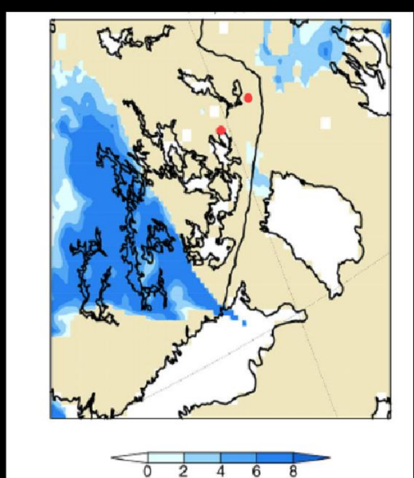
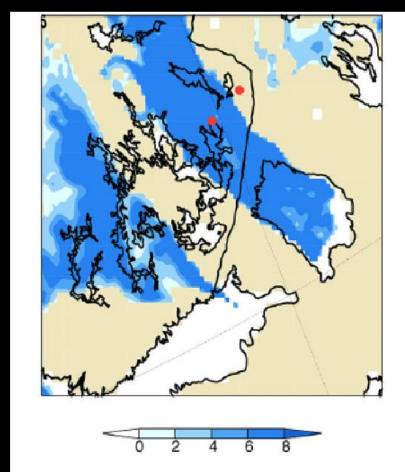


Simulated cloud cover

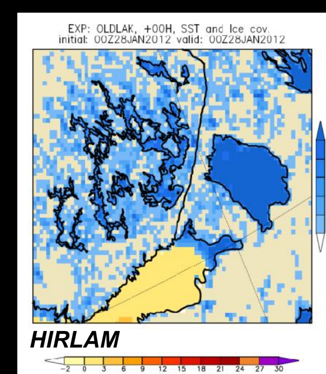


Simulated cloud cover

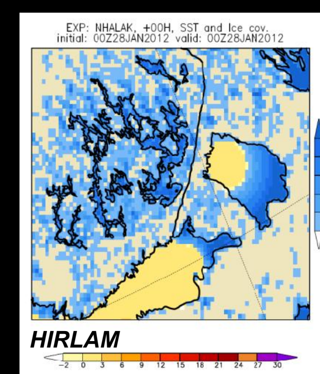
HIRLAM Forecast

MODIS visible image
28 January 2012
Lake Ladoga, RU

Analyzed ice cover without assimilation



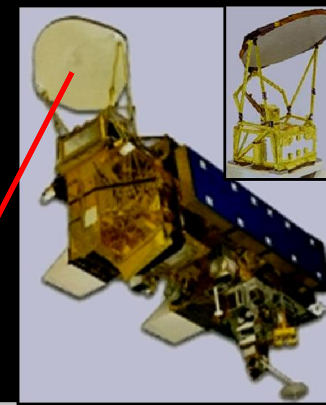
Analyzed ice cover with assimilation



HIRLAM Analysis

Eerola et al., 2014
Kheyrollah Pour et al., 2014

Ice thickness retrieval using passive microwave sensors e.g. AMSR-E



- The spatial footprint of the lower frequencies of passive microwave sensors is relatively large (20–50 km) , 76×44 km at 6.9 GHz
- Higher frequencies are more sensitive to the atmosphere.
- 6×4 km at 89.0 GHz

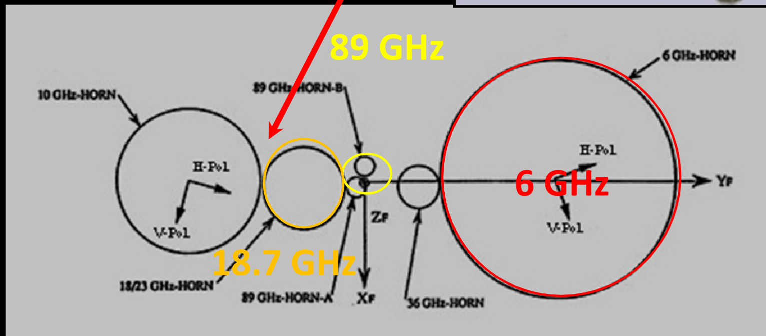
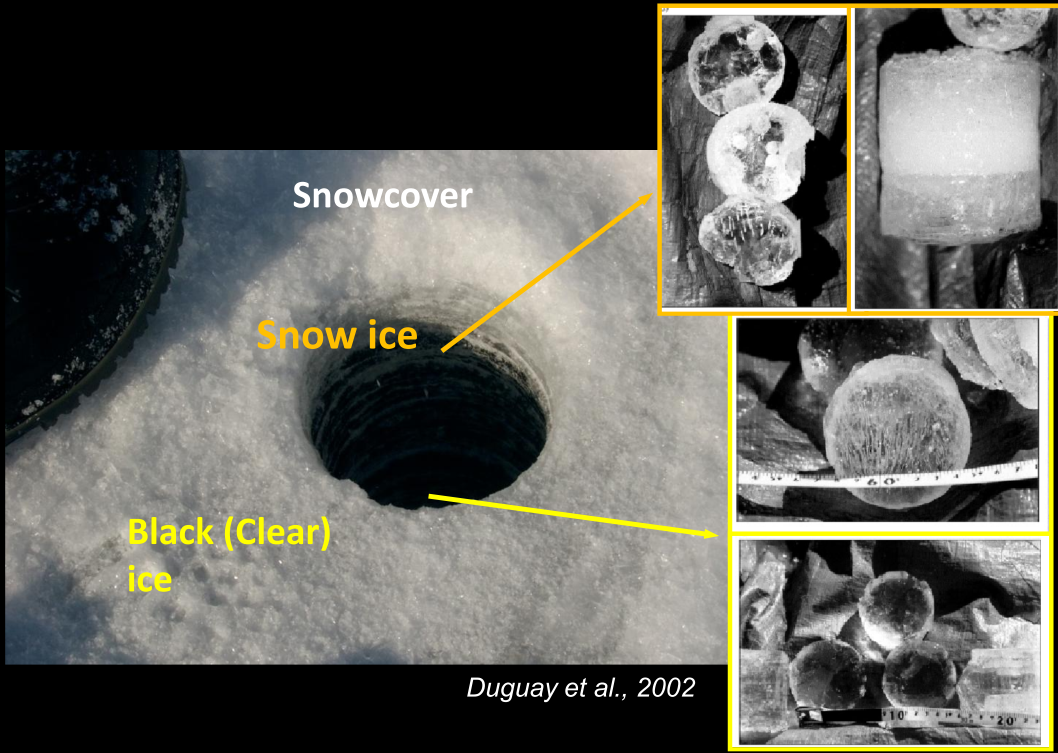


