Freeboard and Snow Depth Estimates on Arctic Winter Sea Ice from Near-Coincident CryoSat-2 and ICESat-2 (CRYO2ICE) Observations during 2020-2022

Renée Mie Fredensborg Hansen, Henriette Skourup, Eero Rinne, Knut Vilhelm Høyland, Jack Christopher Landy, Ioanna Merkouriadi, and René Forsberg

A first examination of along-orbit satellite-derived snow depth …

from dual-frequency altimetry using CryoSat-2 and ICESat-2 (CRYO2ICE) orbits over Arctic sea ice 2020—2022

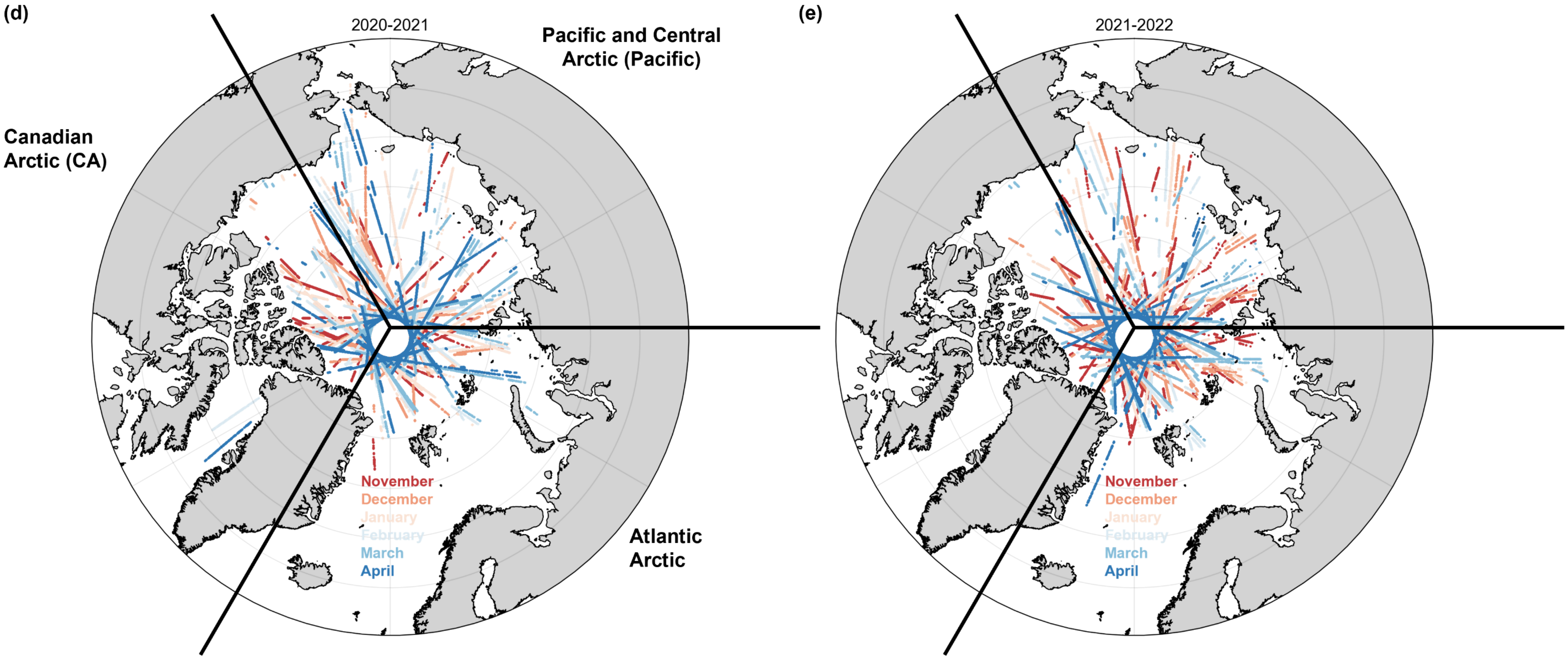
- Using assumptions of zero and full penetration using laser and Ku-band radar (LaKu) observations, to what extent can we estimate reasonable snow depth along orbits with the recent CRYO2ICE alignment over Arctic sea ice in the winter?
- How do such estimates snow depths compare with other daily snow depth composites or reference (*in situ*) observations?
- How do along-orbit snow depth estimates compare with other monthly LaKu products based on gridded observations?

