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# Impact of varying snow and ice properties of northern lakes on backscatter and brightness temperature measurements from altimetry missions: Results from the ESA LIAM project


C. Duguay[1,2], G. Picard[3], E. Zakharova[4,5], J. Murfitt[1], M. Restano[6], and J. Benveniste[7]

[1] University of Waterloo, Waterloo, Canada
[2] H2O Geomatics, Waterloo, Canada
[3] Université Grenoble Alpes, Grenoble, France
[4] EOLA, Toulouse, France
[5] Water Problem Institute of RAS, Moscow, Russia
[6] SERCO c/o ESA-ESRIN, Frascati, Italy
[7] ESA-ESRIN, Frascati, Italy

# LAKE ICE THICKNESS: OBSERVATIONAL REQUIREMENTS

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## Global Climate Observing System (GCOS) Requirements

| ECV Lake Ice Thickness | |
|---|---|
| Measurement uncertainty | 1-2 cm |
| Stability | N/A |
| Spatial resolution | 100 m |
| Temporal resolution | Monthly |

GCOS-200, 2016. The Global Observing System for Climate: Implementation Needs.

Revised/refined for *2022 GCOS Implementation Plan*

(currently under Public Review)

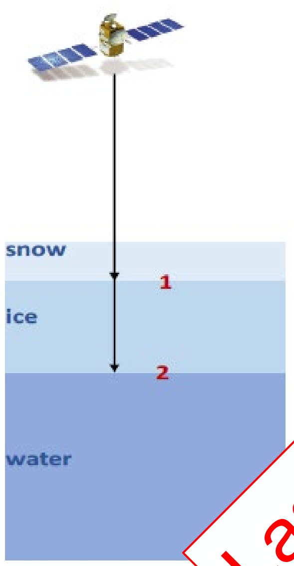
## Climate Community Requirements

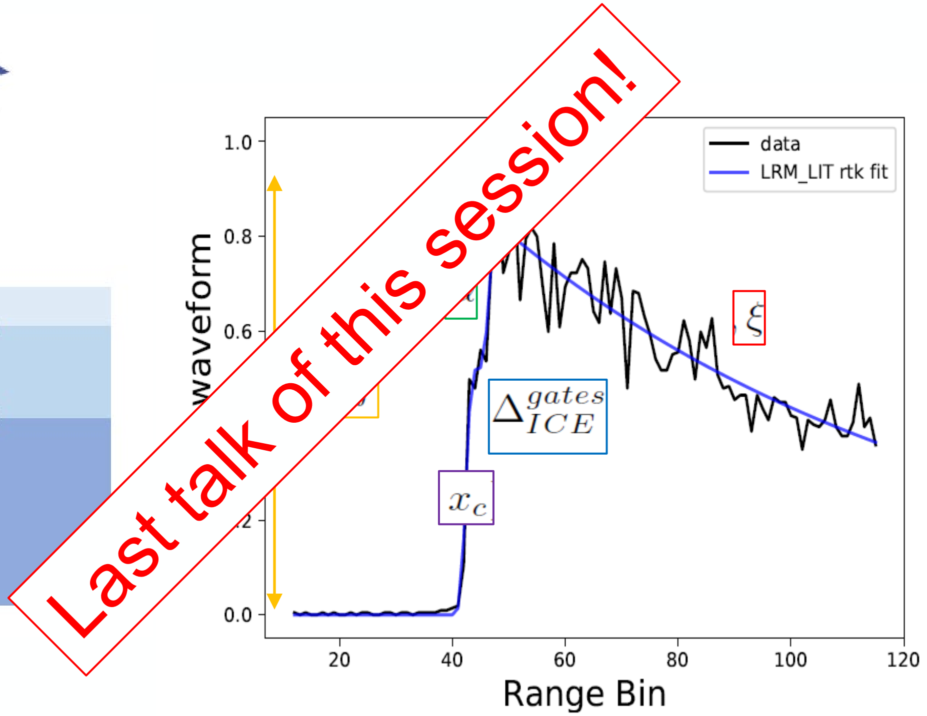
| Parameter | Application | Horizontal Resolution | Observing Cycle | Precision | Accuracy | Stability |
|---|---|---|---|---|---|---|
| **Lake Ice Thickness** | Trend monitoring | < 200 m | Weekly | 5 cm | 5 cm | |
| | Seasonal / decadal forecasting | 10 / 25 km | Weekly | 10 cm | 10 cm | |
| | Reanalyses | 10 / 25 km | Daily | 10 cm | 10 cm | |

Table adapted from: CMUG CCI+, 2020. *Deliverable 1.1: Climate Community Requirements*, v2.2, 9 November 2020.

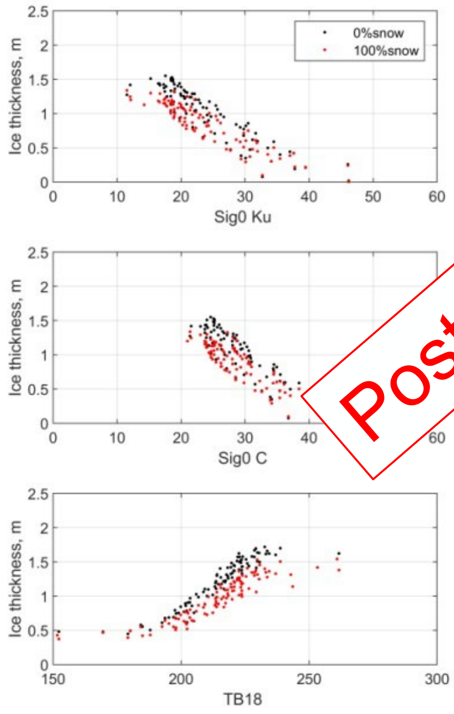
# ESTIMATION OF LAKE ICE THICKNESS FROM ALTIMETRY MISSIONS

## Physical/Analytical Approach[1]

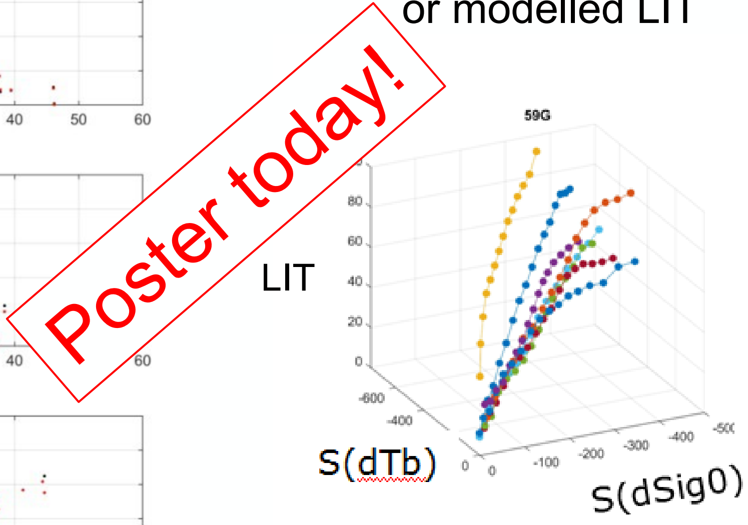



## Empirical Approach[2]




Requires in situ measurements or modelled LIT




LIT= f(Sig0,Tb)

LIT = f(dSig0/dt)

LIT = f(dTb/dt)

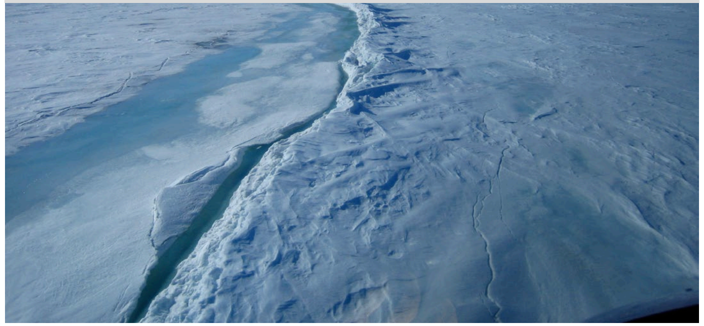

**1** Mangilli, A., P. Thibaut, C.R. Duguay, and J. Murfitt, accepted. A new approach for the estimation of lake ice thickness from conventional radar altimetry. *IEEE Transactions on Geoscience and Remote Sensing*.

**2** Zakharova, E., S. Agafonova, C. Duguay, N. Frolova, and A. Kouraev, 2021. River ice phenology and thickness from satellite altimetry. Potential for climate studies and ice bridge road operation. *The Cryosphere*, 15: 5387-5407.