Table 1. AMSR-E PERFORMANCE CHARACTERISTICS

CENTER FREQUENCIES (GHz)	6.925	10.65	18.7	23.8	36.5	89.0
BANDWIDTH (MHz)	350	100	200	400	1000	3000
SENSITIVITY (K)	0.3	0.6	0.6	0.6	0.6	1.1
MEAN SPATIAL RESOLUTION (km)	56	38	21	24	12	5.4
IFOV (km x km)	74 x 43	51 x 30	27 x 16	31 x 18	14 x 8	6 x 4
SAMPLING RATE (km x km)	10 x 10	10 x 10	10 x 10	10 x 10	10 x 10	5 x 5
INTEGRATION TIME (MSEC)	2.6	2.6	2.6	2.6	2.6	1.3
MAIN BEAM EFFICIENCY (%)	95.3	95.0	96.3	96.4	95.3	96.0
BEAMWIDTH (degrees)	2.2	1.4	0.8	0.9	0.4	0.18

Ice thickness



Duguay et al., 2002

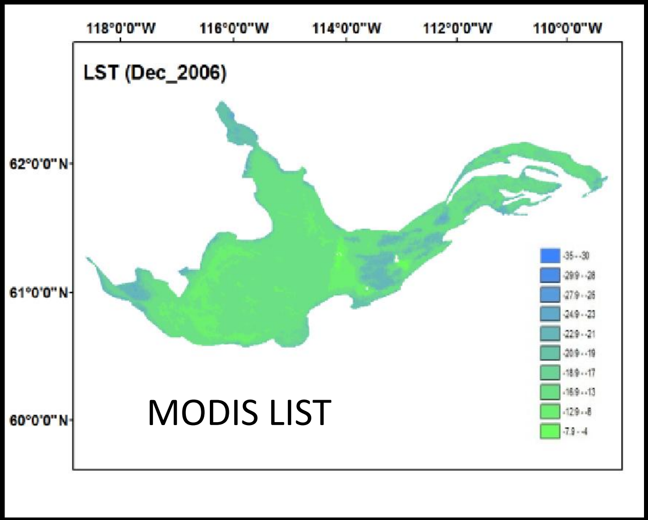
Snow ice
- Rounded-shape (spherical) bubble

Black ice
- Elongated-shape (cylindrical) bubble

Retrieval of ice thickness is challenging in high latitude regions at a time when such measurements are increasingly being requested by operational weather forecasting and ice centers

Motivation

This study aimed to improve the previous approach using thermal infrared observations to estimate ice thickness. The approach is based on the use of Moderate Resolution Imaging Spectroradiometer lake ice surface temperature (MODIS LIST) and with snow depth calculated by the 1-D thermodynamic Canadian Lake Ice Model (CLIMo).



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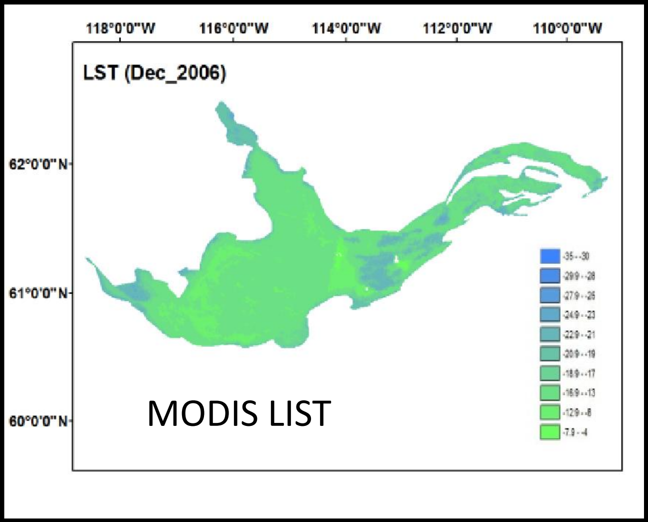
Previous studies snow depth approach:

Empirical relationship between snow and ice

$$h_s = 0 \quad \text{for } H_i < 0.05 \text{ m}$$
$$h_s = 0.05 H_i \quad \text{for } 0.05 \text{ m} \leq H_i \leq 0.2 \text{ m}$$
$$h_s = 0.2 H_i \quad \text{for } H_i > 0.2 \text{ m}.$$

