Monitoring lake ice phenology from CYGNSS: Algorithm development and assessment using Qinghai Lake, Tibet Plateau, as a case study

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1. Abstract

This study introduces the first use of Global Navigation Satellite System Reflectometry (GNSS-R) for monitoring lake ice phenology. This is demonstrated using Qinghai Lake, Tibetan Plateau, as a case study. Signal-to-Noise Ratio (SNR) values obtained from the Cyclone GNSS (CYGNSS) constellation over four ice seasons (2018 to 2022) were used to examine the impact of lake surface conditions on reflected GNSS signals during open water and ice cover seasons. A moving t-test algorithm was applied to time-varying SNR values allowing for the detection of lake ice at daily temporal resolution. Good agreement was achieved between ice phenology records derived from CYGNSS data and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. The CYGNSS timings for freeze-up, i.e., the period starting with the first appearance of ice on the lake (freeze-up start; FUS) until the lake becomes fully ice covered (freeze-up end; FUE), as well as those for breakup, i.e., the period beginning with the first pixel of open water (breakup start; BUS) and ending when the whole lake becomes ice-free (breakup end; BUE), were validated against the phenology dates derived from MODIS images. Mean absolute errors are 7, 5, 10, 4 and 5 days for FUS, FUE, BUS, BUE and ice cover duration, respectively. Observations revealed the sensitivity of GNSS reflected signals to surface melt prior to the appearance of open water conditions as determined from MODIS, which explains the larger difference of 10 days for BUS. While the CYGNSS constellation is limited to the coverage of lakes between 38° S and 38° N, the approach presented herein will be applicable to data from other GNSS-R missions that provide opportunities for the monitoring of ice phenology from large lakes globally (e.g., Spire constellation of satellites and upcoming HydroGNSS mission, planned for launch in 2024).