# ICE AND SNOW PROPERTIES ENCOUNTERED ON NORTHERN LAKES

Ice with low and no snow

Pressure ridge
(2 m high, several km long)



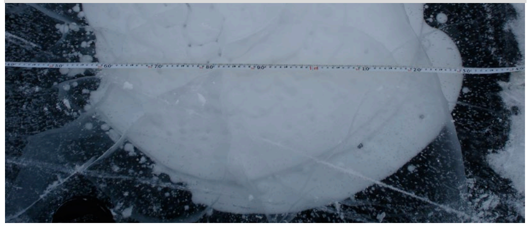
Roughness at ice-water interface

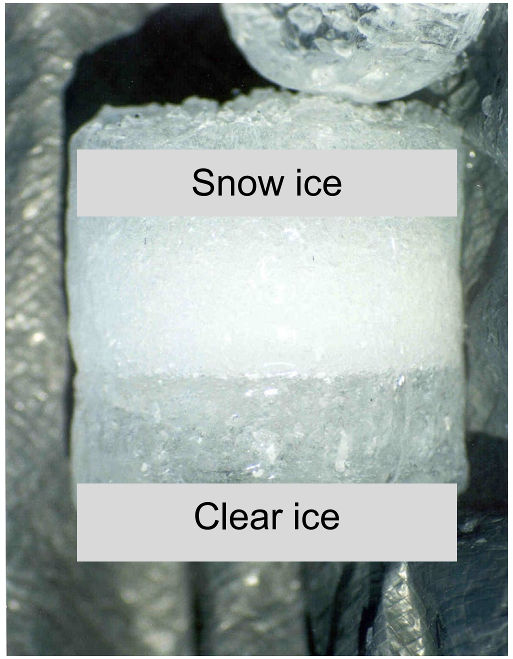
Clear ice / grey ice with small bubbles

Snow on ice

Slushing / snow ice

Clear ice with large bubble





# LIAM (LAKE ICE FROM ALTIMETRY MISSIONS) PROJECT

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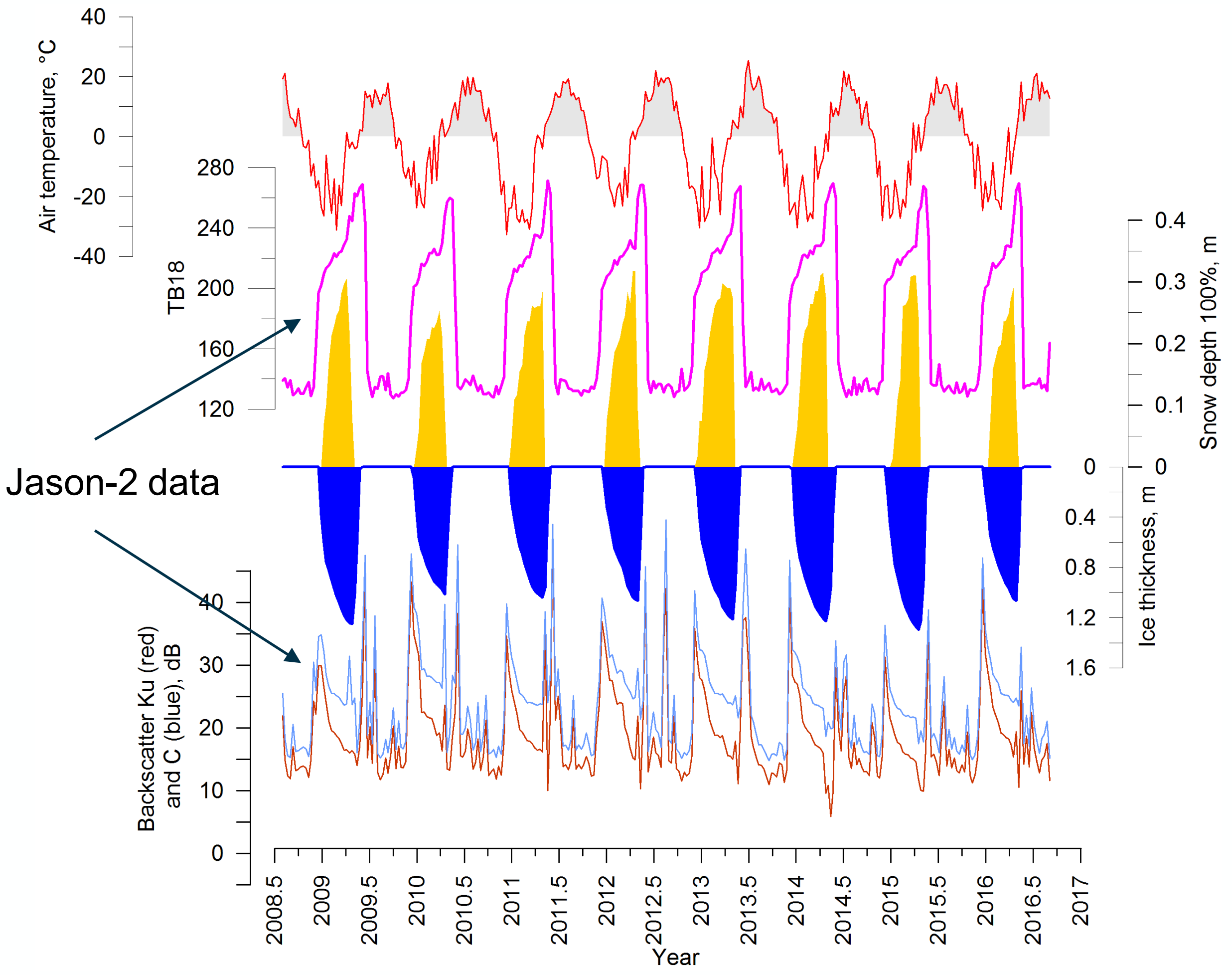
## Objective

Examine the sensitivity of brightness temperature (Tb) and backscatter (σ°) measurements from altimetry missions to LIT of varied ice and overlying snow properties.

## Approach

- Forward simulations using a radiative transfer model with input from a thermodynamic lake ice model.
- Analysis/interpretation of satellite measurements (Tb, σ° and waveforms).
- Comparison of forward simulations with satellite measurements.

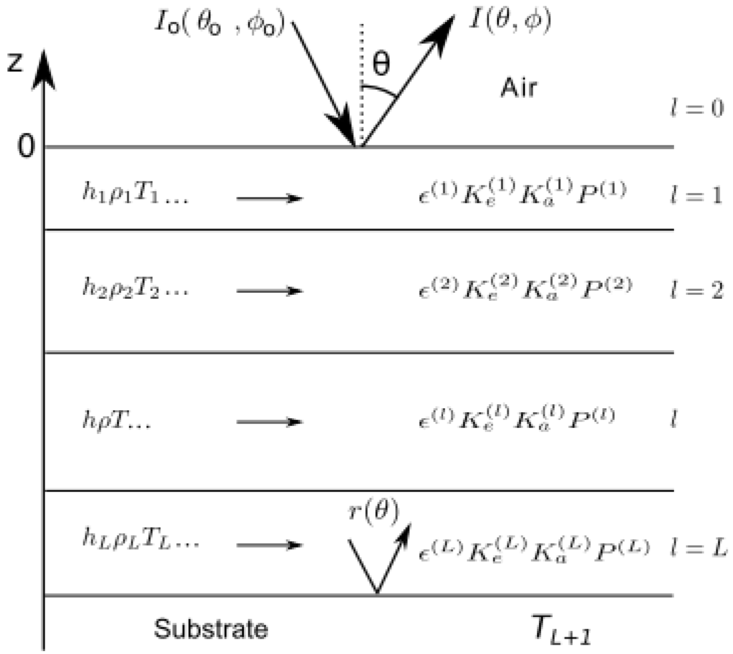



Great Slave Lake (Canada)

# FORWARD SIMULATIONS: MODELS

## SMRT

Radiative transfer model that is usable for multilayer snowpacks and ice columns in both passive and active microwave