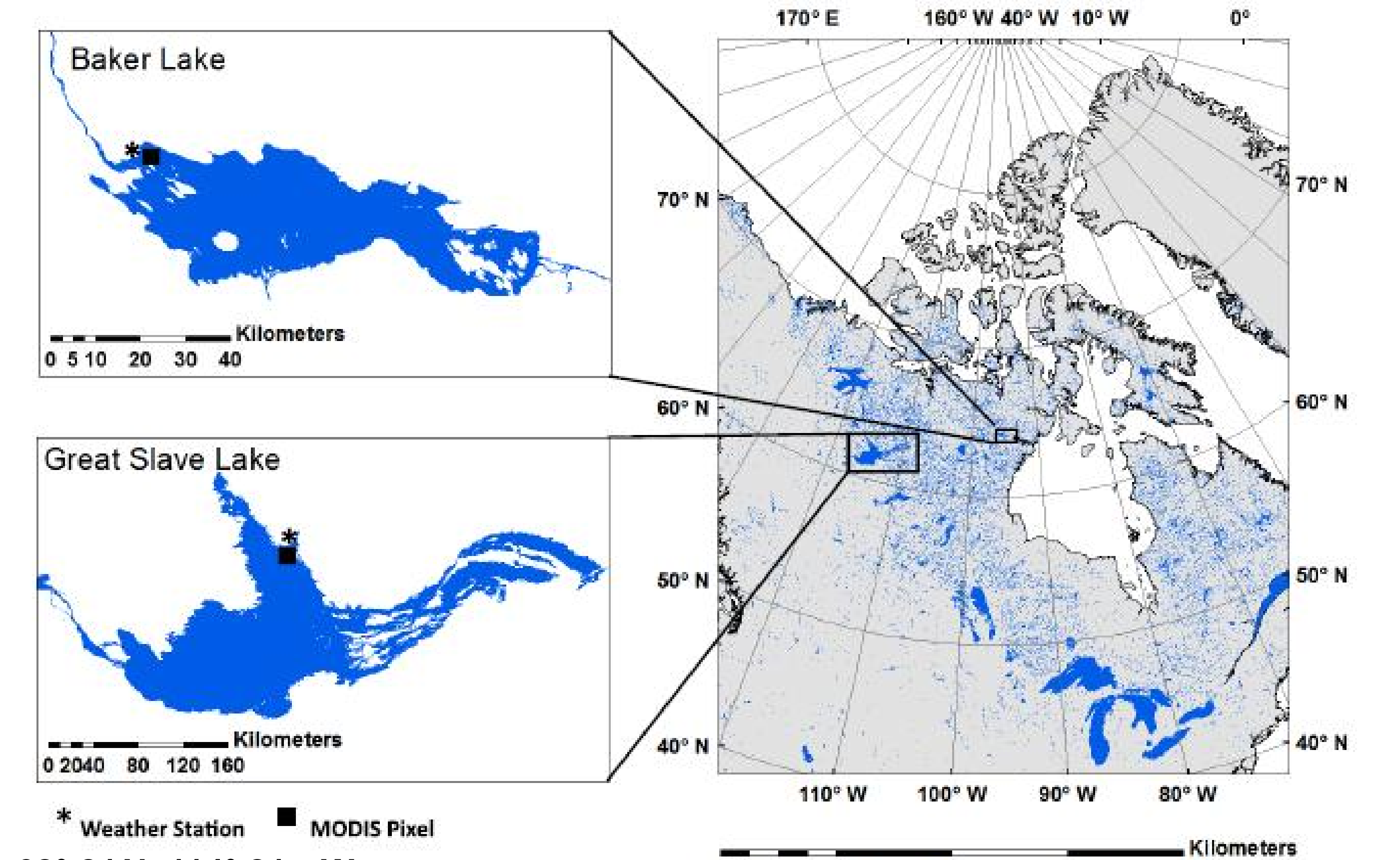


Study area

Great Slave and Baker Lake, Canada

- **<u>Baker Lake, Nunavut:</u>**
- Maximum depth: 60 m
- Area: 182.2 km^2
- Covered by ice usually from Nov.-May

- **<u>Great Slave Lake, NWT:</u>**
- Maximum depth: 614 m
- Mean depth: 41 m
- Area: 27,000 km^2
- Covered by ice usually from Dec.-May



62° 21 N, 114° 21 135 W

Heat balance equation

$$(1-\alpha)F_r - I_0 - F_l^{up} + F_l^{dn} + F_s + F_e + F_c = F_a$$

α = albedo
I_0 = penetration radiation through ice
F_r=downward shortwave radiation
F_l^{up}=upward longwave radiation
F_l^{dn}=downward longwave radiation
F_s=sensible Heat Flux
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F_c=conductive heat flux
F_a=residual heat flux
(F_a assumed to be zero)

Heat balance equation/ MODIS LIST

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T_s = MODIS night-time LIST observations

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$$F_c = \gamma\ (T_f - T_s)$$

T_f = freezing temperature

T_s = MODIS night-time LIST observations

γ = thermal conductance of the ice/snow

Heat balance equation/ MODIS LIST/ One-Dimensional Thermodynamic Ice Model

$$~~(1-\alpha)F_r - I_0~~ - F_l^{up} + F_l^{dn} + F_s + F_e + F_c = F_a$$

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F_c=conductive heat flux
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(F_a assumed to be zero)

$$F_c = \gamma\ (T_f - T_s)$$
$$\gamma = (k_i k_s)/\ (k_s H + k_i h)$$

T_f = freezing temperature
T_s = MODIS night-time LIST observations
γ = thermal conductance of the ice/snow
k_i, k_s= Ice and snow conductivity

$k_i, k_s \propto snow\ deph\ and\ density$
Snow density= 330 kg/m3

Heat balance equation/ MODIS LIST/ One-Dimensional Thermodynamic Ice Model

$$\cancel{(1-\alpha)F_r - I_0} - F_l^{up} + F_l^{dn} + F_s + F_e + F_c = F_a$$

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$$H_i = \frac{k_i \times k_s - \left(\frac{F_C}{T_s - T_f} \times k_i \times h_s\right)}{\frac{F_C}{T_s - T_f} \times k_s}$$

T_f = freezing temperature
T_s = MODIS night-time LIST observations
γ = thermal conductance of the ice/snow
k_i, k_s= Ice and snow conductivity
H= Ice thickness
h= snow depth from CLIMo parameterization

$k_i, k_s \propto$ *snow deph and density*
Snow density= 330 kg/m3

Canadian Lake Ice Model (CLIMo)

