Arctic freeboards and snow depths from near-coincident CryoSat-2 and ICESat-2 (CRYO2ICE) observations during the winter 2020-2021

An examination across changing sea ice conditions

This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

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Highlights

- Along-track altimetry-derived snow depth estimates presented
- Negative correlation observed between CRYO2ICE and estimates from acoustic buoys
- Limited seasonal snow accumulation observed due to little increase in laser freeboard – further investigation needed

Summary

In the summer of 2020, CryoSat-2's orbit was aligned to periodically overlap with ICESat-2 to allow for near-coincident laser and radar altimetry (CRYO2ICE) over polar regions. Here, we examine the CRYO2ICE orbits acquired over sea ice for one winter season and evaluate the potential of estimating snow depth along the satellite track.

Background

- The difference in penetration between laser (λ = 532 or 1064 nm) or Ka-band (λ = 1.1 – 0.75 cm) and Ku-band (λ = 2.5 – 1.67 cm), assuming Ku-band penetrates fully to the snow-ice interface, allows for determination of snow depth on sea ice, accounting for slower wave propagation speed through snow. Utilizing this, monthly snow depth estimates has been derived using a combination of CryoSat-2/SARAL (Guerreiro et al., 2016; Lawrence et al., 2018; Garnier et al., 2022) for Ku/Ka snow depths or CryoSat-2/ICESat-2 (Kwok et al., 2020; Kacimi and Kwok, 2022) for Ku/laser snow depths.
- However, with the expected launch of the dual-frequency CRISTAL mission in 2027, a mission requirement is determining snow depth at 25 km orbit segments. Here, CRYO2ICE provides an excellent opportunity to investigate this possibility with already available missions.
- However, CRYO2ICE observations have different configurations instrument characteristics and alignment restrictions, complicating the process of making the observations comparable.

Data and methods

- Winter season 2020-2021 CRYO2ICE orbits identified using www.cs2eo.org with specific search requirements.
- Freeboards from CryoSat-2 ($h_{f_{CS2}}$) with three re-trackers: ESA Baseline-D, threshold-first-maximum-retracker-algorithm at 50% (TFMRA50 from the Climate Change Initiative (CCI) project) and the log-normal re-tracker algorithm model (LARM), and ATL10 freeboards from ICESat-2 ($h_{f_{IS2}}$) are used. ATL10 freeboards within a search radius of 3500 m are considered with an inverse-distance-weighting applied when computing CRYO2ICE ICESat-2 comparable freeboards.
- Snow depth is estimated as follows, where ρ_s is the bulk snow density:

$$h_s = \frac{h_{f_{IS2}} - h_{f_{CS2}}}{\eta_s}, \text{ where } \eta_s = (1+0.51\rho_s)^{1.5} \qquad \text{(Kwok et al., 2020)}$$

Along-track freeboards and snow depth

- Radar observations are noisy. To limit the impact of noise, we apply a lowess filter (Locally Weighted Scatterplot Smoothing) with a fraction of 1/50 (based on qualitative comparison) to smooth with. ICESat-2 observations are generally smoother than original CryoSat-2 observations. Of the smoothed data, similar relations are observed along the track with some discrepancies at times – this is related the smoothing solution. **Future work includes investigating other smoothing methods or rely only on a segment-based analysis.**
- Compared with nearest-neighbouring points of daily snow depth composites (passive-microwave-derived using AMSR2 data (AMSR2) or evolving snow-model; SMLG v1 and v2), we see some similarities with SMLG v1/v2, whereas AMSR 2 is generally higher (**Figure 1**) – note the coarser resolution of the daily composites.
- CRISTAL's mission requirement states snow depths must be available at high accuracy at 25 km segments → **orbit-segment analysis next.**