2. Study Area

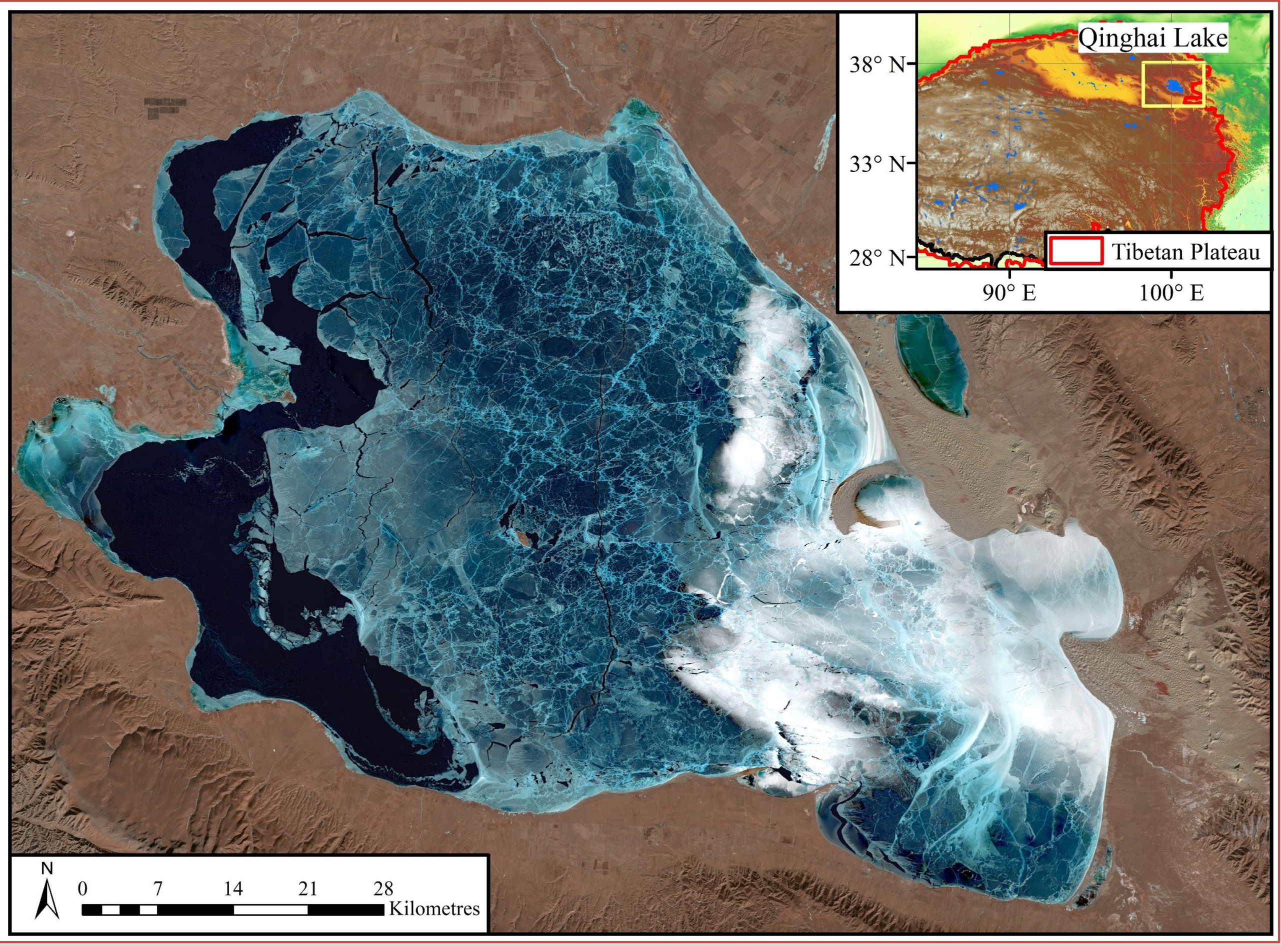


Figure 1. Qinghai Lake, Tibet Plateau, Altitude: 3,260 m; Area: 4,186 km²; Salinity: 12.5 ppt
Source: Landsat-8 Level-1 OLI/TIRS image, USGS; DOI: /10.5066/F71835S6

3. Data Description

- CYGNSS data Level-1 (Version 3.0): Signal-to-Noise Ratio (SNR)
- MODIS imagery
- MODIS daily Land Surface Temperature (LST): MYD/MOD11A1.006
- MODIS daily albedo data products: MOD10A1 and MYD10A1
- European Space Agency Lakes Climate Change Initiative (ESA Lakes_cci) Lake Ice Cover (LIC) data products
- ERA5-Land Lake Ice Surface Temperature

4. Methods

- Comparing CYGNSS SNR with MODIS products (LST and Lake_cci) to see the impact of lake ice on GNSS-R SNR
- Running a moving t-test (MTT) to detect abrupt changes in CYGNSS SNR timeseries
- Compare MTT results with phenology dates extracted from MODIS images to evaluate the CYGNSS ability in lake ice phenology analysis