Inputs

- Air temperature
- Relative humidity
- Wind speed
- Cloud cover
- Snow fall

Model simulation

5 scenarios

1- 100% snow

2- 75% snow

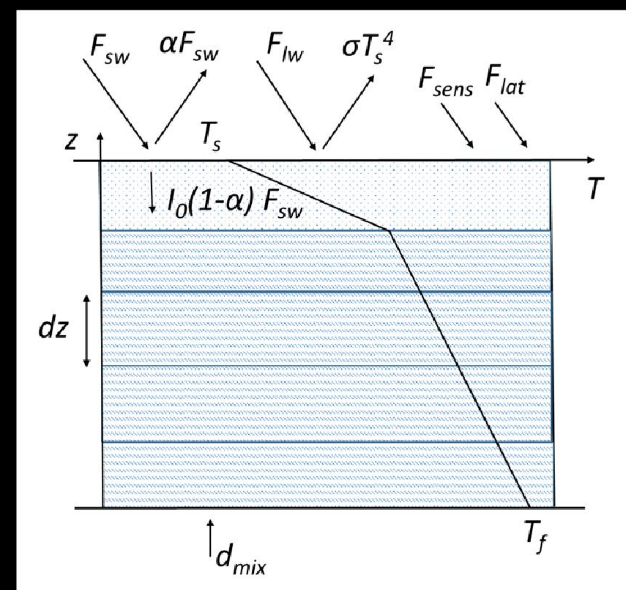
3- 50% snow

4- 25% snow

5- 0% snow

Outputs

- Energy balance components
- On-ice snow depth
- Annual break up /freeze up
- Ice thickness
- Temperature profile (snow/ice)



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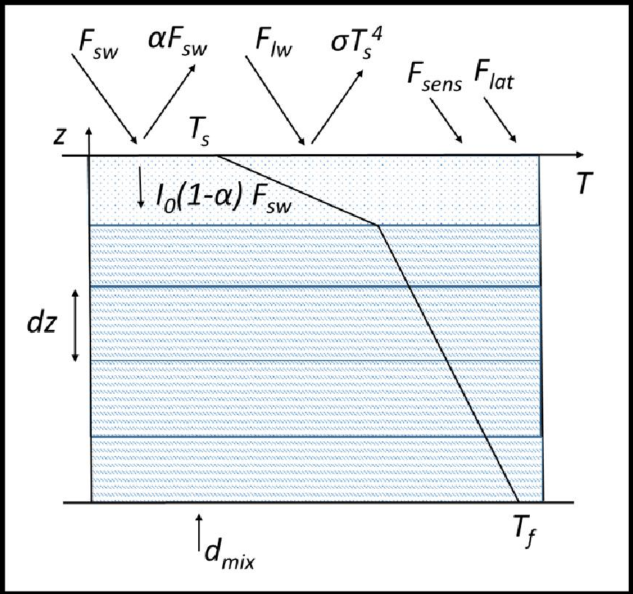
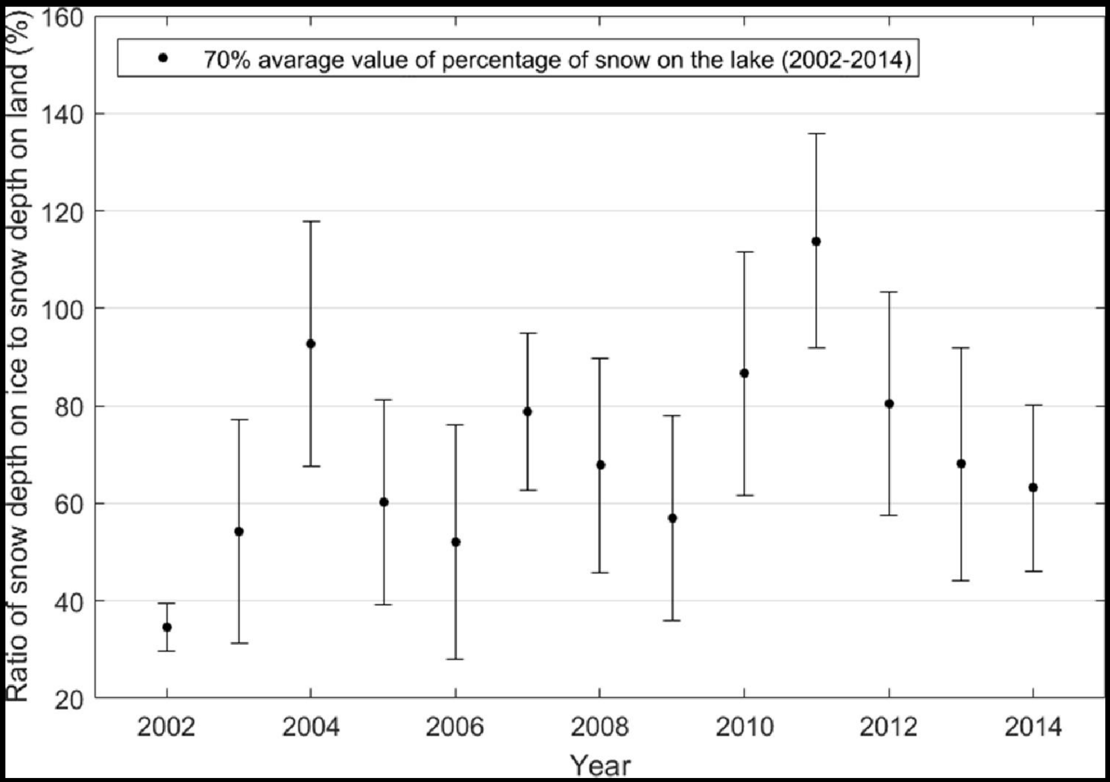
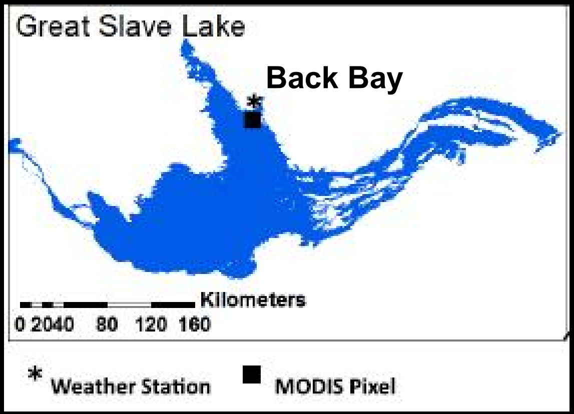


Calculated ice thickness from MODIS vs. in-situ ice thickness (GSL)