Published in Earth and Space Science (Fredensborg Hansen et al., 2024): https://doi.org/10.1029/2023EA003313

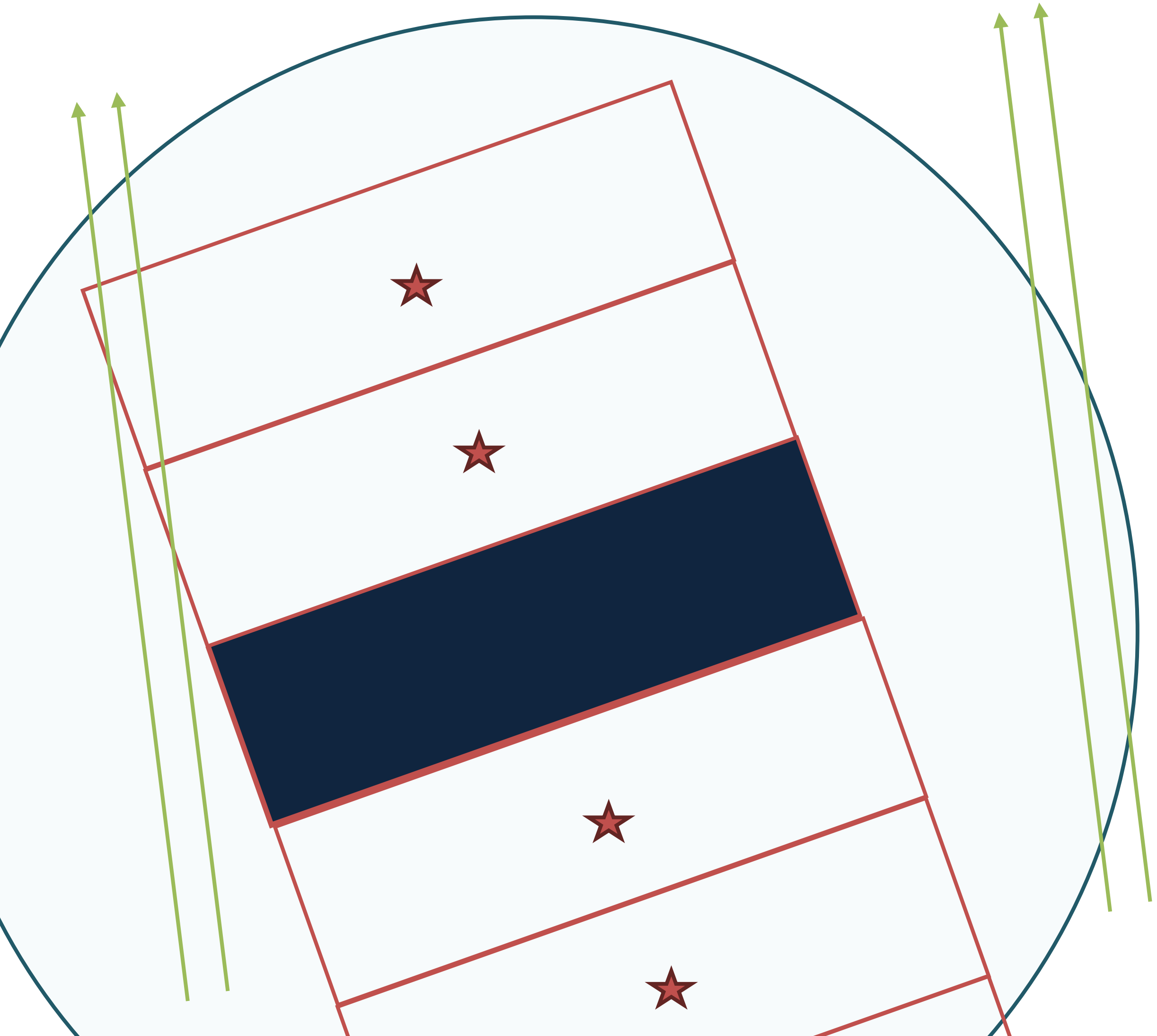
Snow depth is the **largest uncertainty** in altimetry-derived sea ice thickness…