5. Results and Discussion

I) Lake Ice Impact on GNSS-R SNR

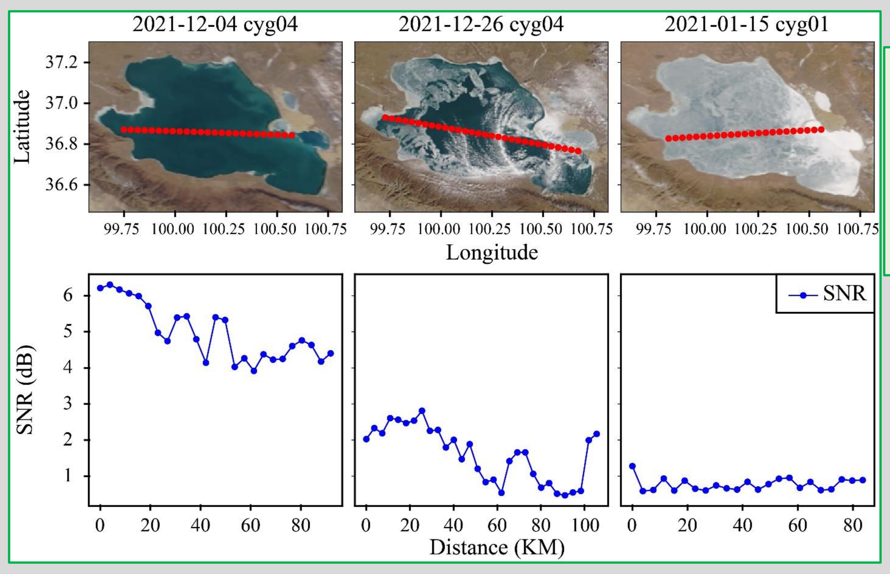


Fig 2-1. CYGNSS tracks over Qinghai Lake under three conditions: open water (left), mix of ice and water during the freeze-up period (center), and fully ice covered (right) during the 2021-2022 ice season.

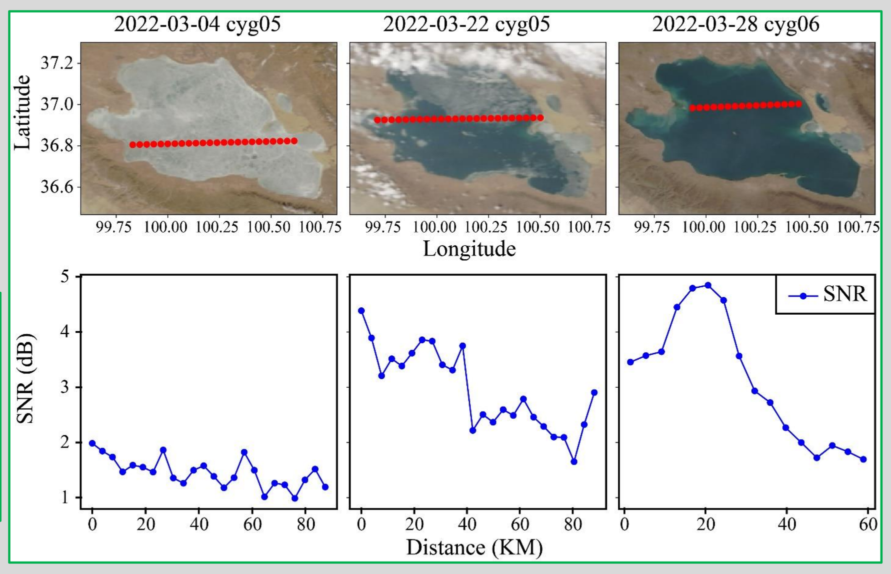


Fig 2-2. CYGNSS tracks over Qinghai Lake under three conditions: fully ice covered before breakup start (left), mix of ice and water during the breakup period (center), and open water (right) during the 2021-2022 ice season.

