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Investigation on the effects of ice on lake water surface height retrieval from Sentinel-3 altimetry data

(project ID: 1804f5)

Zhaoqin Li and Shusen Wang

Canada Centre for Remote Sensing

Natural Resources Canada

zhaoqin.li@NRCan-RNCan.gc.ca

shusen.wang@NRCan-RNCan.gc.ca

January 4, 2021

Canada

Research rationales

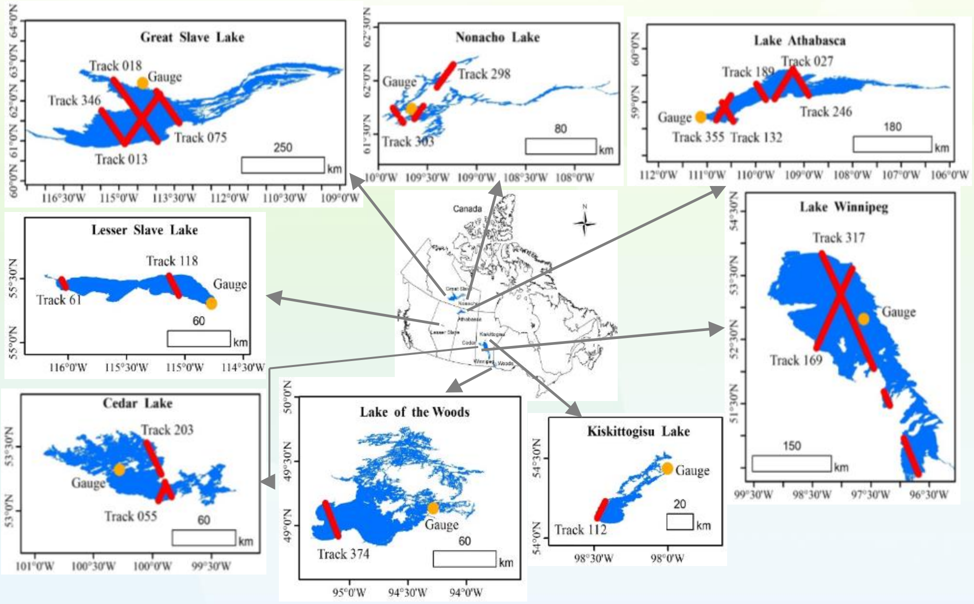
- A large number of lakes in cold regions have ice covers in winter
- Ice cover is one of major factors that reduce the accuracy of lake surface water level (SWL) retrieval (Birkett, 1995; Birkett and Beckley, 2010; Nielsen et al., 2020; Shu et al., 2020; Ziyad et al., 2020)
- Effects of ice cover on lake SWL retrieval are less understood
- New models are needed to improve the accuracy of SWL retrieval over ice-covered lakes

Objectives

- To investigate ice cover effects on lake SWL retrieval from Sentinel-3 altimetry data

- To develop a new model to improve accuracy of SWL retrieval over ice-covered lakes

Study lakes in Canada



The geographic location of the study lakes in Canada, the gauge stations (orange circles) over the lakes, and the Sentinel-3A ground tracks (red lines).

The study lakes, gauges, and the period of SWL data measurements.

Lakes	Lake area (km^2)	Gauge	Latitude	Longitude	Gauge data period
Great Slave	26734.29	Yellowknife	62° 26' 29" N	114° 20' 59" W	2019/09/01-2021/05/31
Winnipeg	23923.04	George Island	52° 49' 06" N	97° 37' 10" W	2019/09/01-2021/05/31
Athabasca	7528.73	Fort Chipewyan	58° 42' 47" N	111° 07' 20" W	2019/09/01-2021/05/31
Lake of the Woods	3472.81	Hanson Bay	49° 07' 58" N	94° 17' 00" W	2019/09/01-2021/05/31
Cedar	2504.26	Oleson Point	53° 19' 10" N	100° 16' 45" W	2019/09/01-2021/05/31
Lesser Slave	1186.51	Slave Lake	55° 18' 20" N	114° 46' 17" W	2019/09/01-2019/12/31; 2020/03/21-2021/05/31
Nonacho	865.24	Lutselk'e (Snowdrift)	61° 44' 01" N	109° 39' 40" W	2019/09/01-2019/12/31; 2020/03/21-2021/05/31
Kiskittogisu	358.57	Whiskey Jack Landing	54° 26' 07" N	98° 00' 10" W	2019/09/01-2019/12/31; 2020/03/21-2021/05/31