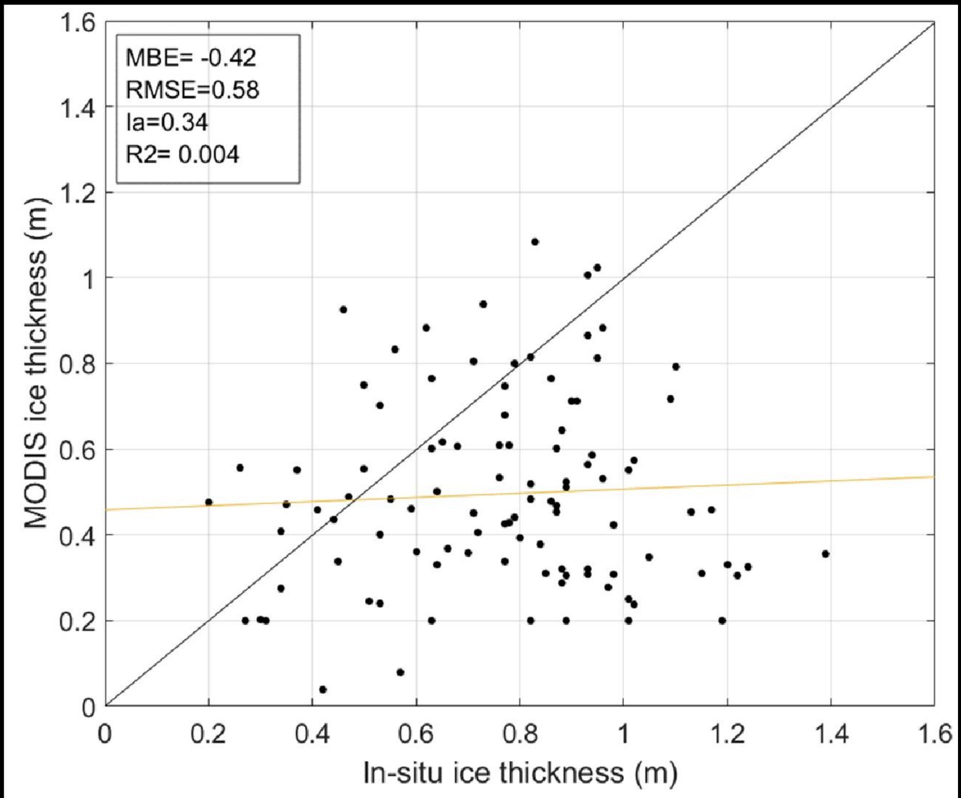
Dots represent average percentage of snow depth on lake for each year and bars are standard deviation.

Percentage of snow depth on lake ice vs. snow depth on the ground at Back Bay weather station (2002–2014).

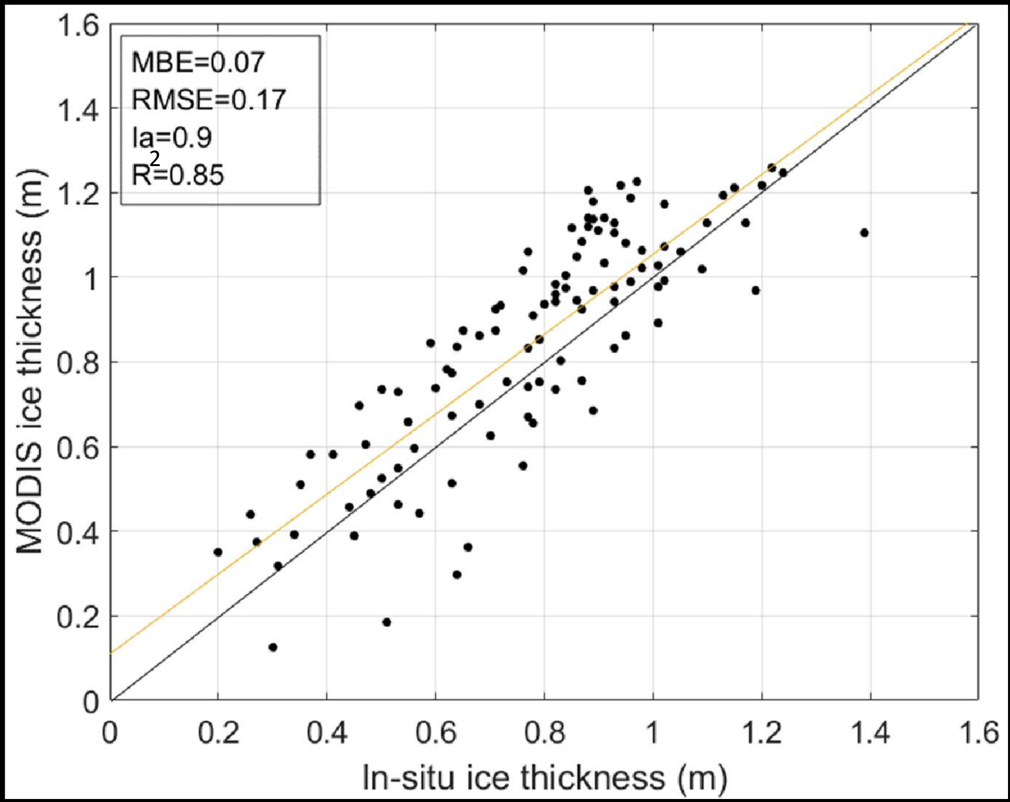


Estimated ice thickness from MODIS vs. in-situ ice thickness (Great Slave Lake)