- Snow is a **complex**, **heterogenous** cover **interacting** with the sea ice and atmosphere – difficult to observe, crucial to know!
- Remote sensing altimetry methods
  - Laser/Ka (La or Ka) as **air-snow** interface
  - Ku-band (Ku) as **snow-ice** interface
- Dual-frequency, **monthly** composites using **LaKu** and **KaKu**
- One of the main mission objectives of dual-frequency mission, **CRISTAL**, along orbits
- But how does snow depth present along orbits? … **CRYO2ICE**

CryoSat-2 and ICESat-2 (CRYO2ICE) Resonance Campaign



Binning CS2 and IS2 data to comparable observations for **snow depth** estimates



Not fully coincident → along different points on the orbit!

Drifting orbits – closer coincidence with time!

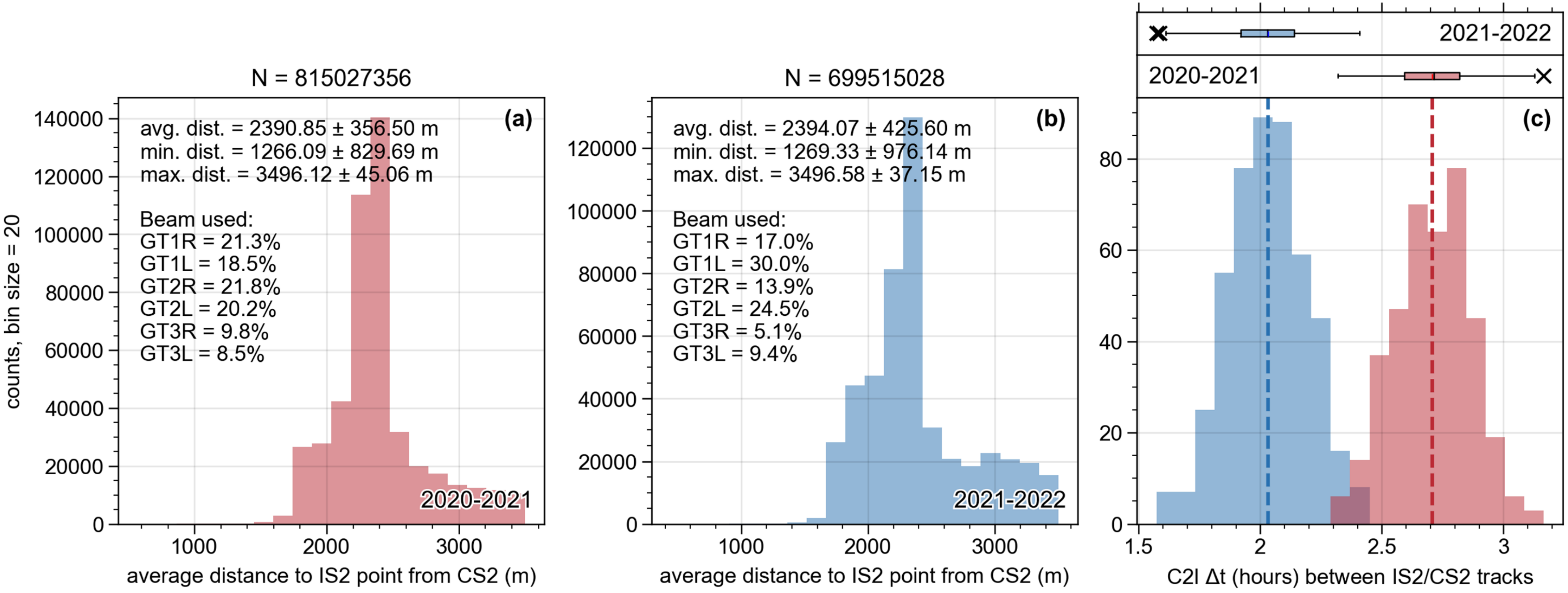
- **CS2** footprint: ~1600 x 300 m, sampling approximately ~300 m (non-filtered data)
- **IS2** footprint: ~11-17 m (elevations achieved by binning 150 photons, providing observations at different length scales, often covering 15-150 m depending on beam)
- IS2 beams: 6 beams (3 beam pairs w/ 1 strong and 1 weak)
  - Beams within beam pairs separated by 90 m across-track and 2.5 km along-track
  - Beam pairs separated by 3.3 km across-track