Sentinel-3A SRAL data

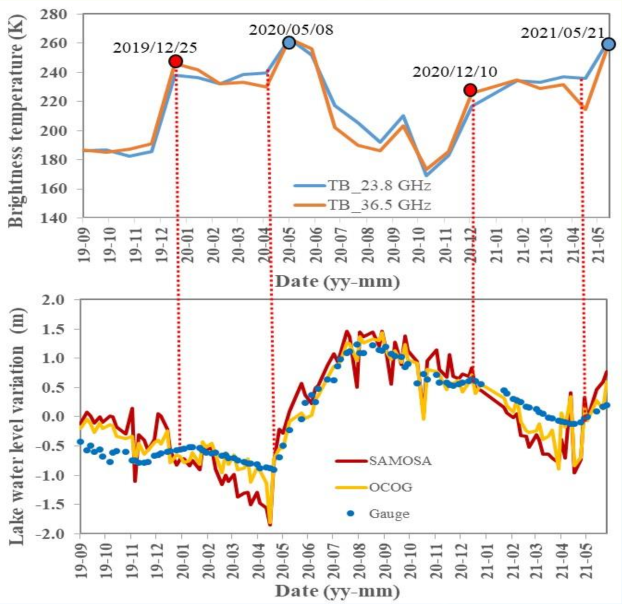
- G-POD data
  - Spatial coverage: Great Slave Lake, Athabasca Lake, and Nonacho Lake
  - Time period: Sep 01, 2019 - May 31, 2020

- SciHub data
  - Spatial coverage: all eight lakes in this study
  - Time period: Sep 01, 2019 - May 31, 2021

Ice cover effects on SWL retrieval

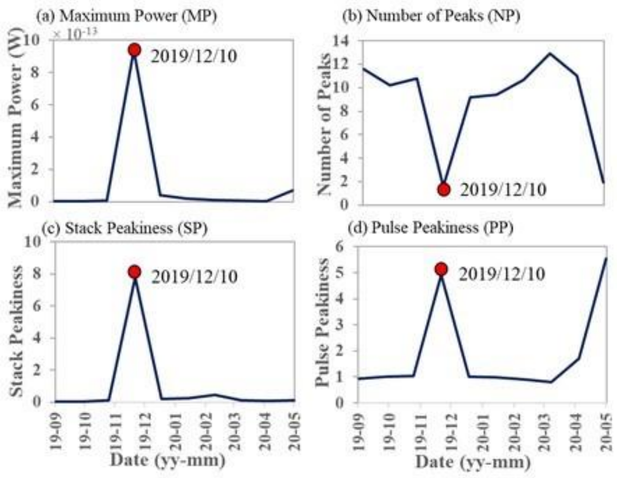
- Presence of ice covers causes bias (mainly negative) on SWL retrieval using SAMOSA and OCOG retrackers from Sentinel-3 SRAL data

- Effects of ice cover on SWL retrieval are highly dependent on ice conditions which influence the penetration of Ku-band radar pulse

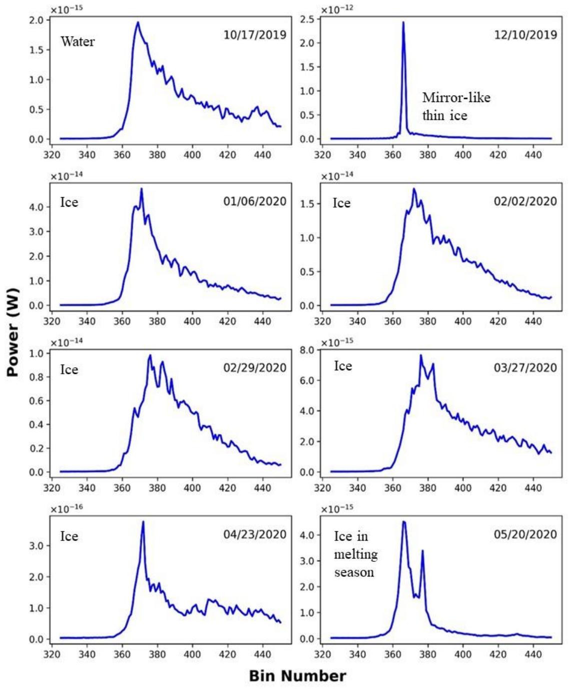


Ice cover phenology detected from the temporal variation of brightness temperature (the top), and *in-situ* SWL gauge measurements and SWL retrieved from Sentinel-3 SRAL data using SAMOSA and OCOG retrackers (the bottom).