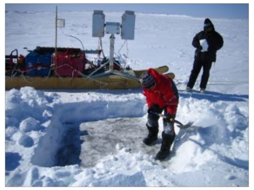

## CLIMo

Thermodynamic lake ice model

**INPUT**

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

**CLIMo**
0% and 100 % snow scenarios



**OUTPUT**

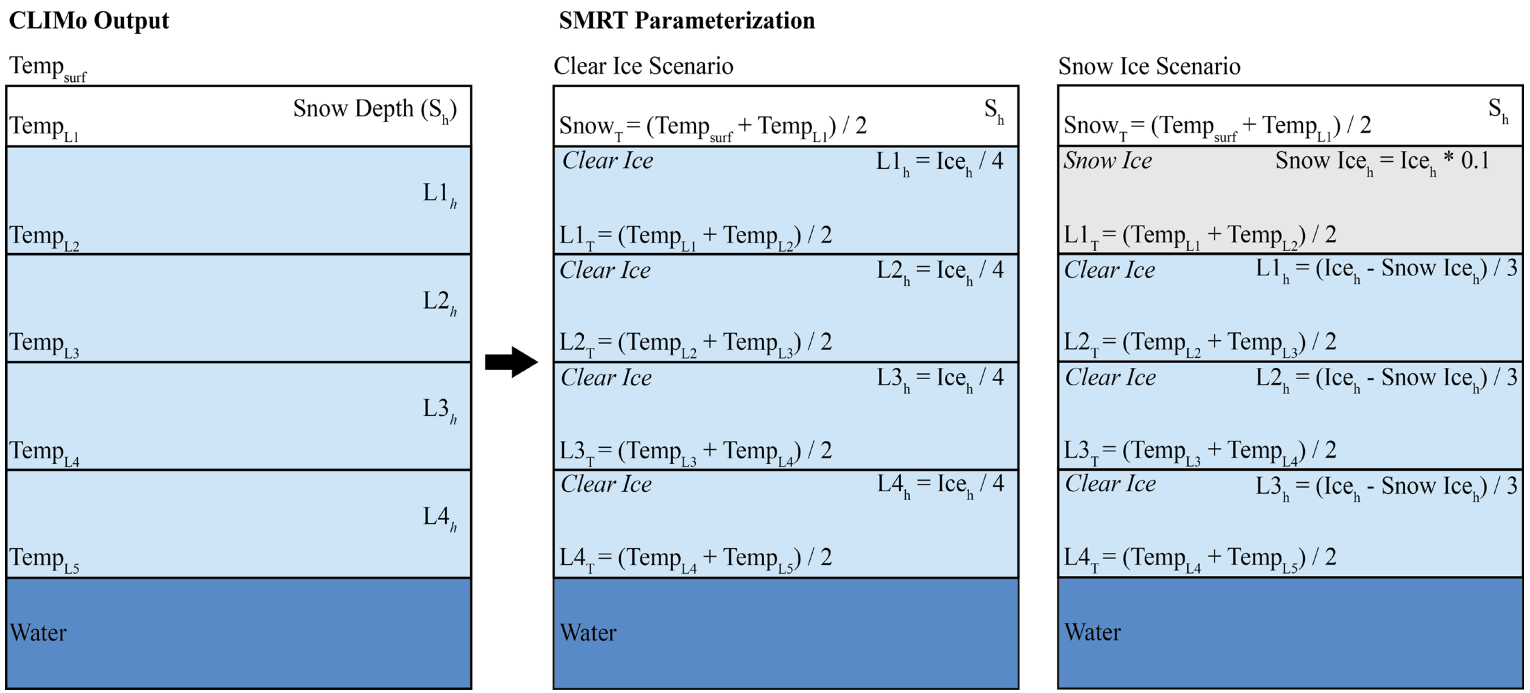
- Freeze-up/Break-up dates
- On-ice Snow Depth
- Ice Thickness (Snow/Clear Ice)
- Temperature Profile (ice and water temperature during the ice-free period)
- Energy Balance Components


**SMRT:** Picard, G., Sandells, M., Löwe, H., 2018. SMRT: An active-passive microwave radiative transfer model for snow with multiple microstructure and scattering formulations (v1.0). *Geoscientific Model Development,* 11: 2763–2788.

**CLIMo:** Duguay, C.R., G.M. Flato, M.O. Jeffries, P. Ménard, K. Morris, and W.R. Rouse, 2003. Ice cover variability on shallow lakes at high latitudes: Model simulations and observations. *Hydrological Processes*, 17(17): 3465-3483.

# FORWARD SIMULATIONS: MODELS AND SENSITIVITY EXPERIMENTS

## CLIMo and SMRT Integration




CLIMo inputs to SMRT are ice thickness, snow depth, ice temperature, and snow temperature.

## Sensitivity Experiments

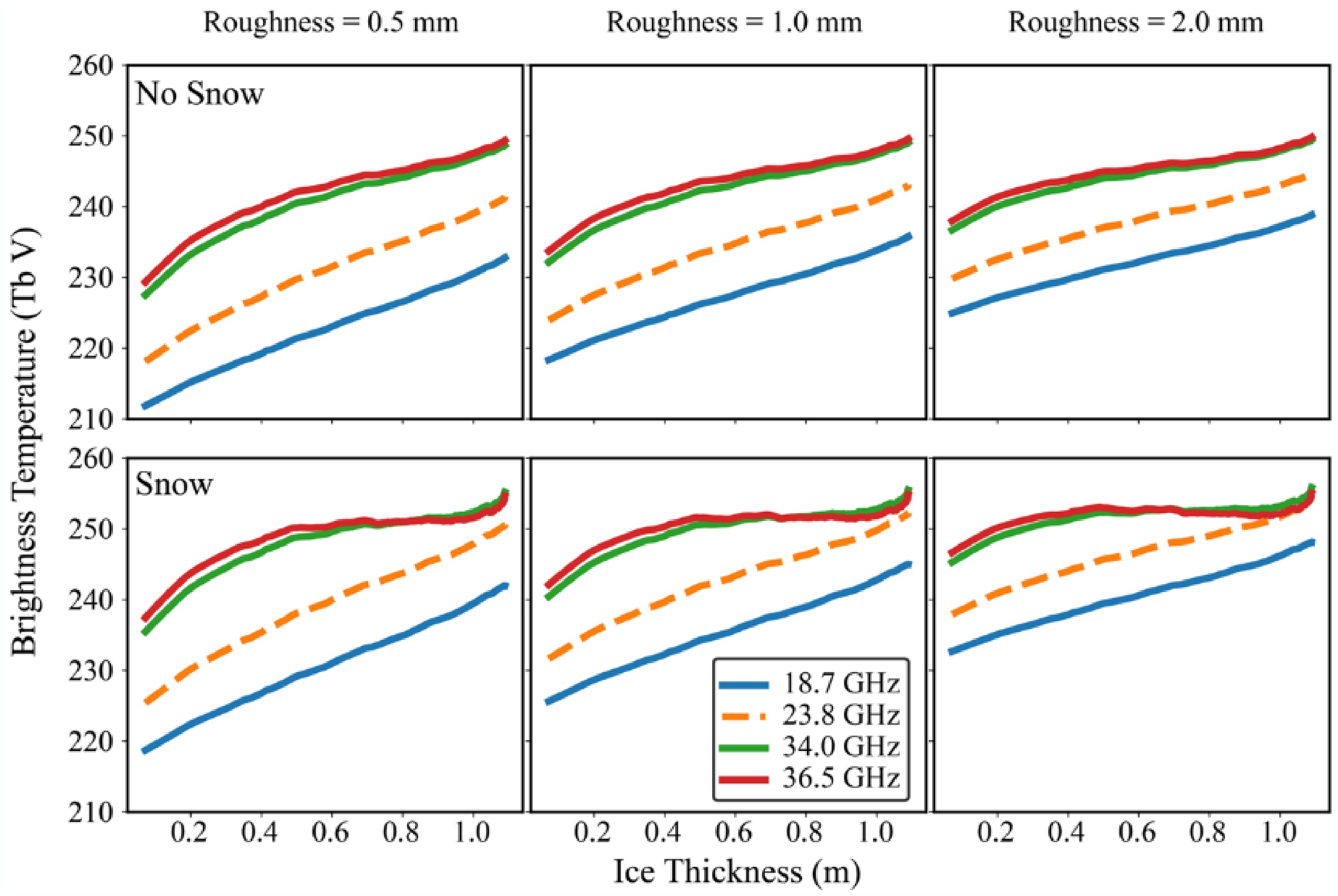
Simulations (3.2 to 36.5 GHz) of Tb and σ° for various scenarios of ice (LIT, roughness at ice-water interface, clear ice, snow ice, bubble radius) and overlying snow (depth, density, wetness) properties.

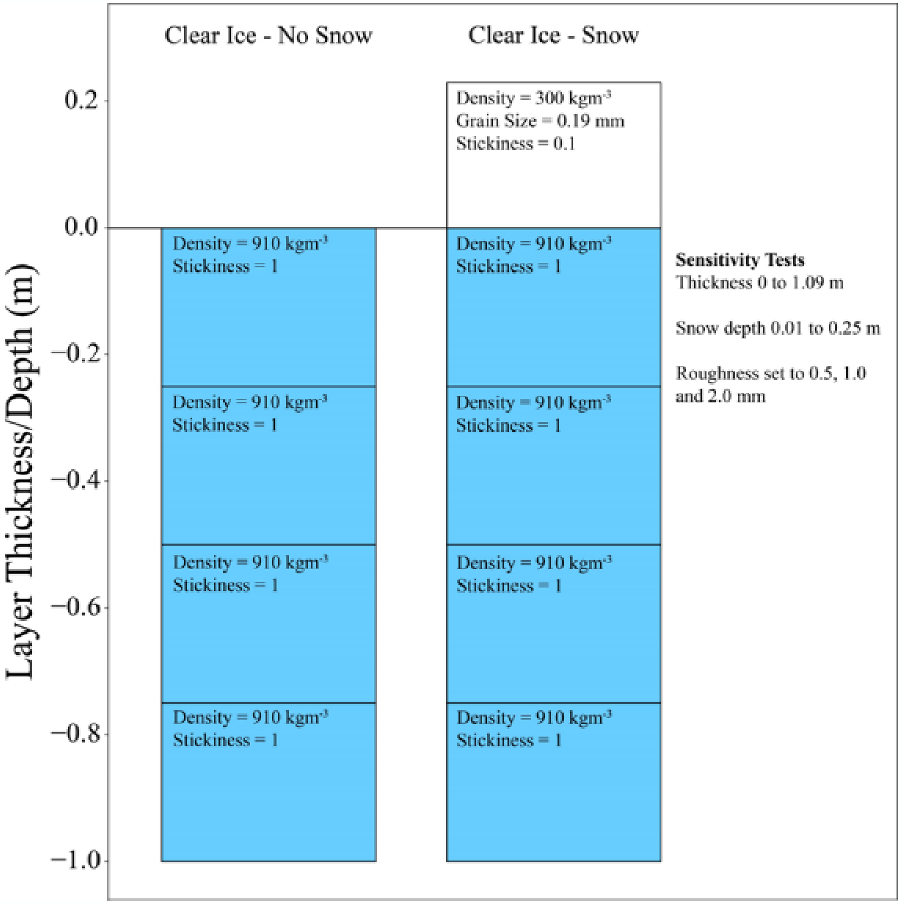
**Note:** Being fundamentally a 1-D model, SMRT cannot account for 3-D features such as pressure ridges and cracks in the ice.