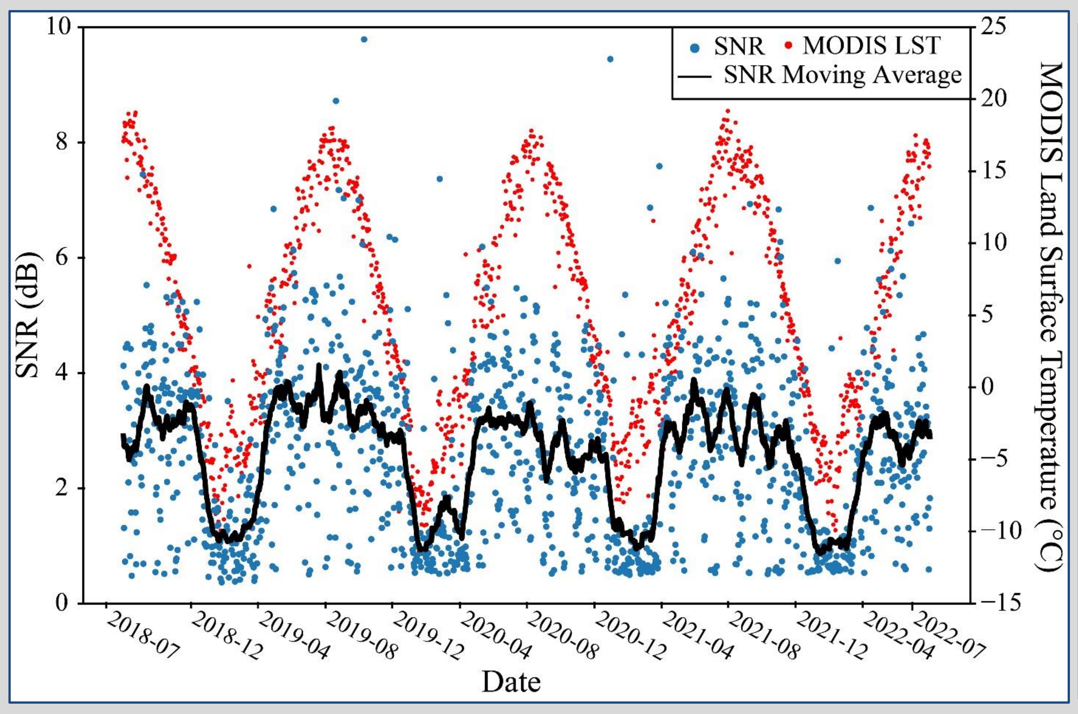
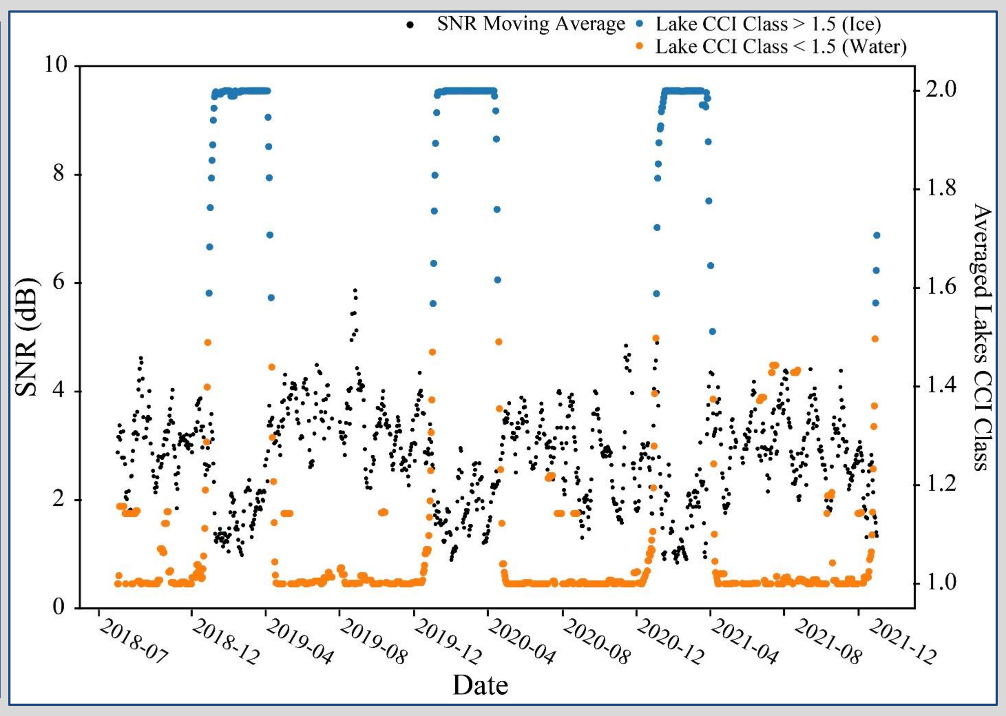


Fig 3. (Left) Variations in CYGNSS SNR (aggregated lake-wide) values over Qinghai Lake (light blue) with a 30-day moving average (dark blue) showing lower reflections during wintertime. MODIS LST variations are shown in dark/light red. (Right) CYGNSS SNR values (blue dots) and Lakes_cci LIC classification from a 7-day moving average. Orange dots correspond to when the moving average for the LIC classification was less than 1.5 (water) and blue dots correspond to when the moving average for the LIC classification was greater than 1.5 (ice). Points where the average is greater than 1.5 likely correspond to the ice season, which matches well the drops in CYGNSS SNR values.