Applicable search area/radius for CRYO2ICE?

Variance analysis showed saturation around **~2000 m (avg. distance ~2500 m from CS2 (barely any less than 1500 m).**

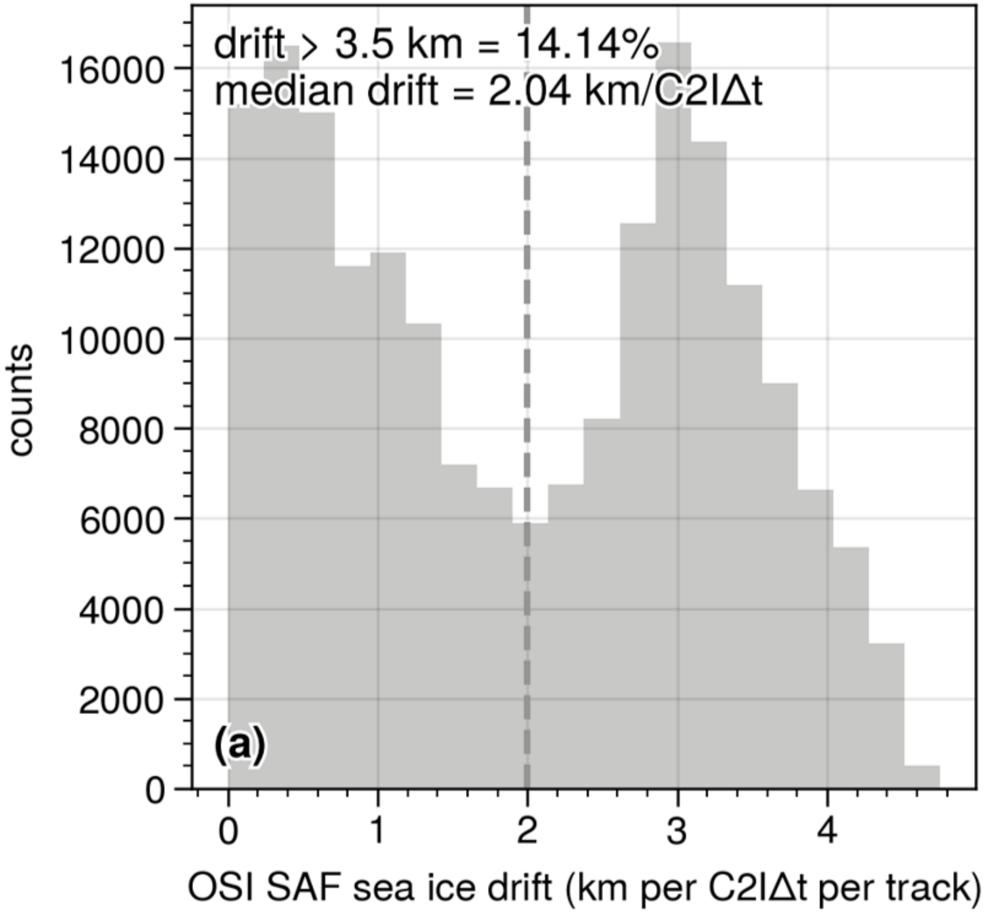
- Choose **3500 m** to include (ideally) all three beam pairs
- **Smooth CS2 data** with same search radius to average speckle noise, cover same area, limit impact of drift