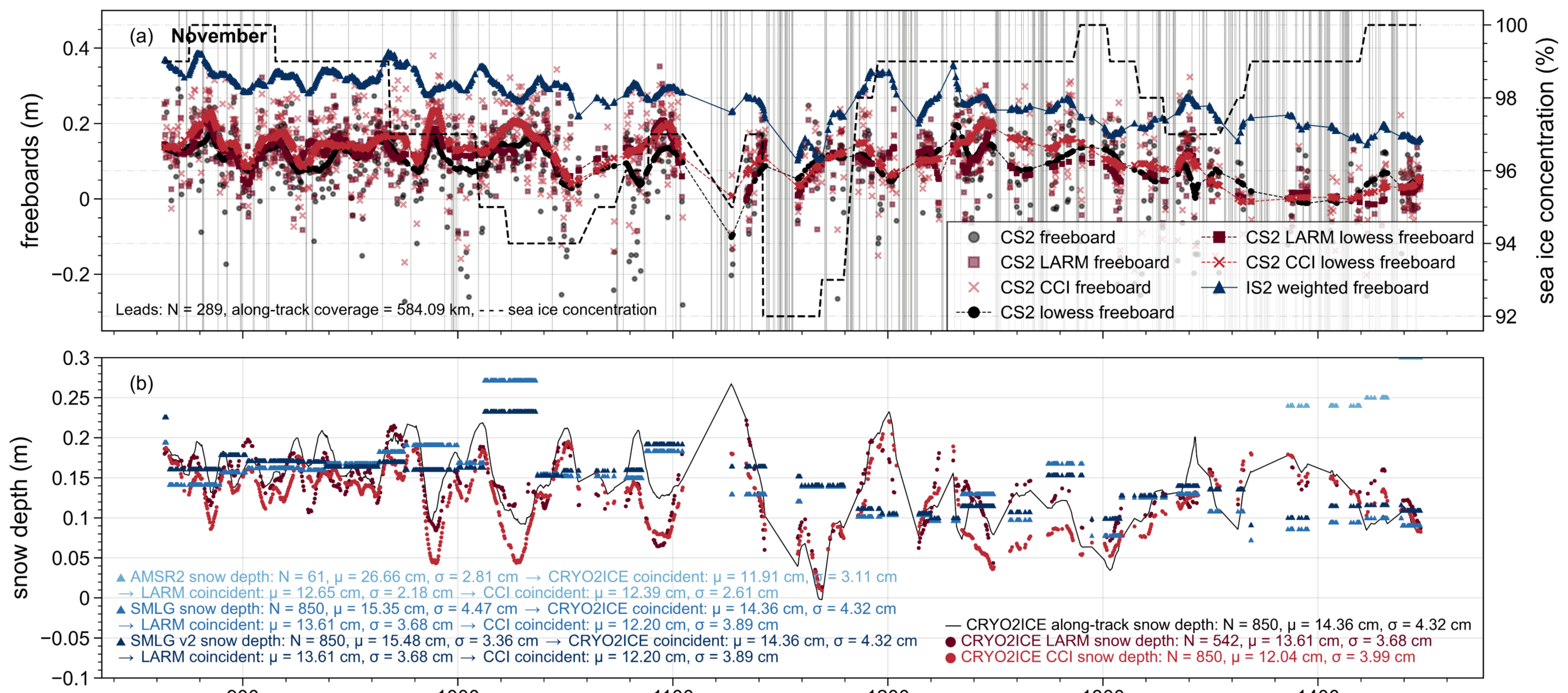

Figure 1. Along-track freeboard and derived snow depth comparisons with nearest-neighbouring points from passive microwave (AMSR2) and reanalysis-based models (SnowModel-LG/SMLG v1 and v2). Grey lines indicated leads identified in Baseline-D L1b. Original freeboard observations and smoothed freeboard (with lowess filter) are shown.

Buoy comparison

- We compare with in situ observations from four acoustic buoys from AWI (**Figure 2**) for validation.
- Daily average buoy data is used and compared with CRYO2ICE observations within 50 km, +/- 2 days.
- Large increase in snow depth for buoys (**Figure 3**) and with negative correlations (**Table 1**).
- Buoys likely overestimates.