# FORWARD SUMULATIONS: SENSITIVITY OF Tb TO ICE THICKNESS

## Great Slave Lake (40-m mixed layer depth)

### Tb simulations (2000-2020 average)

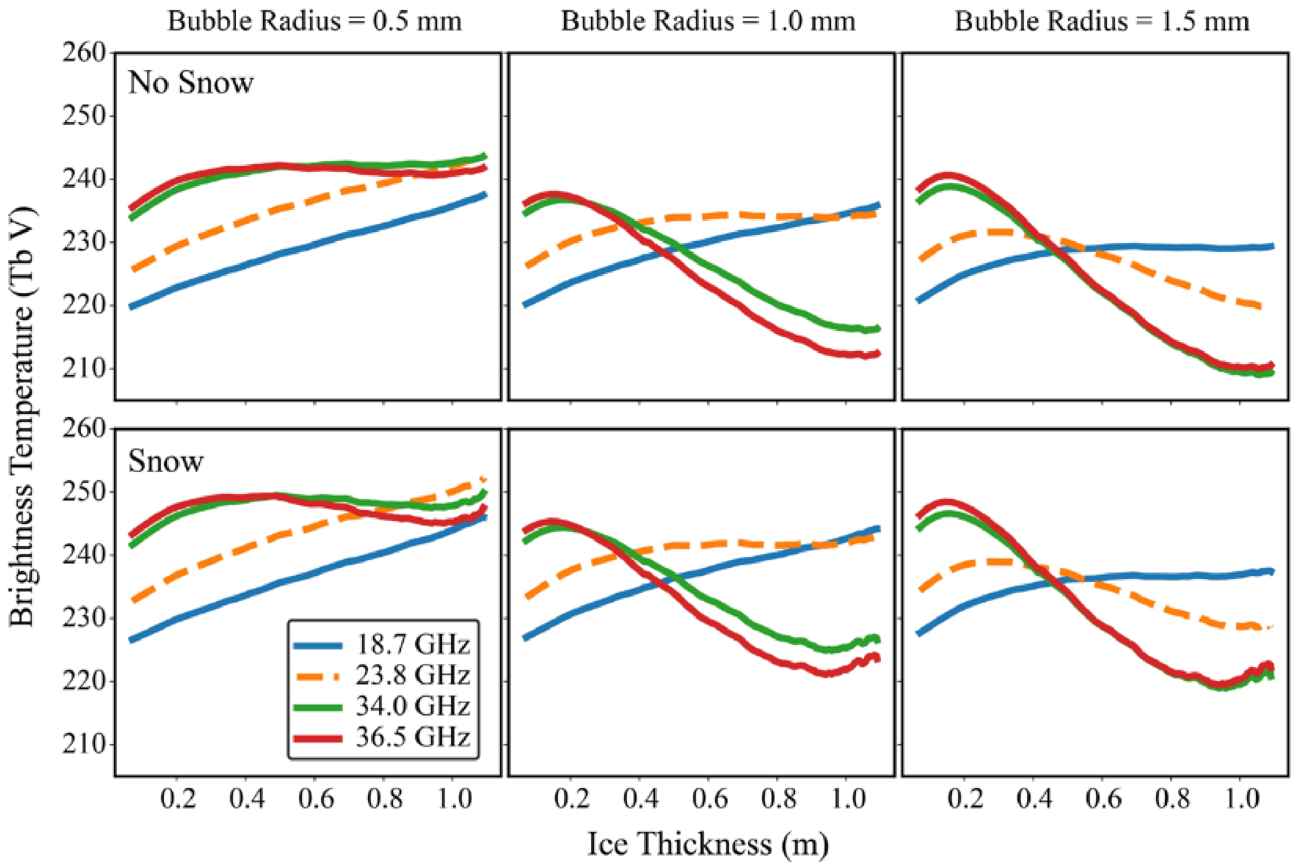


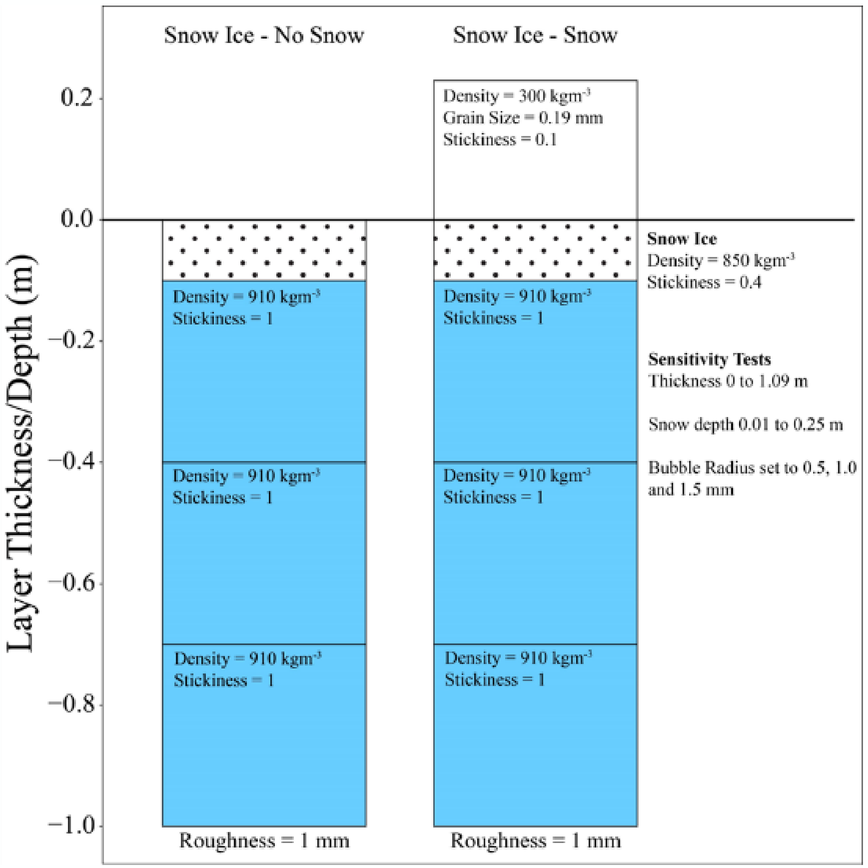
# FORWARD SUMULATIONS: INFLUENCE OF SNOW ICE ON RELATION BETWEEN Tb AND ICE THICKNESS