CRYO2ICE coincidence (2020-2022)



The dynamic ice cover … drift

- Requires ice drift observations at **hourly** temporal resolution and at **5-7 km** spatial resolution (ideally)
- **Evaluation of expected drift** based on medium resolution OSI SAF PMW observations
- Median drift of **2.04 km/time-lag** (14.14% > 3.5 km drift)
- **Expected minimized** with smoothing radius



Data and auxiliary products

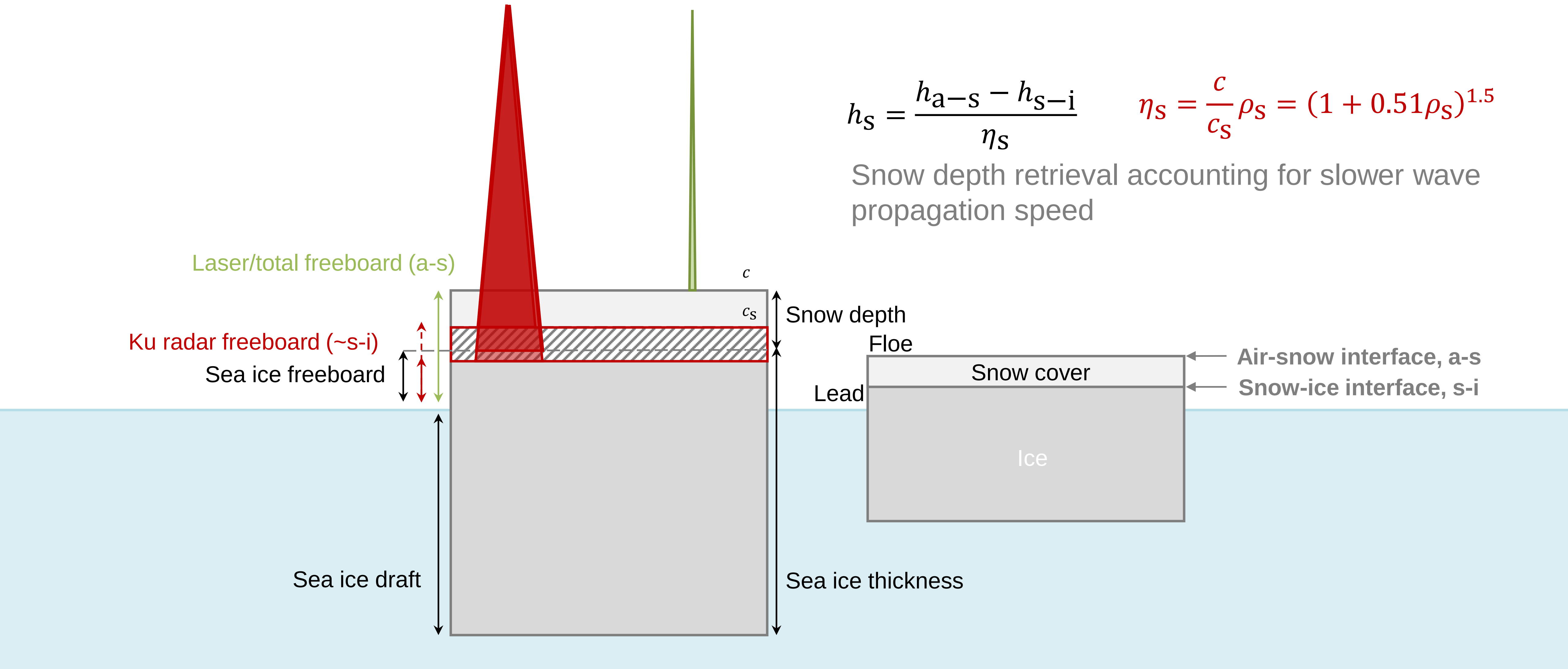
- CryoSat-2 **radar freeboards**
  - ESA Ice Baseline-E (**ESA-E**) operational product
  - ESA Climate Change Initiative (**CCI+)** product (until end of 2021)
  - Lognormal Altimeter Re-tracker Model (**LARM**; Landy et al., 2020)
- ICESat-2 ATL10 **total freeboards**