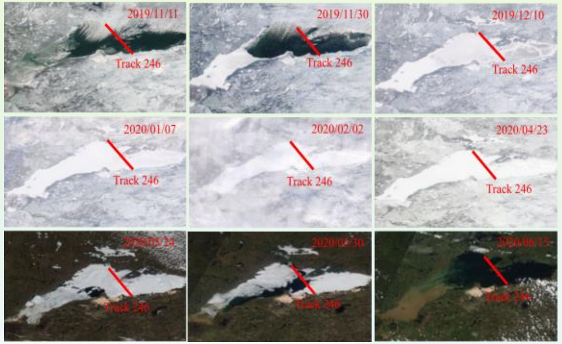
The mechanism behind ice cover effects



Waveform evolution during a water-ice-water cycle demonstrated using the averaged waveform parameters along Sentinel-3A track 246 over Lake Athabasca.



Waveform evolution at the center tracking point of Sentinel-3A track 246 over Lake Athabasca.



Lake ice progress on the Athabasca Lake from November 2019 to June 2020, derived from MODIS images (Date format: yyyy\mm\dd).

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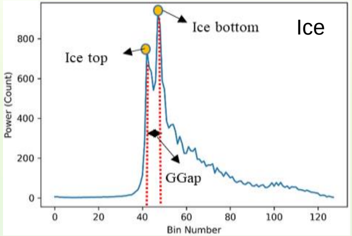
The gap in addressing ice cover effects

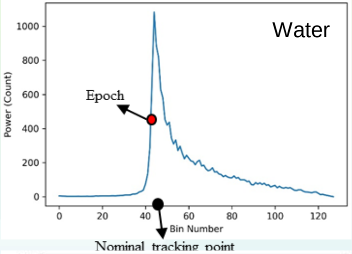
- Bimodal correction improved SWL estimation on lakes (e.g., Great Slave Lake) where bimodal waveforms were generated (Shu et al. 2020)

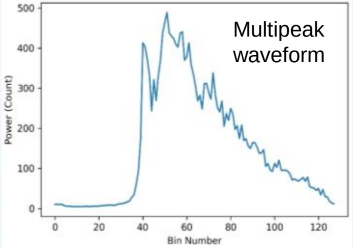
$$SWL_{ice\_corrected} = SWL_{ice\_top} - (\rho_{water} - \rho_{ice}) \times Ice_{thickness}$$

where SWL_{ice_top} is the height of the top ice surface, calculated from the leading edge of the first peak, ρ_{water} is density of water, ρ_{ice} is density of ice, and $Ice_{thickness}$ is ice thickness

- Limitations of the bimodal correction
  - The correction is not working on multipeak waveforms affected by environmental factors, such as topographic relief
  - SWL_{ice_top} was calculated from the leading edge of the first peak, causing a bias measured by the travel distance between mid-point and first peak





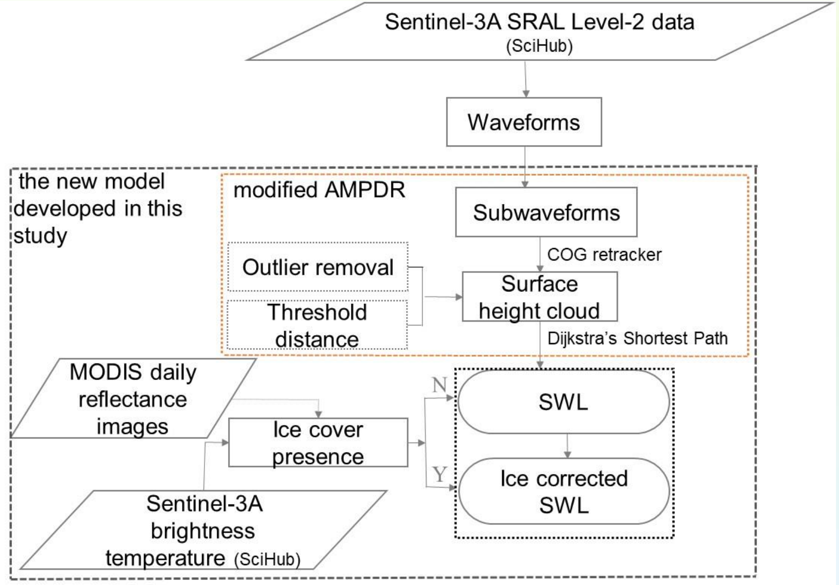


The new model to address the gap

To overcome the limitation of the bimodal correction, we developed a new model to reduce ice cover effects on SWL retrieval from multipeak waveforms following two steps:

- Modified the multiscale-based peak detection retracker (AMPDR) developed by Chen et al. (2020) to retrieve SWL from multipeak waveforms

- Corrected SWL retrieval from the modified AMPDR (mAMPDR) using ice thickness



Addressing ice cover effects in the new model

Assuming SWL retrieved using the mAMPDR retracker was from the leading edge of the waveform peak generated at the ice-water interface, water-equivalent lake surface level ($SWL_{ice\_corrected}$) was estimated using

$$SWL_{ice\_corrected} = SWL + (\rho_{water} - \rho_{ice}) \times Ice_{thickness}$$

where SWL is the surface water level retrieved using the modified AMPDR

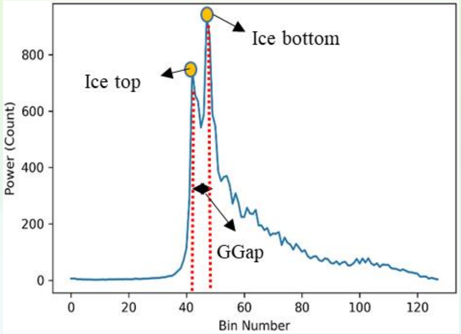
ρ_{water} is water density (1000 kg/m^3)

ρ_{ice} is ice density (915 kg/m^3)

$$Ice_{thickness} = \frac{(GGap \times 3.125 \times C_{ice})}{2}$$

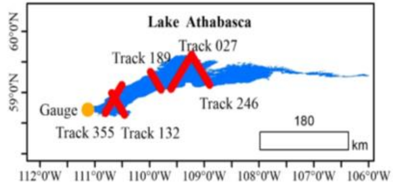
Beckers et al. (2017)

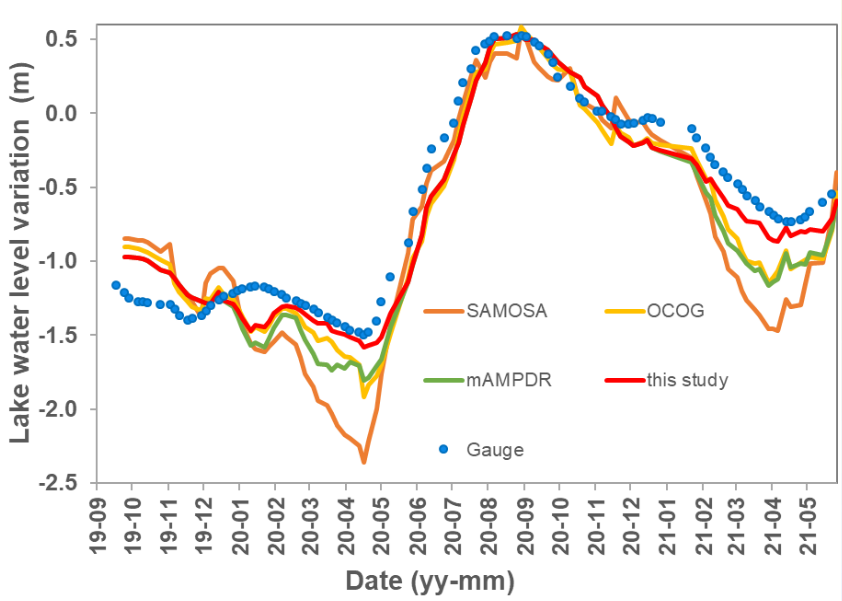
where $GGap$ is the gate gap between the peak of the waveform generated at the ice-water interface and the peak at the ice-snow\air interface; and C_{ice} is the propagation velocity of light in ice.