## Great Slave Lake (40-m mixed layer depth)

### Tb simulations (2000-2020 average)



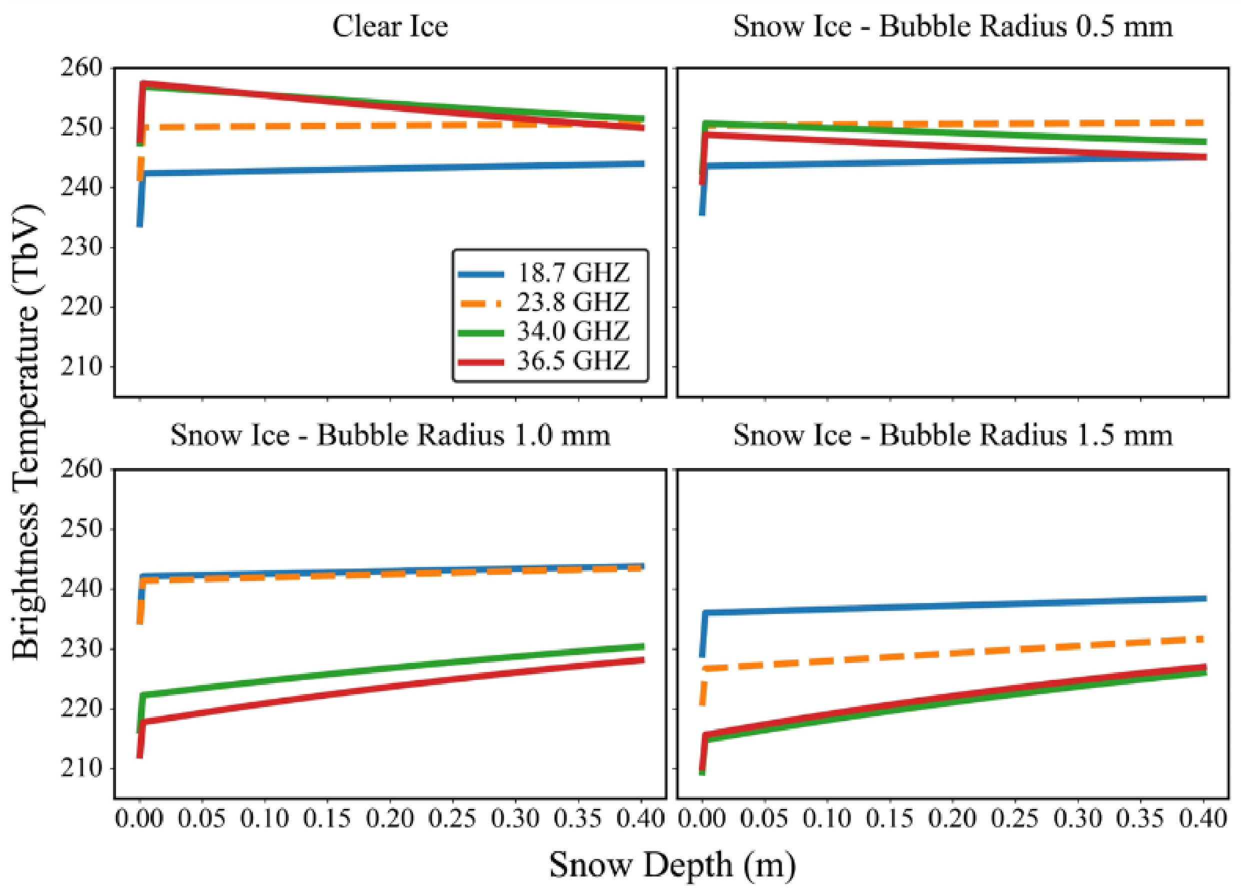

Snow ice set at 10% of the total ice column

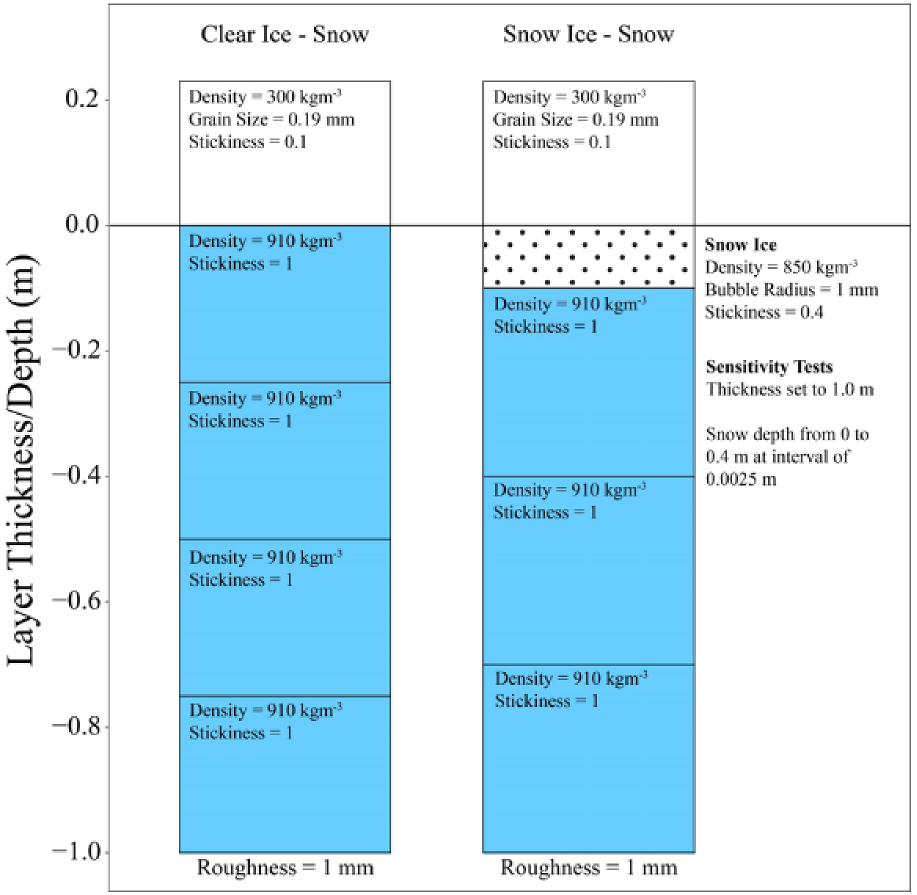


# FORWARD SUMULATIONS: SENSITIVITY OF Tb TO SNOW DEPTH

## Great Slave Lake (40-m mixed layer depth)

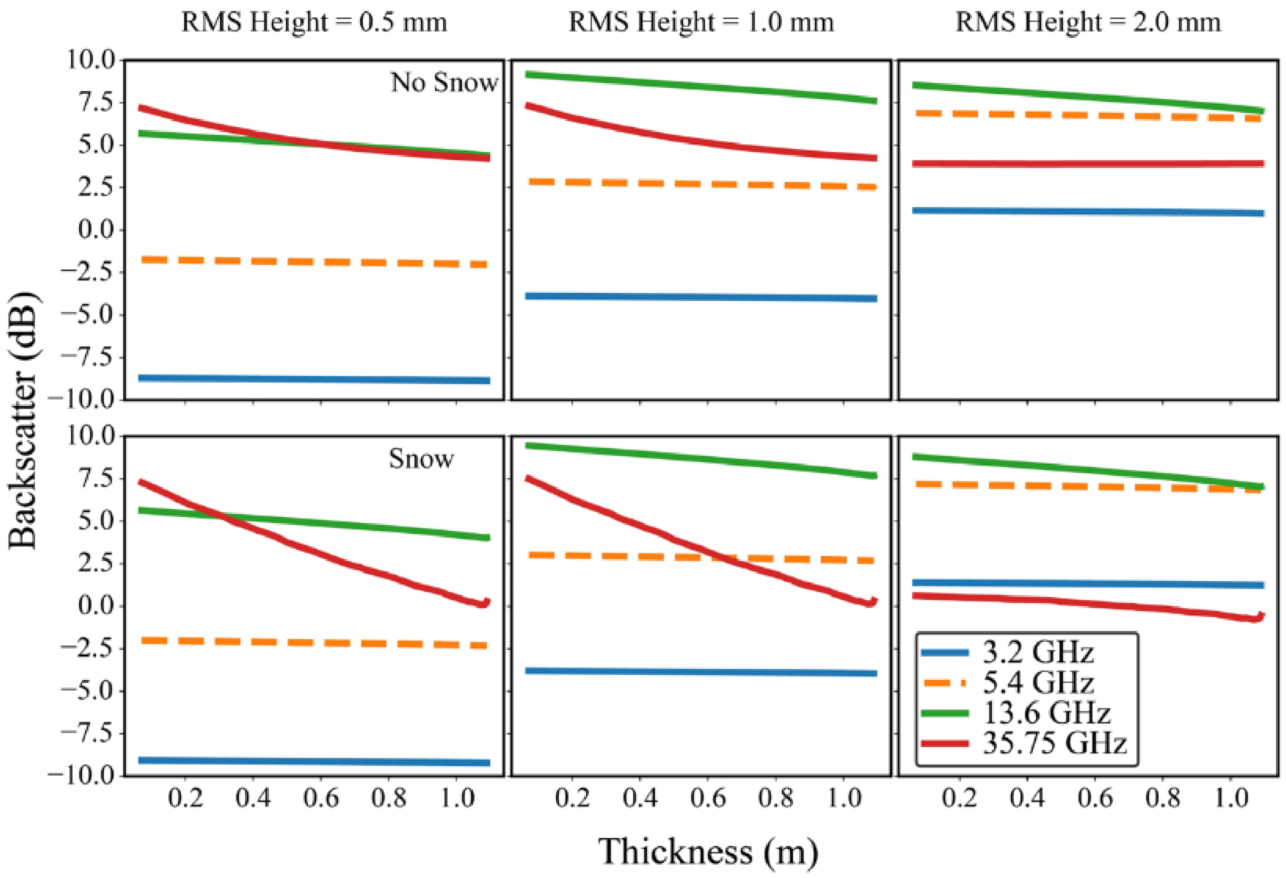
### Tb simulations (2000-2020 average)

