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 (MTT) algorithm was applied to time-varying SNR values allowing for the detection of lake ice at daily temporal resolution. Strong agreement is observed between ice phenology records derived from CYGNSS and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. Differences during freeze-up (i.e., the period starting with the first appearance of ice on the lake until the lake becomes fully ice covered) ranged from 3 to 21 days with a mean bias error (MBE) and mean absolute error (MAE) of 10 days, while those during breakup (i.e., the period beginning with the first pixel of open water and ending when the whole lake becomes ice-free) ranged from 3 to 18 days (MBE and MAE: 6 and 7 days, respectively). Observations during the breakup period revealed the sensitivity of GNSS reflected signals to the onset of surface (snow and ice) melt before the appearance of open water conditions as determined from MODIS. 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).

2. Study Area

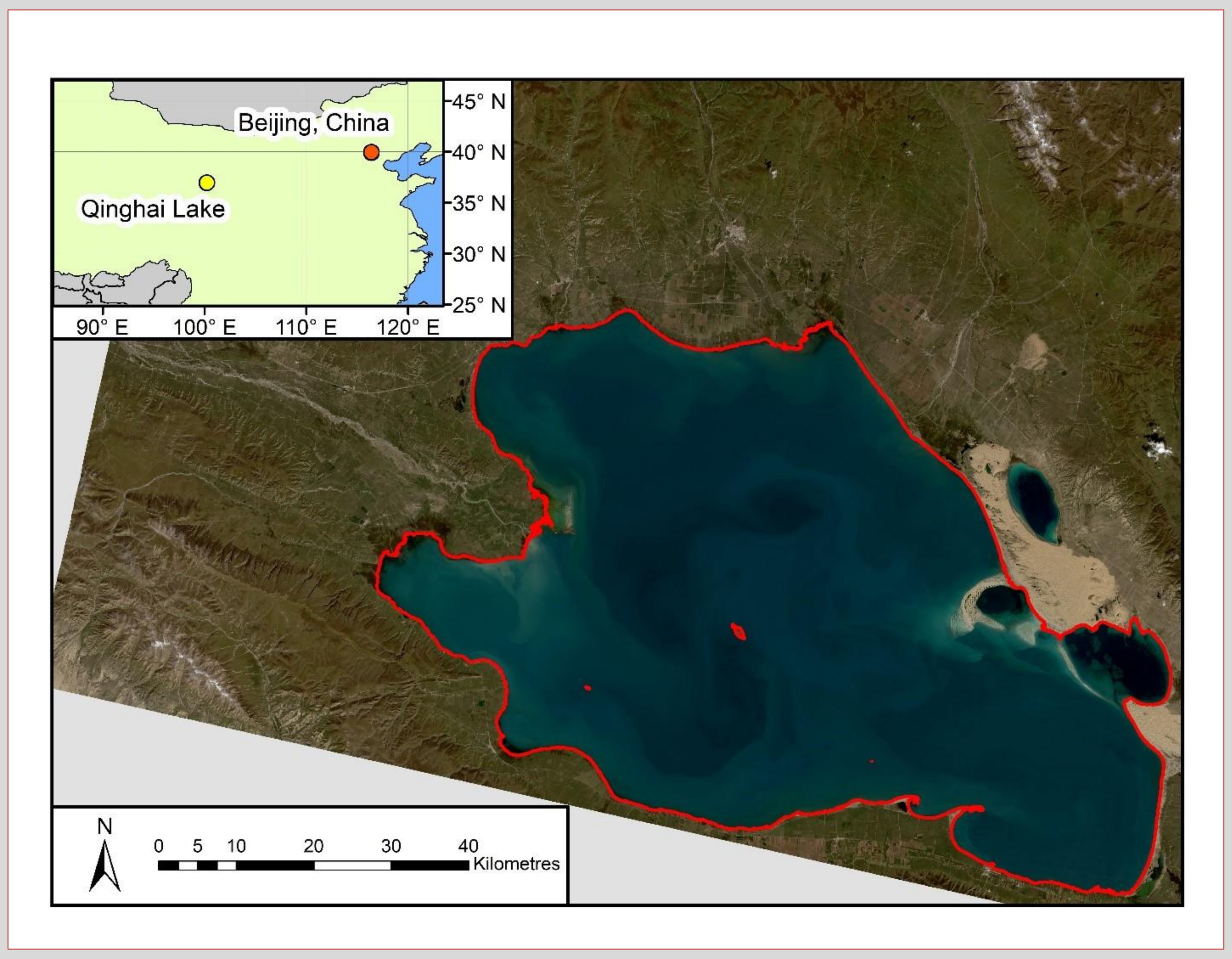


Figure 1. Qinghai Lake, Tibet Plateau, Altitude: 3,260 m; Area: 4,186 km²; Salinity: 12.5 ppt
Source: Landsat-8 Level-1 OLI/TIRS image, USGS; DOI: /10.5066/F71835S6

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

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

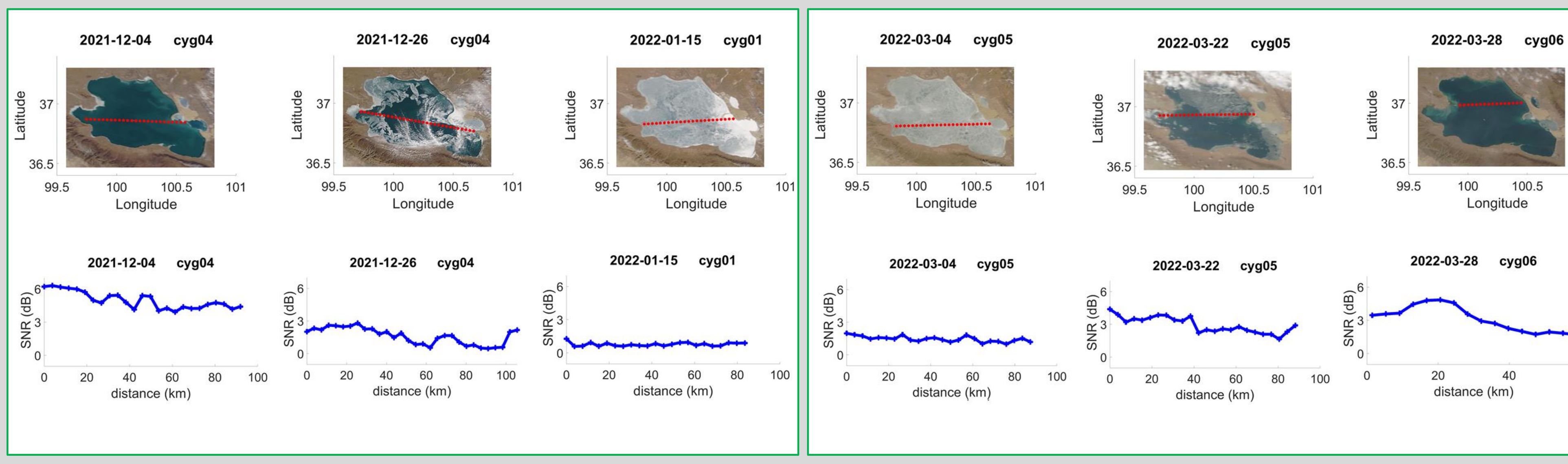


Fig 2. CYGNSS tracks over the lake during (left) freeze-up and (right) breakup periods along with the SNR variation for three conditions of open water, ice-water mix, and fully ice cover