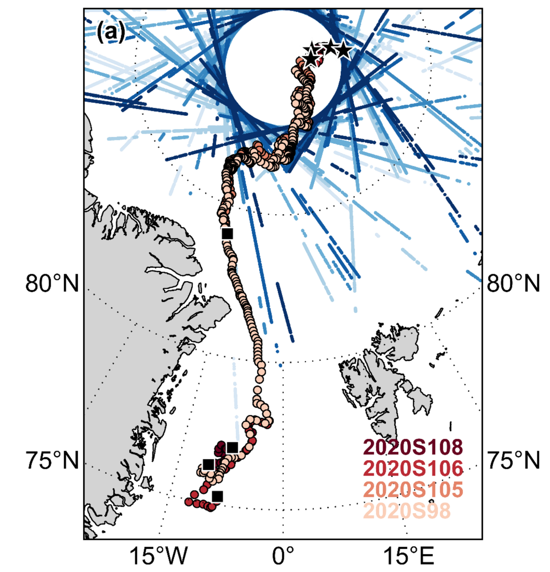

Figure 2. Buoy trajectories of four active snow depth buoys during the winter season 2020-2021. CRYO2ICE tracks shown from November (light blue) to April (dark blue).

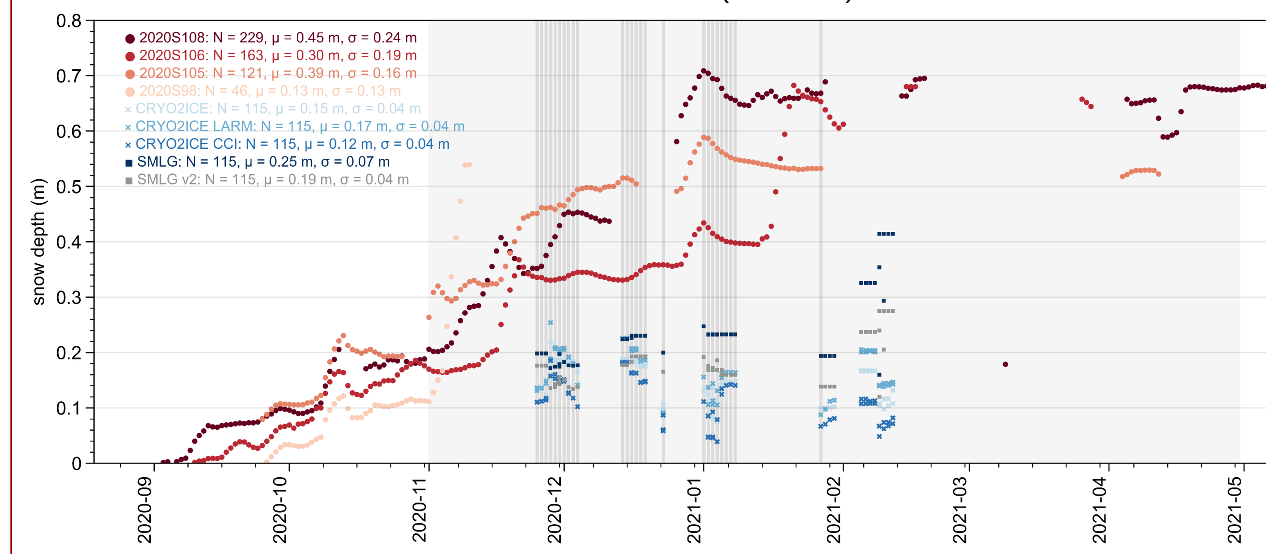

Figure 3. AWI snow depth buoy and comparable CRYO2ICE observations shown for the period of September 2020 to May 2021, where the light grey shadowed area denote the winter of 2020-2021 and the grey lines indicated near-coincident CRYO2ICE observations. Statistics are shown for the all points available from September 2020 to August 2021 (not shown).

Table 1. Statistics between AWI buoys and CRYO2ICE data within 50 km, +/- 2 days.