II) Lake Ice Phenology

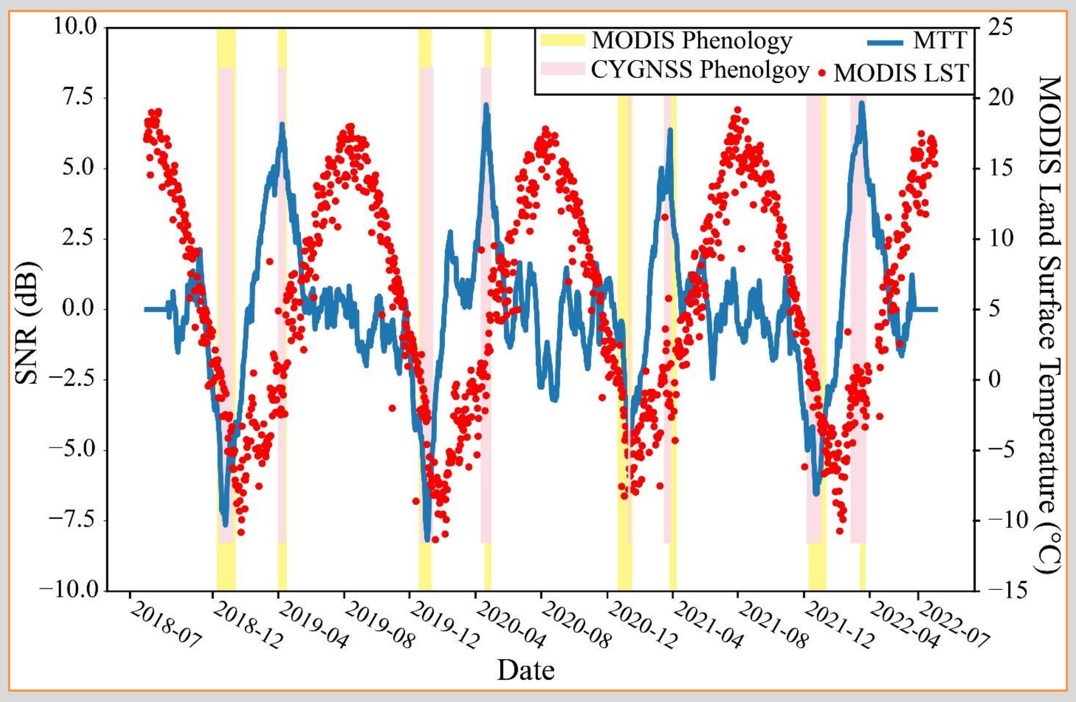


Figure 4. CYGNSS SNR MTT from 1 August 2018 to 1 August 2022. Pink bars are ice phenology periods obtained from CYGNSS and yellow bars are those visually determined from MODIS images over four FU and four BU periods. MODIS LST values are also plotted (brown dots) to show that the timing of the FU and BU periods closely match below and above freezing temperature of 0°C, respectively.

	2018-2019		2019-2020		2020-2021		2021-2022	
	FU	*BU*	*FU*	*BU*	*FU*	*BU*	*FU*	*BU*
MODIS	Dec 9 – Jan 13	Apr 4 – Apr 18	Dec 18 - Jan 11	Apr 18 – May 1	Dec 20 - Jan 17	Mar 26 - Apr 9	Dec 10 - Jan 11	Mar 16 – Mar 25
CYGNSS	Dec 13 – Jan 9	Apr 1 – Apr 14	Dec 21 - Jan 14	Apr 10 - Apr 30	Jan 10 - Jan 12	Mar 17 - Mar 29	Dec 6- Jan 2	Feb 26 – Mar 26
MTT spike	Dec 25	Apr 9	Jan 4	Apr 24	Jan 10	Mar 28	Dec 27	Mar 19
MODIS ICD	95 days		110 days		82 days		73 days	
CYGNSS ICD	95 days		106 days		76 days		83 days	