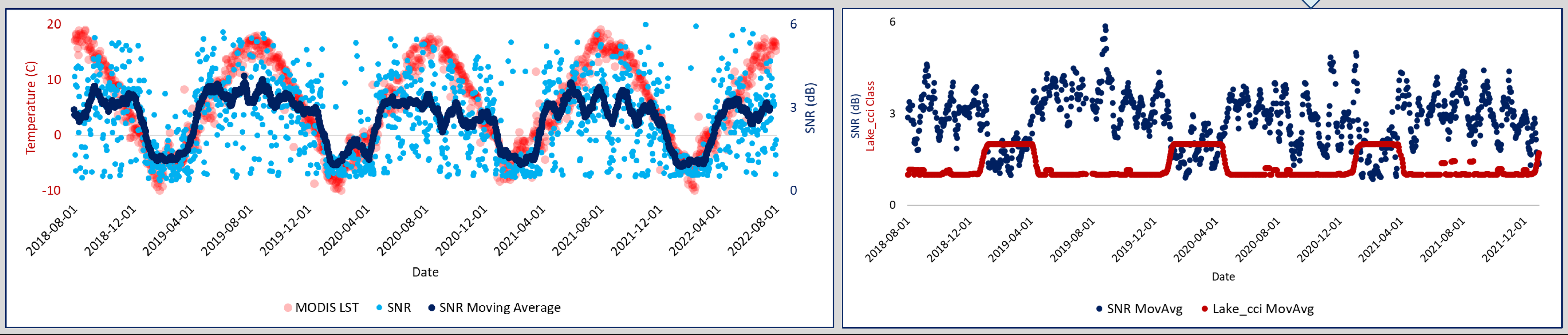


Fig 3. CYGNSS SNR variation obtained from Qinghai Lake against (left) temperature from MODIS LST and (right) lake condition from Lake_cci data products (1 = open water; 2 = lake ice)