- SnowModel-LG (**SMLG**) and **ASMR2** passive-microwave snow depth “daily” composites (gridded) for comparison (nearest-neighboring)
- Accumulation snow buoys (**AWI**) or ice mass balance buoys (**SIMBA**) for evaluation (± 2 days, 50 km)
- Modified Warren et al. 1999 (**mW99**) available in ESA-E

Basic method/assumptions

$$h_s = \frac{h_{a-s} - h_{s-i}}{\eta_s} \qquad \eta_s = \frac{c}{c_s}\rho_s = (1 + 0.51\rho_s)^{1.5}$$

Snow depth retrieval accounting for slower wave propagation speed

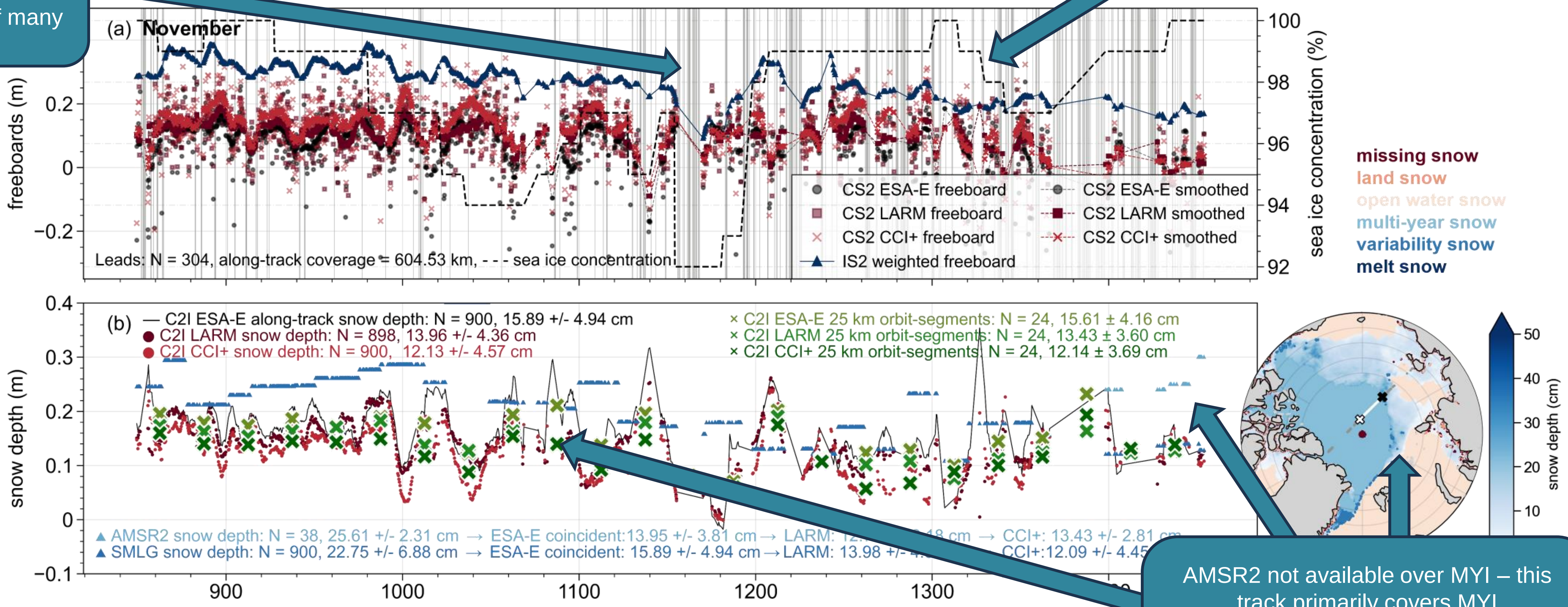


Along-track example (freeze-up)