Re-tracker	Correlation	Root-mean-square-deviation (RMSD) [m]	Slope [m]	Intercept [m]
Baseline-D	-0.38	0.33	-1.07	0.62
LARM	-0.31	0.31	-0.82	0.59
CCI	-0.37	0.35	-0.96	0.57

25 km segments

- To compare with the mission requirement of CRISTAL (25 km), we average to orbit-segments of 25 km to comply with the CRISTAL requirement **(Figure 5**: CRYO2ICE tracks for winter 2020-2021**).**
- Growth rates (**Figure 4**) show a more comparable seasonal evolution over FYI, and no seasonal evolution over MYI. Correlations (**Figure 6**) show a strong correlation in the beginning of the season (November) and decreases afterwards.

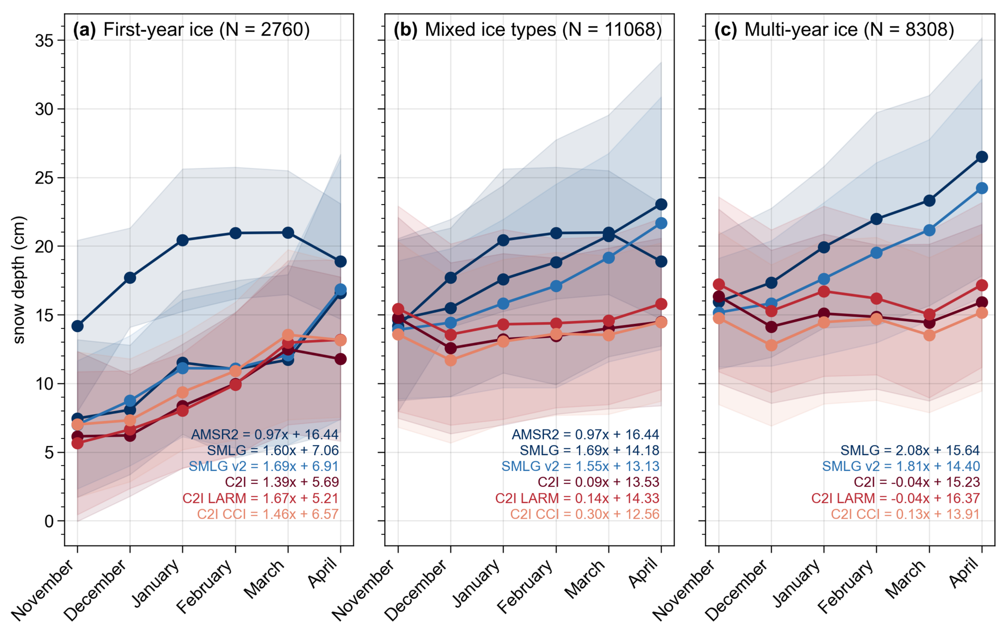

Figure 4. Growth rates (monthly average) for winter season 2020-2021.

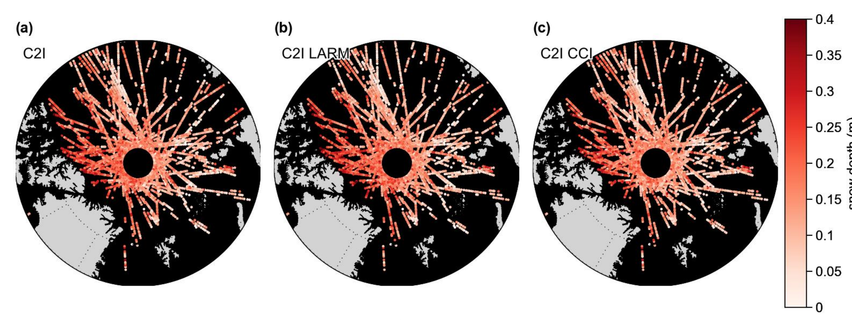

Figure 5. CRYO2ICE (C2I) snow depths for winter season 2020-2021.