	Freeze up		Break up	
	FUS	*FUE*	*BUS*	*BUE*
MBE	6 days	-4 days	-10 days	-4 days
MAE	7 days	5 days	10 days	4 days
ICD MBE	0 days			
ICD MAE	5 days			

Table 1. (Top) Summary of FU and BU periods, ICD, and MTT spike dates for each year from 2018 to 2022 determined from CYGNSS data and MODIS images. The first and last dates of the FU and BU periods correspond to FUS, FUE, BUS, and BUE. (Bottom) Mean bias error (MBE) and mean absolute error (MAE) for FUS, FUE, BUS, BUE, and ICD between CYGNSS and MODIS (number of days).

III) GNSS-R Sensitivity to Spring Melt Onset

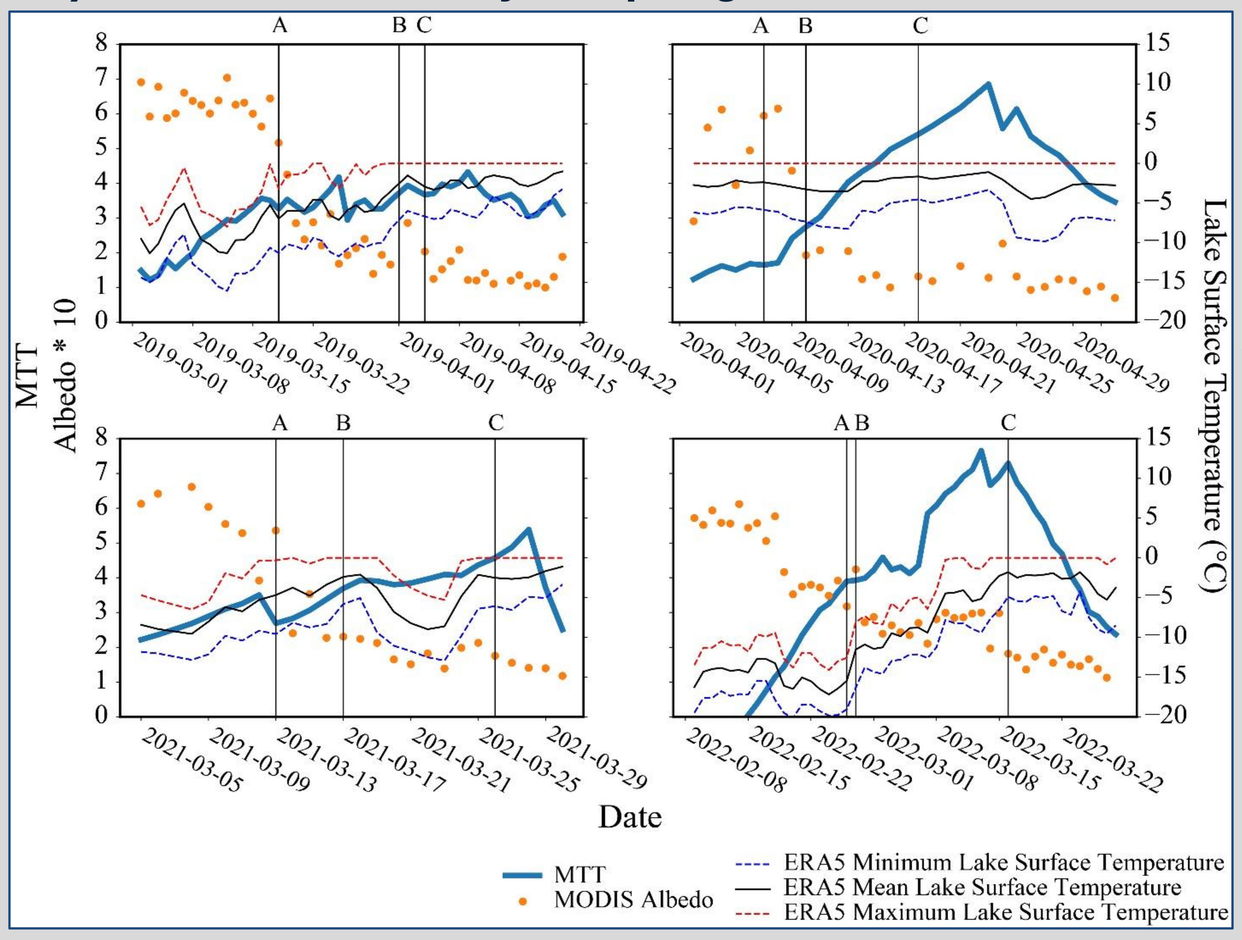
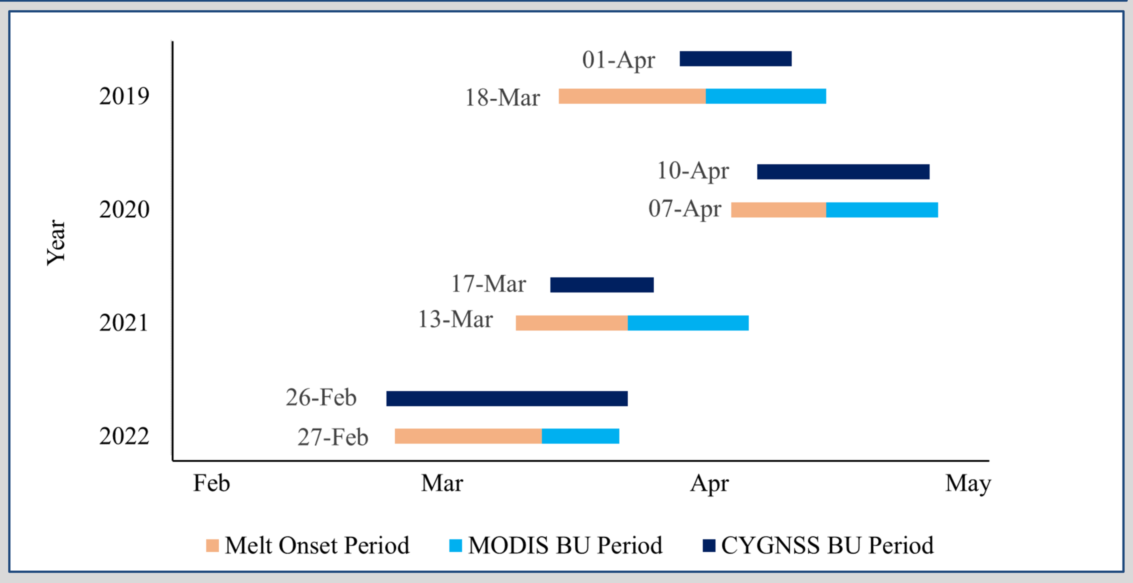


Fig 5. (Left) . . Surface albedo during springtime for each year along with MTT changes. Albedo values are scaled (multiplied by 10) for display on the same axis as MTT values. Dashed lines represent the maximum, mean, and minimum lake ice surface temperatures obtained from ERA5-Land data product. Vertical black lines correspond to estimated dates of melt onset (A) from MODIS surface albedo and ERA5-Land lake ice surface temperature, CYGNSS timing for BUS (B), and MODIS-derived timing for BUS (C). The vertical black lines clearly show the sensitivity of CYGNSS to the surface melt onset.(Right) CYGNSS timing for breakup compared against the melt onset dates and breakup dates obtained from MODIS.



6. Conclusion and Prospects

- GNSS signals reflected from lake ice are generally in lower power
- GNSS-R shows potential in lake ice phenology analysis
- Other GNSS-R sensors (e.g., Spire and HydroGNSS) to be tested for northern lakes
- Machine- and Deep-learning techniques to be used to extract lake ice effects on DDMs

Scan to see more about GNSS-R

Scan to see the abstract at EGU website