II) Lake Ice Phenology

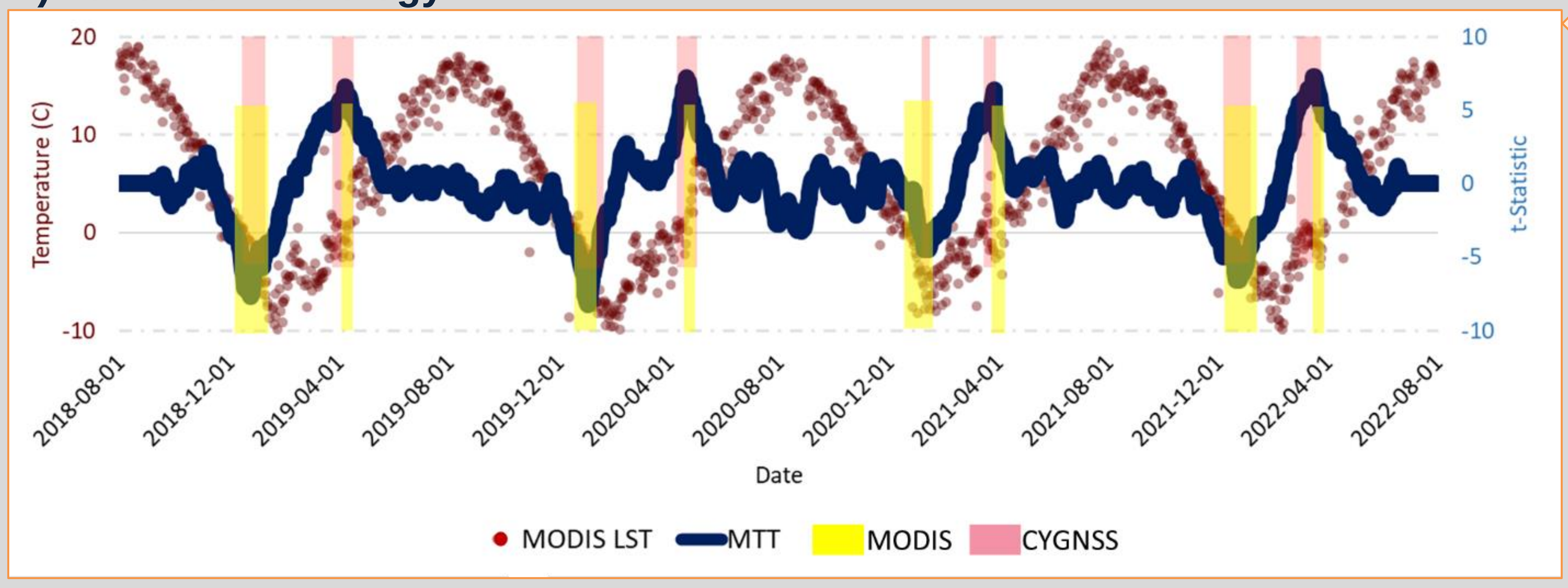


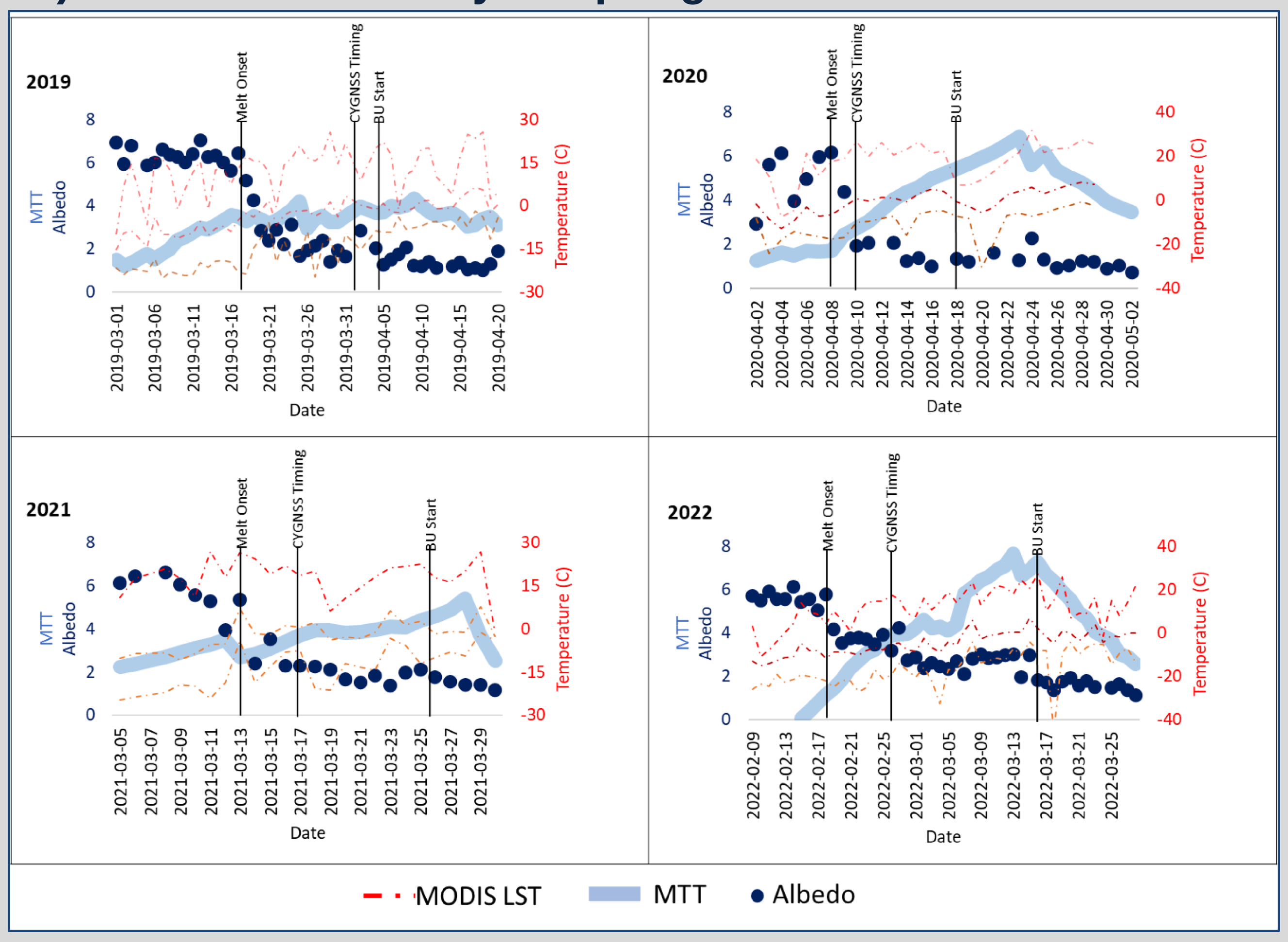
Figure 4. CYGNSS SNR variation from August 2018 to August 2022 along with t-statistic values obtained from the MTT algorithm. Light-pink bars are phenology periods obtained from CYGNSS and light-yellow bars are phenology periods visually determined from MODIS images. Temperature variation obtained from MODIS LST is also shown in dots.