Using empirical relationship of snow depths

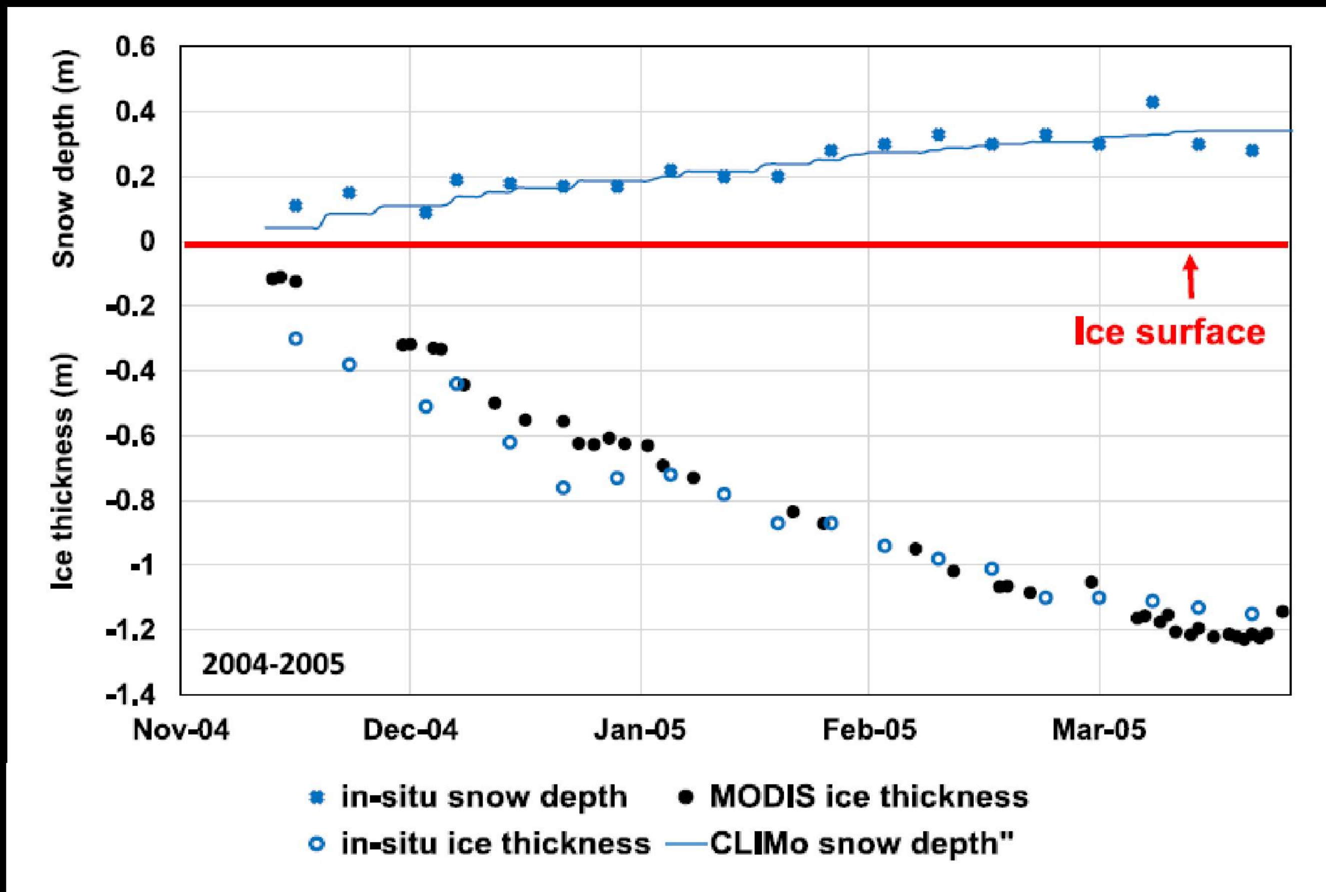


Using CLIMo parameterization

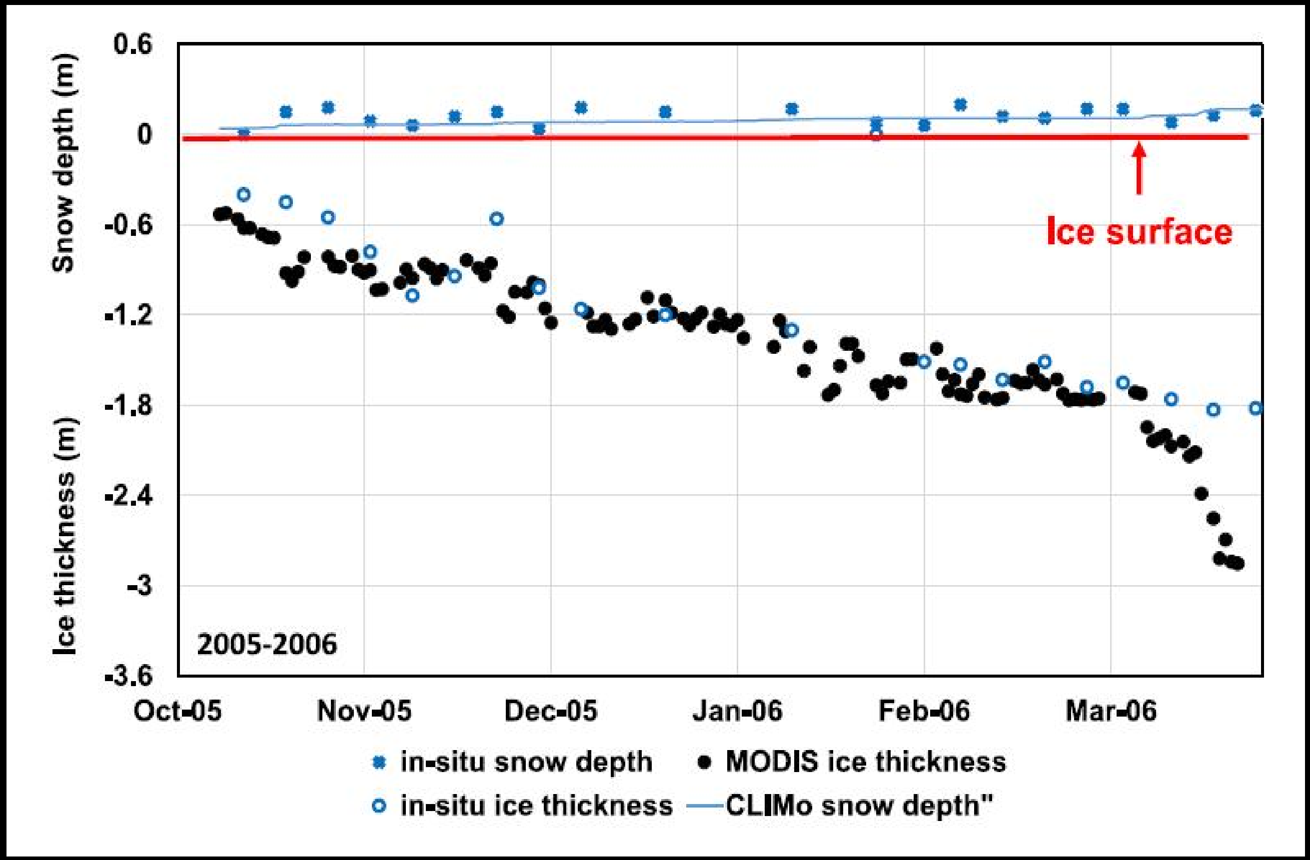


The unit of MBE and RMSE is meter.
Orange solid line is the correlation fit and the black line is the 1:1 line.