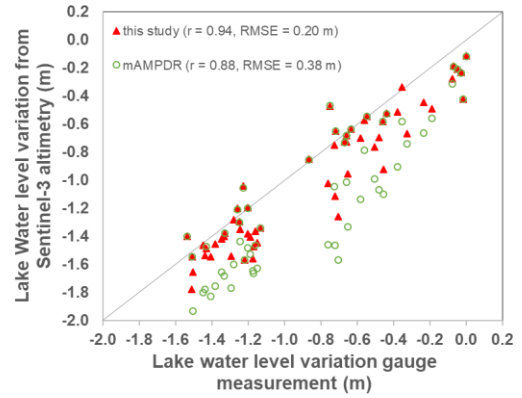


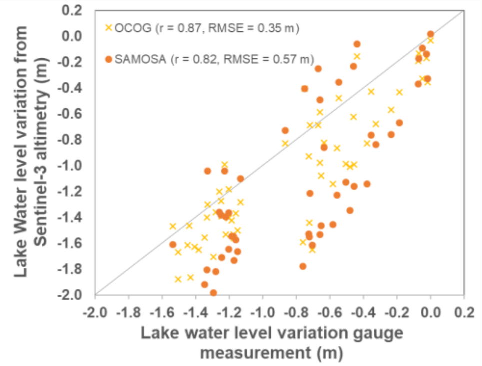
Water level retrieval

Lake Athabasca (59.11°N, 109.88°W)









Left panel: the temporal variation of in-situ water level and water level retrieved on Lake Athabasca using single-peak retracking methods (SAMOSA and OCOG), modified multi-peak waveform retracker (mAMPDR), and ice cover corrected mAMPDR (this study) from Sentinel-3A SRAL altimetry during the period of September, 2019 to May, 2021. Middle and right panel: the scatter plots between water level gauge measurements and water level retrieved from Sentinel-3 altimetry during the winter seasons of 2019-2020 and 2020-2021.

Water level retrieval in winter

(on the other study lakes)

The absolute mean error (m) of water level retrieved using four models against in-situ gauge measurements in the winters of 2019-2020 and 2020-2021. The models are single-peak waveform retracker SAMOSA and OCOG, modified multi-peak waveform retracker (mAMPDR), and ice cover corrected mAMPDR (this study).

Lakes	SAMOSA	OCOG	modified AMPDR	this study
Lake of the Woods	0.42	0.13	0.20	0.10
Great Slave Lake	0.61	0.30	0.18	0.11
Kiskittogisu Lake	0.63	0.53	0.19	0.15
Lake Winnipeg	0.49	0.39	0.35	0.20
Nonacho Lake	0.34	0.24	0.38	0.25
Cedar Lake	0.61	0.66	0.41	0.38
Lesser Slave Lake	0.69	0.58	0.59	0.49

Discussion

- The new model allows retrieving SWL from multi-peak waveforms complexed by the presence of ice covers and environmental factors (e.g., surrounding topographic relief)

- The new model is applicable to waveforms of multi-satellite altimeters, contributing to a long-term SWL data series generation in cold regions

Discussion (cont.)

- The new model might be limited when all the waveforms along the track are heavily contaminated

- The implementation of the new model may face an challenge of identifying ice cover duration and measuring ice thickness on some lakes
  - Determining the duration of ice-thickening using brightness temperature (T_B) at 23.8 GHz and 36.5 GHz may be difficult on some lakes because of the low frequency of T_B and the fact that T_B at 23.8 GHz and 36.5 GHz could increase abruptly
  - Ice thickness may not be measured at some track points, because
    - the empirical approach failed to find the peaks of the ice/water interface
    - Ku-band's penetration capacity may be limited by ice cover conditions
  - Ice thickness estimates were not validated because of the lack of in-situ measurements

Conclusion

- Ice covers affected maximum power and number of peaks of waveforms, further causing a bias on SWL retrieval

- The new model developed in this study improved the accuracy of SWL retrieval, reducing absolute mean error by 3 to 15 cm over the ice-covered lakes

Zhaoqin Li and Shusen Wang. A novel method for retrieving water levels over ice-covered lakes. Remote Sensing of Environment. (under review)

Future research

- Improve the accuracy of SWL retrieval over ice-covered lakes through better understanding ice cover effects on Ku-band SAR echo waveforms

- Increase the temporal and spatial coverage of water level at catchment level in northern environments by integrating Sentinel-3 altimetry with other satellite altimetry, including Radar and LiDAR

- Integrate Satellite altimetry data into water resources management

Acknowledgements

- Project funded by Cumulative Effects program of Natural Resources Canada
- Project supported by European Space Agency (ESA) Network of Resources Initiative
- Marco Restano and Américo Ambrózio at ESA for helping understand the G-POD data and use the BRAT, respectively
- Amber Brown and Angus Pippy at Environment and Climate Change Canada (ECCC) for water level gauge data

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