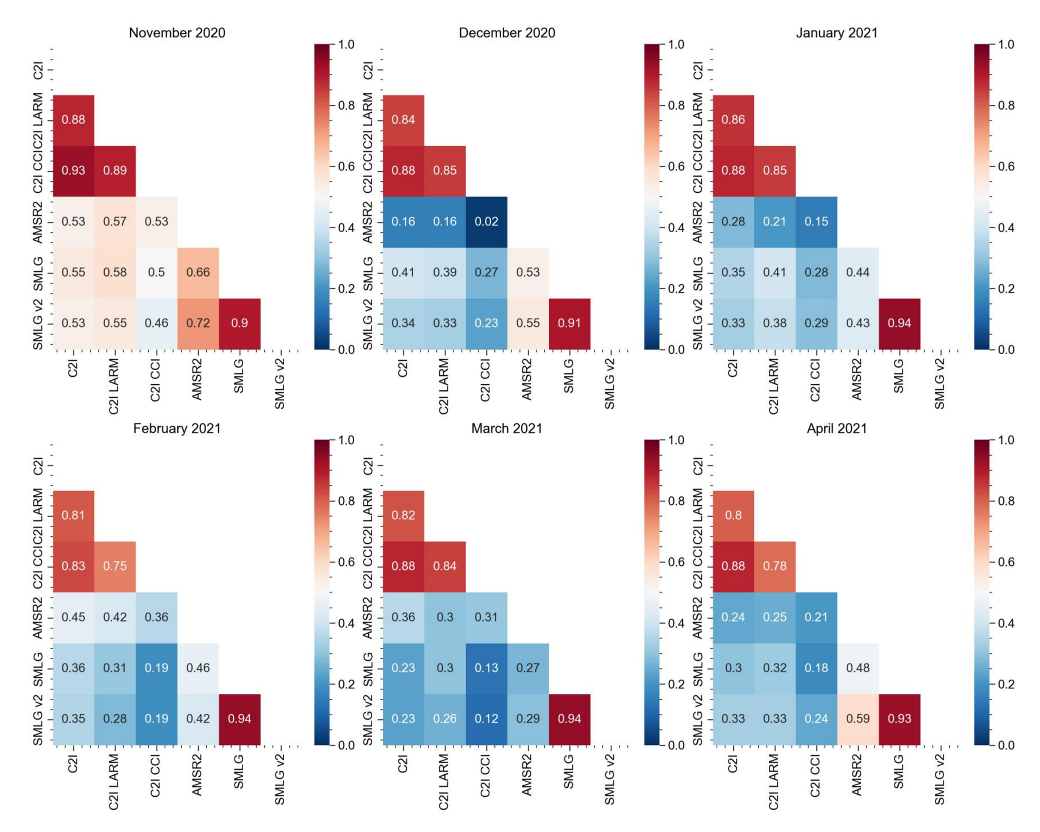

Figure 5. Monthly correlations between snow depth (passive microwave and reanalysis-based) and altimetry-derived averaged to orbit segments of 25 km.

Next steps

- Identify and solve for the limited seasonal snow accumulation (ICESat-2 freeboards not increasing – binning methodology examination)
- Smoothing/orbit-based segments: what is the best way forward? LOESS filter works differently depending on # observations, normal smoothing filters does not work well over data with irregular sampling
- Assumptions: SMLG is the truth and full penetration to snow-ice interface – when is it valid?
- Overall differences over different ice regimes/products – distributions and specific patterns. Note the limitations due to significant incomplete and inconsistent data coverage.

References

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Data availability

CryoSat-2 Baseline-D L1b and L2 retrieved from the European Space Agency (ESA). ICESat-2 ATL10 retrieved from the National Aeronautics and Space Administration (NASA). LARM provided by Jack Christopher Landy. CryoSat-2 Climate Change Initiative (CCI) retrieved from Alfred Wegener Institute (AWI). Passive microwave (AMSR2) retrieved from NSIDC. SnowModel-LG (v1) retrieved from NSIDC, (v2) provided by Ioanna Merkouriadi. Buoy measurements retrieved from AWI.

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