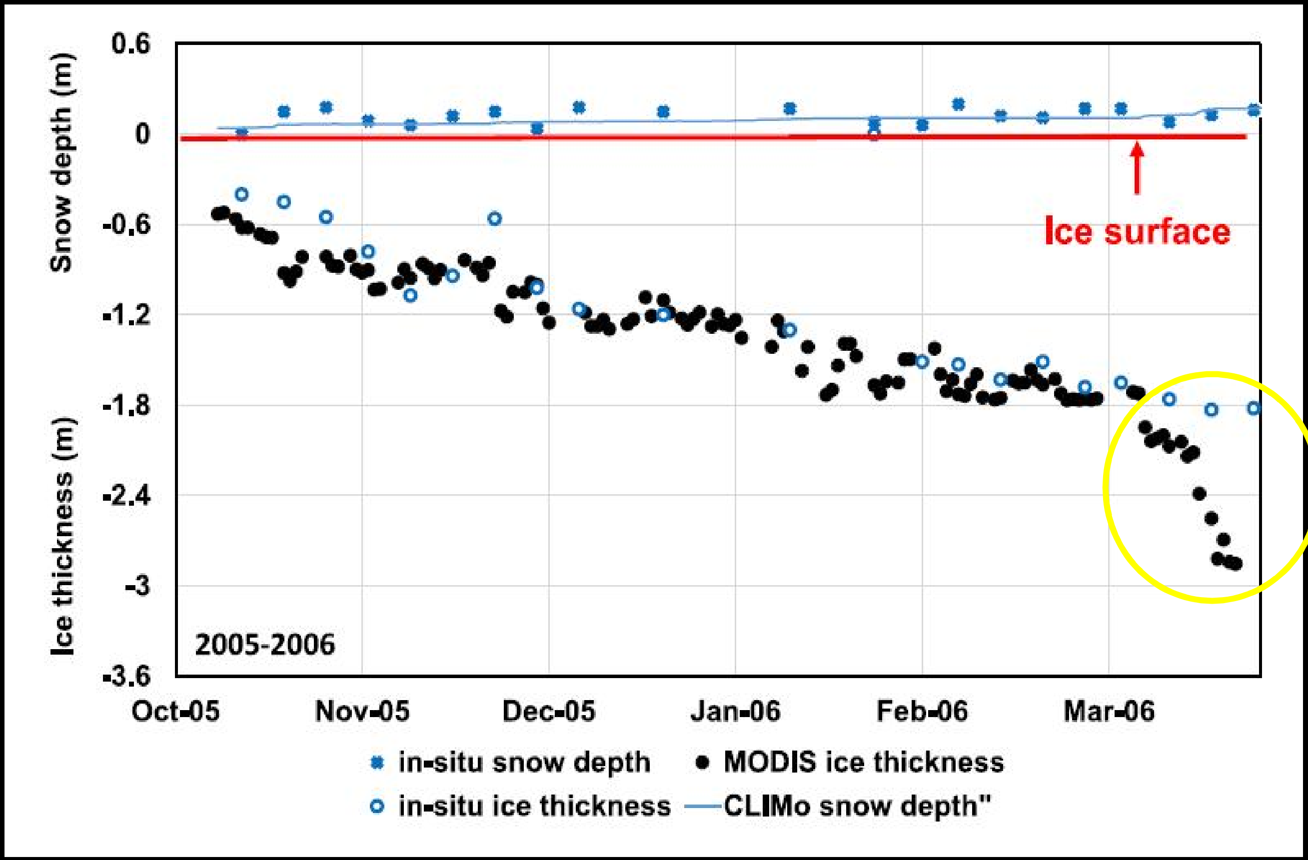
Snow and ice thickness from MODIS vs. in-situ ice thickness
Great Slave Lake