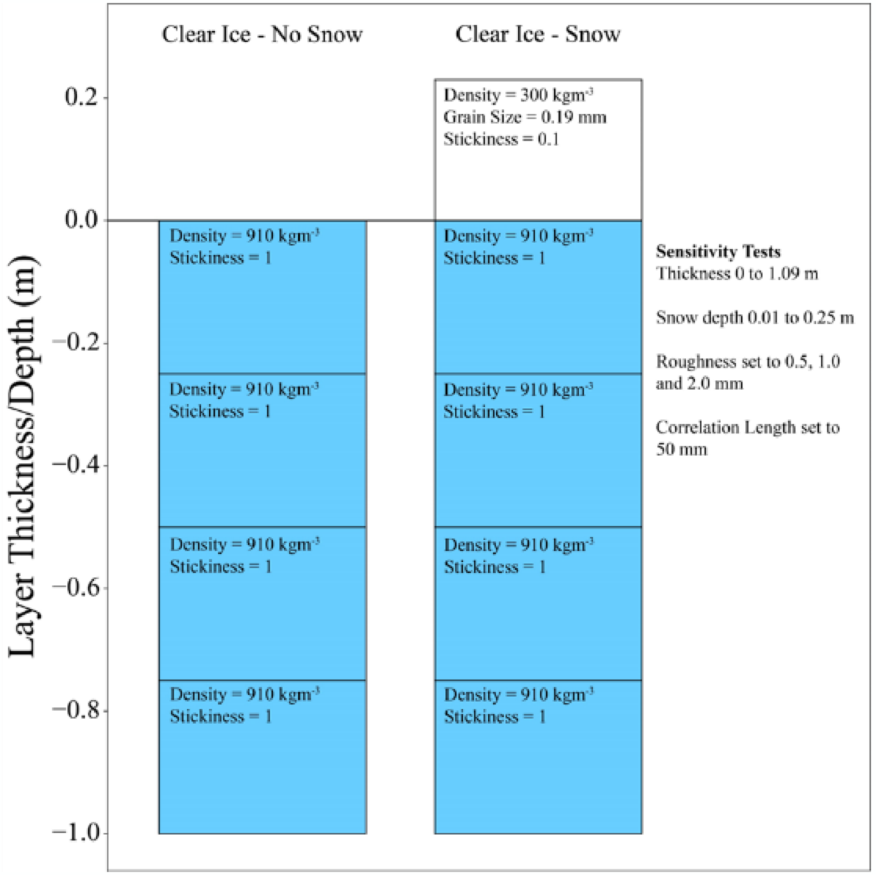


# Great Slave Lake (40-m mixed layer depth)

## σ° simulations (2000-2020 average)

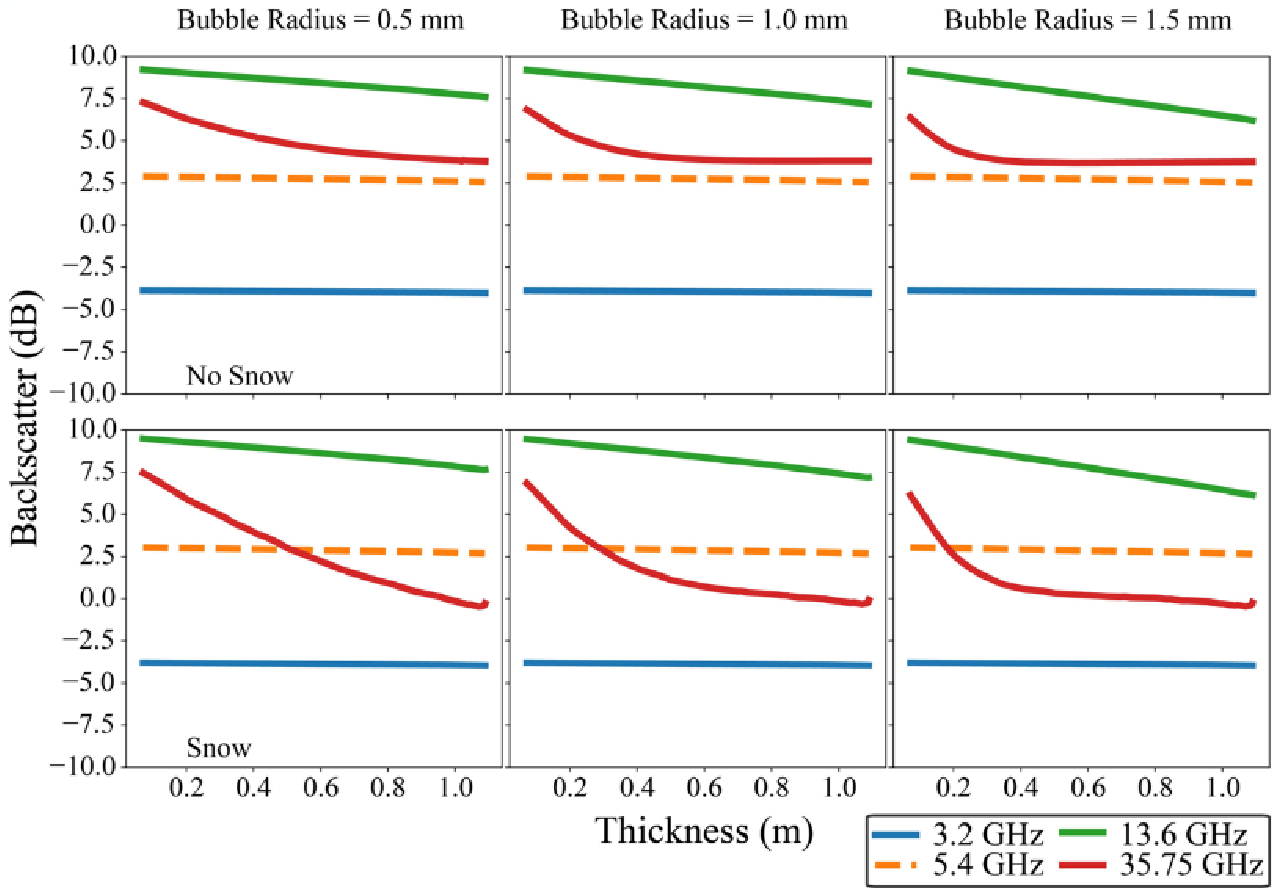


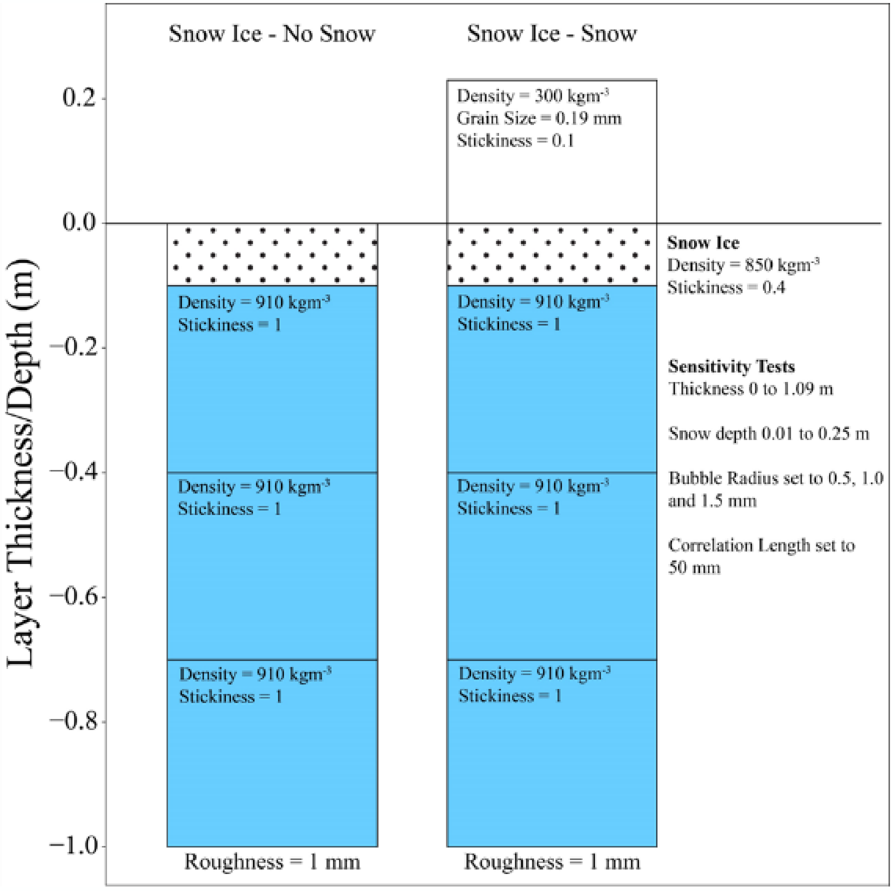
# FORWARD SUMULATIONS: INFLUENCE OF SNOW ICE ON RELATION BETWEEN σ° AND ICE THICKNESS