Table 1. (Right) freeze-up (FU) and breakup (BU) periods, and ice cover durations, MTT spike dates, and ice cover duration (ICD) for each year from 2018 to 2022 obtained from CYGNSS data and MODIS. (Left) Uncertainties of CYGNSS in FU and BU determination and ICD compared against MODIS images.

	FU onset	FU end	BU onset	BU end
MBE	6 days	-4 days	-10 days	-4 day
MAE	7 days	5 days	10 days	4 days

	FU 18-19	BU 19	FU 19-20	BU 20	FU 20-21	BU 21	FU 21-22	BU 22
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 17 – Mar 25
CYGNSS	Dec 11 - Jan 12	Mar 14 - Apr 19	Dec 19 - Jan 15	Apr 13 - May 5	Jan 10 - Jan 14	Mar 8 - Mar 29	Dec 6 - Jan 2	Feb 26 - Mar 25
MTT Spike	Dec 25	Apr 9	Jan 4	Apr 24	Jan 10	Mar 28	Dec 27	Mar 19

III) GNSS-R Sensitivity to Spring Melt Onset



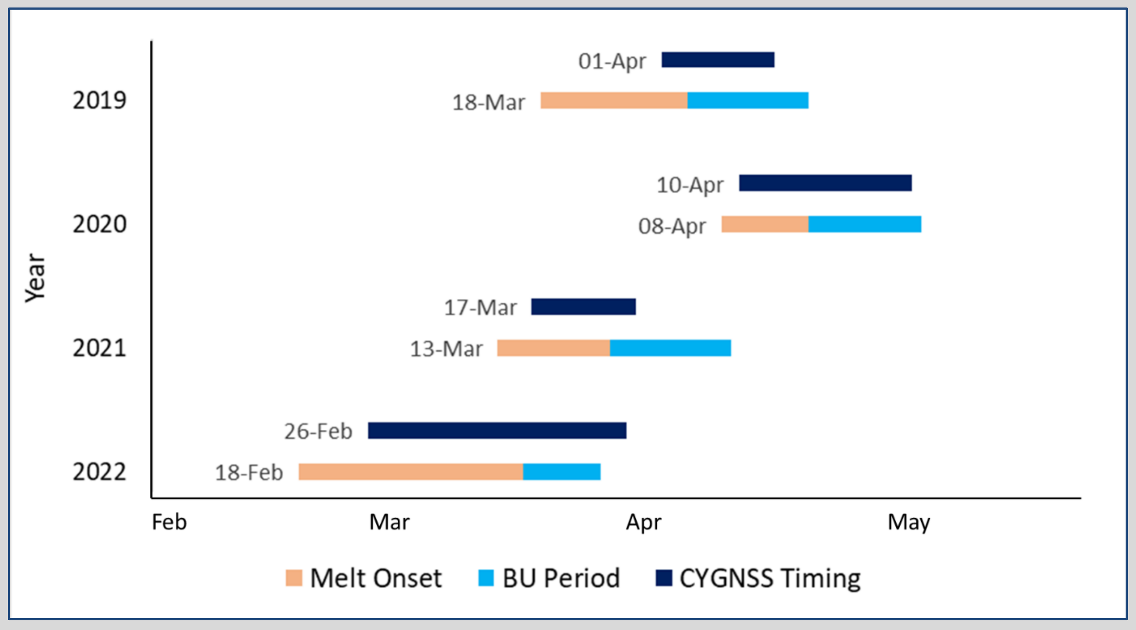


Fig 5. (Left) albedo variation during springtime for each year along with MTT changes. Dashed lines represent maximum, average, and minimum temperature obtained from MODIS LST data product. Thick black lines suggest the snow melt timing, CYGNSS timing for the breakup start, and MODIS-derived timing for the beginning of breakup. The vertical black lines clearly show the sensitivity of CYGNSS to the 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

See more about GNSS-R at https://www.GPSCAT.ca