Snow and ice thickness from MODIS vs. in-situ ice thickness Baker Lake

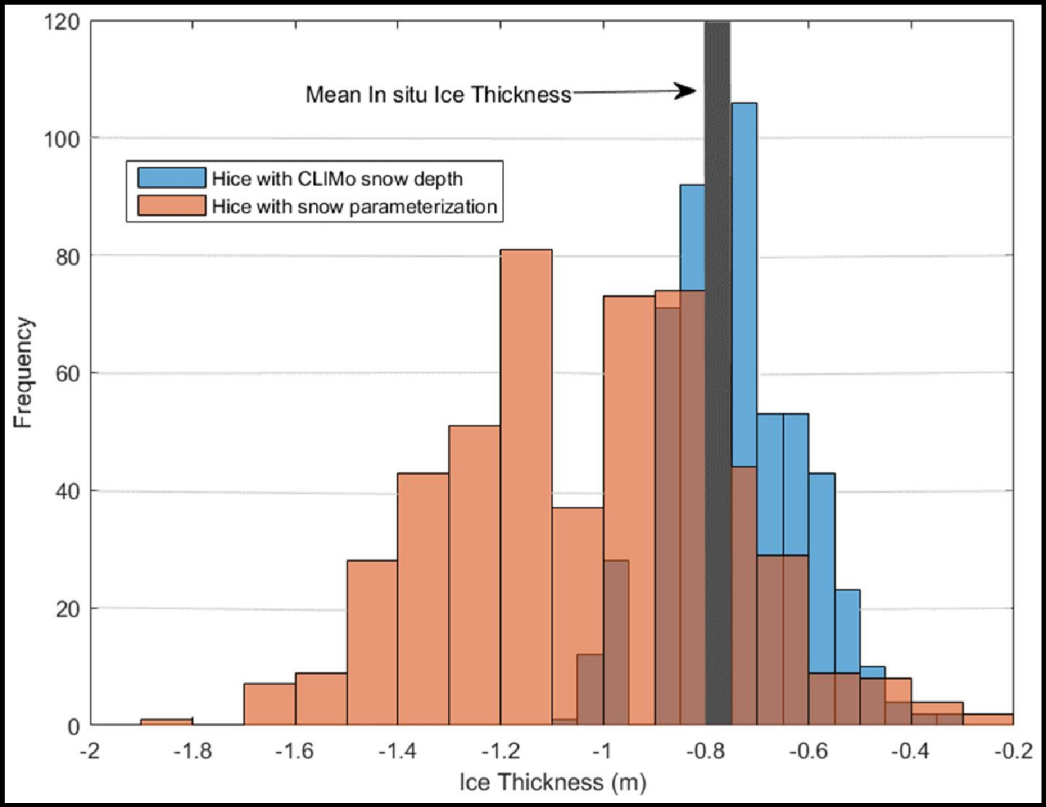


Snow and ice thickness from MODIS vs. in-situ ice thickness
Baker Lake



When accurate snow depth information is available, ice of thickness up to 1.7 m can be retrieved

Sensitivity of the snow depth ice thickness retrieval to the heat flux



Mean ice thickness value calculated from empirical snow depth is farther from the in situ mean ice thickness value vs. mean ice thickness value calculated from CLIMo parameterization

Sensitivity of the snow depth ice thickness retrieval to the heat flux

February 2006	$\overline{LIST}$(K)	$\overline{Hs}$(m)	δHs (m)	$\overline{Fc}$ (W/m^2)	δFc (W/m^2)	$\overline{Hi}$ (m)	δHi (m)	$\delta Hi/\overline{Hi}$
EXP1	251.8	0.21	--	9.94	1.65	0.7	0.07	0.05
EXP2	251.8	0.21	0.07	9.94	--	0.9	0.1	0.12
EXP3	251.8	--	--	9.94	1.65	1.02	0.18	0.17

EXP1: *Hs* constant, *Fc* varied by choosing 500 samples from a distribution $N(\overline{Fc}, \delta Fc)$.

EXP2: *Fc* constant, *snow depth* varied by choosing 500 samples from a distribution $N(\overline{Hs}, \delta Hs)$.

EXP3: *Fc* varied by choosing 500 samples from a distribution $N(\overline{Fc}, \delta Fc)$ and the *Hs* used empirical relationship of snow depths and ice thickness.

Sensitivity of the snow depth ice thickness retrieval to the heat flux

February 2006	$\overline{LIST}$(K)	$\overline{Hs}$(m)	δHs (m)	$\overline{Fc}$ (W/m²)	δFc (W/m²)	$\overline{Hi}$ (m)	δHi (m)	$\delta Hi/\overline{Hi}$
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Sensitivity of the snow depth ice thickness retrieval to the heat flux

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Sensitivity of the snow depth ice thickness retrieval to the heat flux
Conclusion

February 2006	$\overline{LIST}$(K)	$\overline{Hs}$(m)	δHs (m)	$\overline{Fc}$ (W/m^2)	δFc (W/m^2)	$\overline{Hi}$ (m)	δHi (m)	$\delta Hi/\overline{Hi}$
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Comparing the standard deviation of ice thickness (δHi) for ***EXP1*** and ***EXP2*** demonstrates that the change in ice thickness was more significant when the snow depth was varied, as compared to the conductive heat flux

Sensitivity of the snow depth ice thickness retrieval to the heat flux Conclusion

February 2006	$\overline{LIST}$(K)	$\overline{Hs}$(m)	δHs (m)	$\overline{Fc}$ (W/m^2)	δFc (W/m^2)	$\overline{Hi}$ (m)	δHi (m)	$\delta Hi/\overline{Hi}$
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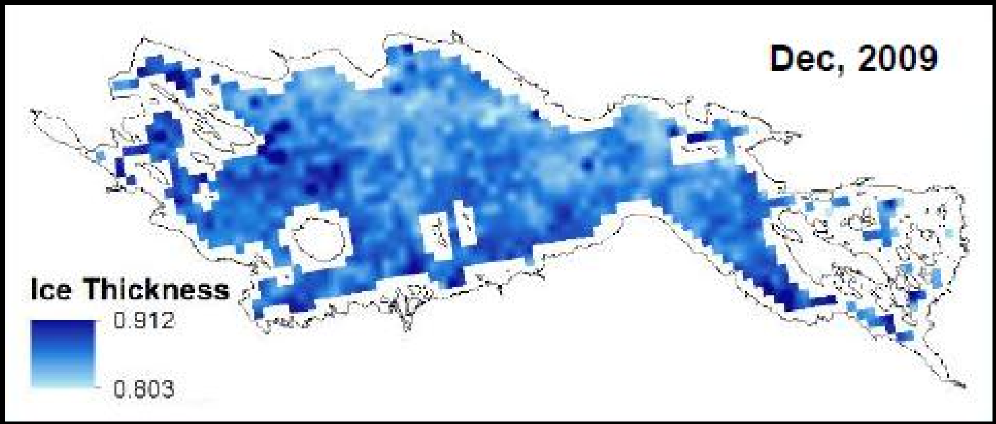
Comparing the standard deviation of ice thickness (δHi) for ***EXP1*** and ***EXP2*** demonstrates that the change in ice thickness was more significant when the snow depth was varied, as compared to the conductive heat flux

Comparing δHi for ***EXP1*** and ***EXP3***, it can be seen that δHi is larger when the empirical relationship of snow depths is used.

Preliminary result of ice thickness simulation on MODIS LIST pixels



Cloud cover, wind speed, and surface air temperature were acquired from ERA-Interim which is a global atmospheric reanalysis product provided by ECMWF.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Thanks for your attention!
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UNIVERSITY OF WATERLOO
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