## Great Slave Lake (40-m mixed layer depth)

### σ° simulations (2000-2020 average)



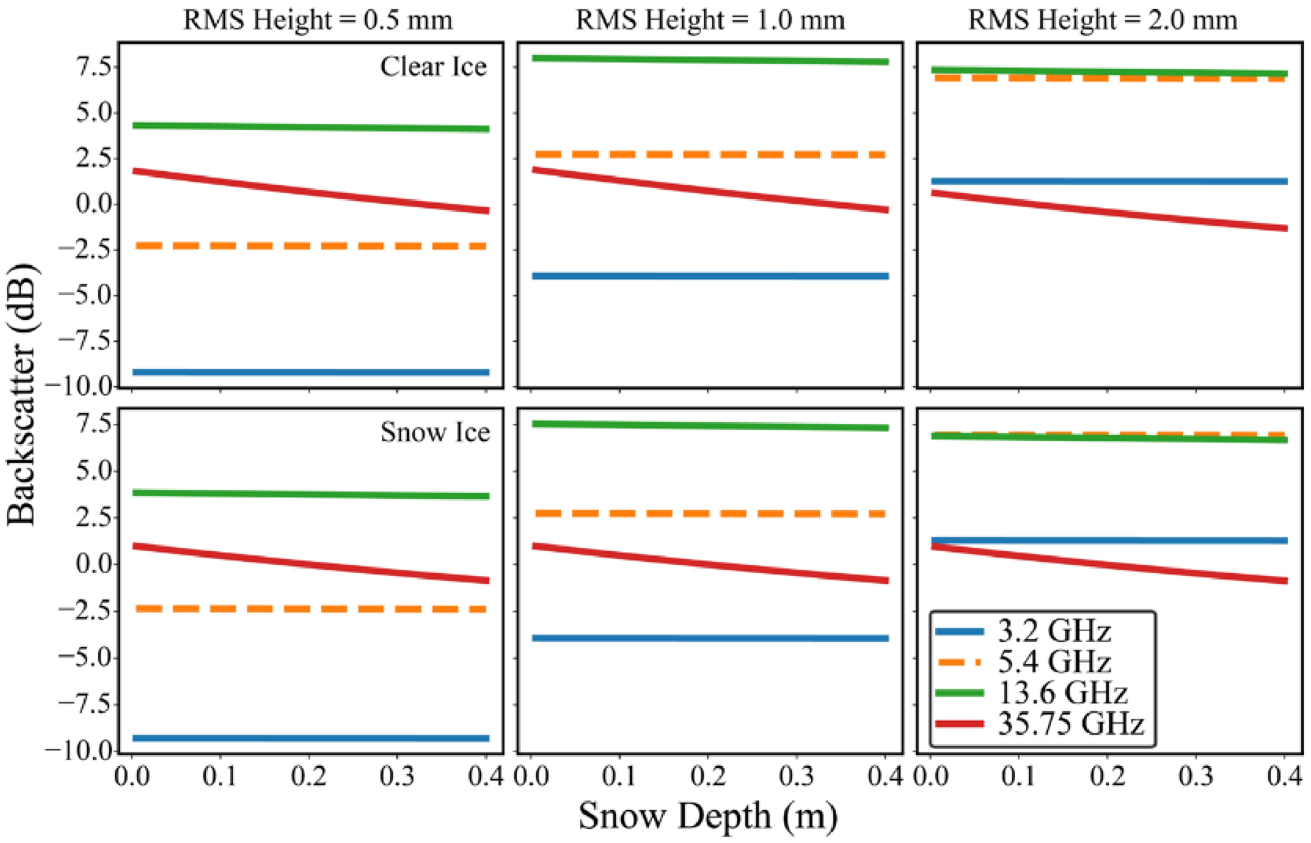

Snow ice set at 10% of the total ice column

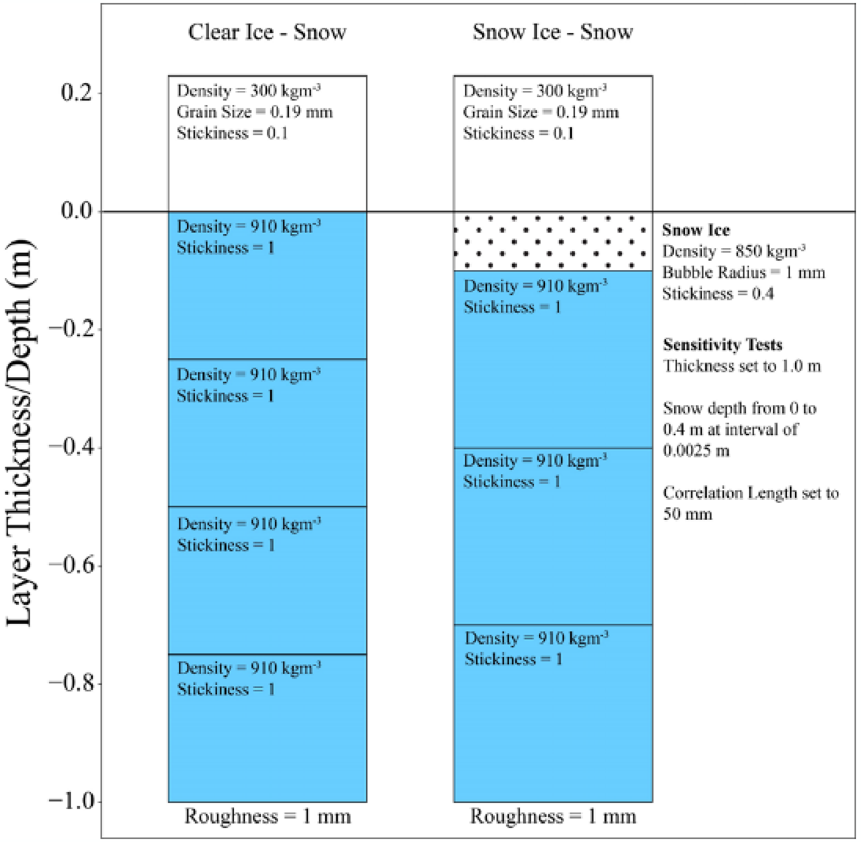


# FORWARD SUMULATIONS: SENSITIVITY OF σ° TO SNOW DEPTH

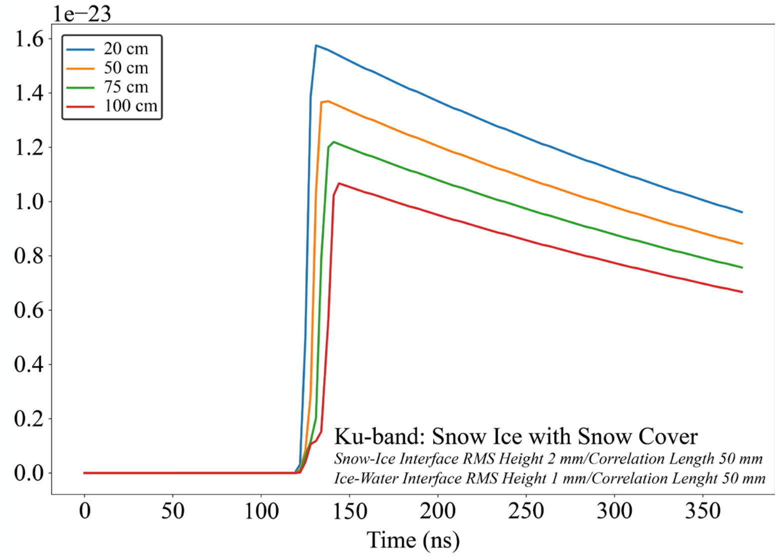
## Great Slave Lake (40-m mixed layer depth)

### σ° simulations (2000-2020 average)



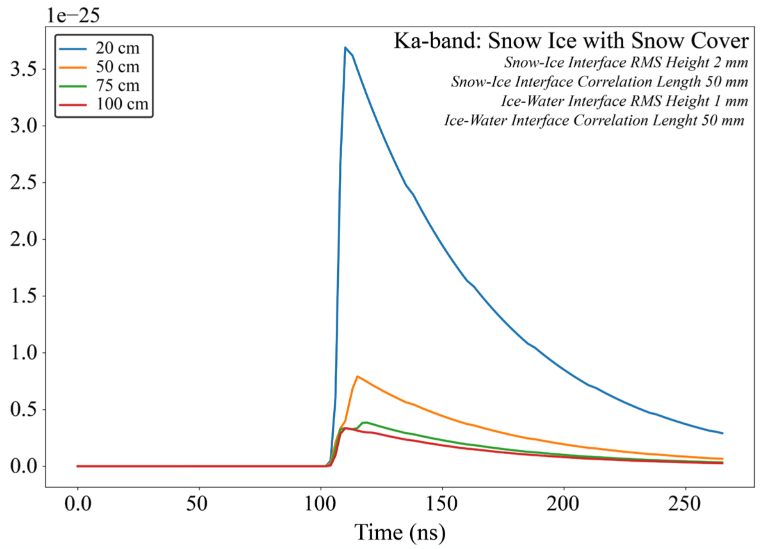
# FORWARD SUMULATIONS: WAVEFORMS




<u>New “nadir LRM altimetry” module implemented in SMRT now being tested for lake ice</u>

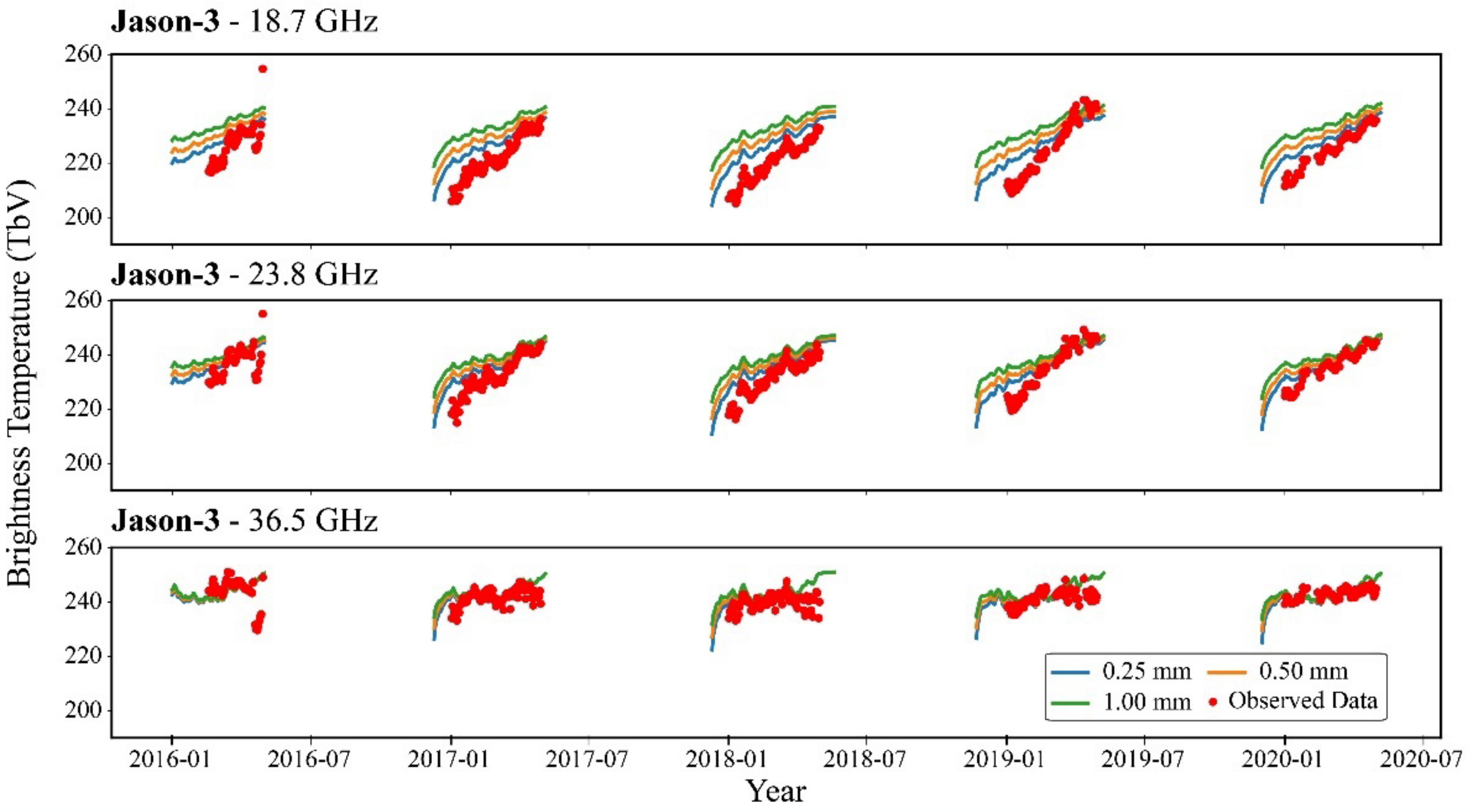
Paper describing the new extension applied to Antarctica:

Larue et al., 2021. Radar altimeter waveform simulations in Antarctica with the Snow Microwave Radiative Transfer Model (SMRT). *Remote Sensing of Environment,* 263, 112534.



# SIMULATIONS vs MEASUREMENTS: BRIGHTNESS TEMPERATURE

## Great Bear Lake (Centre)




RMSE = 6.85
ρ = 0.98*

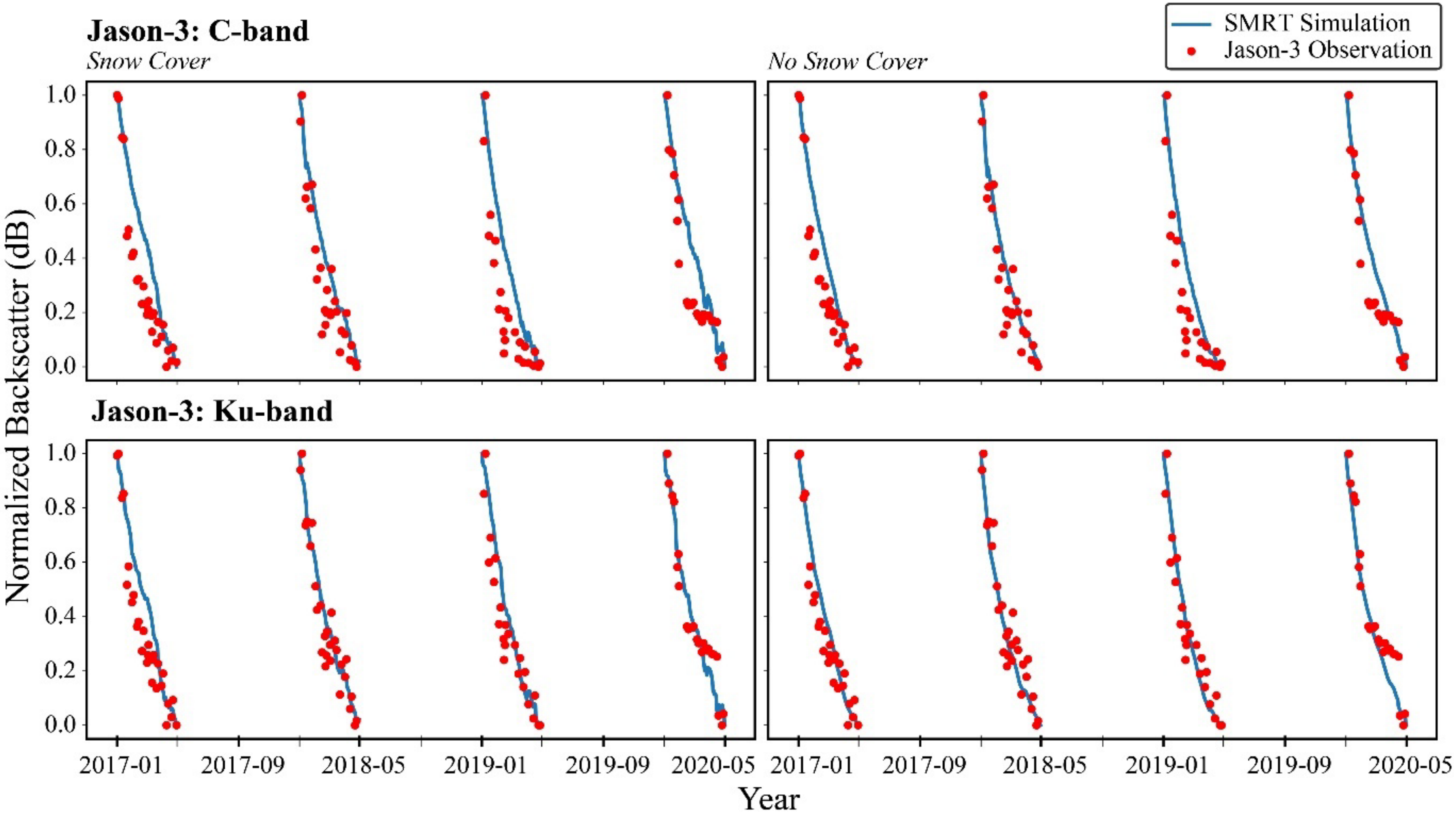
RMSE = 4.70
ρ = 0.95*

RMSE = 4.30
ρ = 0.39*

*Denotes significance $p < 0.05$

# SIMULATIONS vs MEASUREMENTS: BACKSCATTER

## Great Bear Lake (Keith Arm)




$0.13 \leq RMSE \leq 0.17$
$\rho = 0.77^*$

$0.08 \leq RMSE \leq 0.11$
$0.78^* \leq \rho \leq 0.79^*$

*Denotes significance $p < 0.05$

# CONCLUSIONS AND PERSPECTIVES

- A thermodynamic lake ice model (CLIMo) has now been "coupled" with SMRT, which allows for more realistic (beyond synthetic) simulations of the impact of varied ice and snow properties with ice growth on brightness temperature, backscatter and waveforms.
    - The new "nadir LRM altimetry" module needs to be further tested and compared to altimeter waveforms.
- The quality of LIT retrievals from physical/analytical and empirical approaches can be affected by ice and overlying snow properties/conditions in addition to ice thickness.
- Sensitivity experiments further support the use of 13.6 GHz radar (Ku-band) and 18-19 GHz radiometer data for the retrieval of LIT and the potential of Ka-band (ca. 34-37 GHz range) used alone or in combination with Ku-band for the retrieval of on-ice snow depth.
    - These results have implications for future work investigating the retrieval of LIT and snow depth from the upcoming SWOT and CRISTAL missions.
- Extension of SMRT to high-resolution SAR altimetry mode is needed for the simulation of waveforms from current (CryoSat-2, Sentinel-3, Sentinel-6) and future missions (SWOT, CRISTAL).

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TAKING THE PULSE OF OUR PLANET FROM SPACE

# THANK YOU FOR YOUR ATTENTION!

LIAM Project website:
https://www.h2ogeomatics.com/lake-ice-from-altimetry-missions-li