Many leads and limited observations in presence of many

Generally, ICESat-2 reflected above CryoSat-2

Smoothing limits impact of noise and within-footprint variability

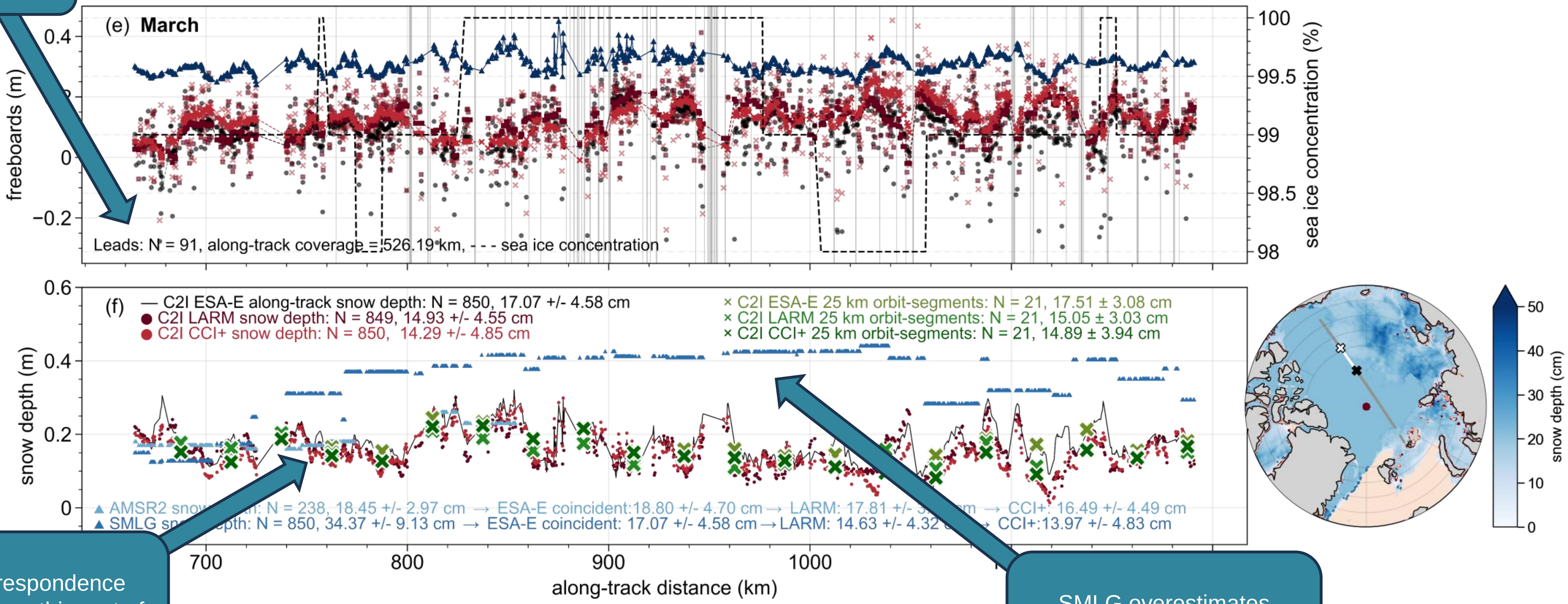


AMSR2 not available over MYI – this track primarily covers MYI

Comparison with SMLG (and AMSR2) shows about or more than 10 cm negative snow depth

Along-track example (pre-melt)

Fewer leads



Better correspondence with AMSR2 on this part of track

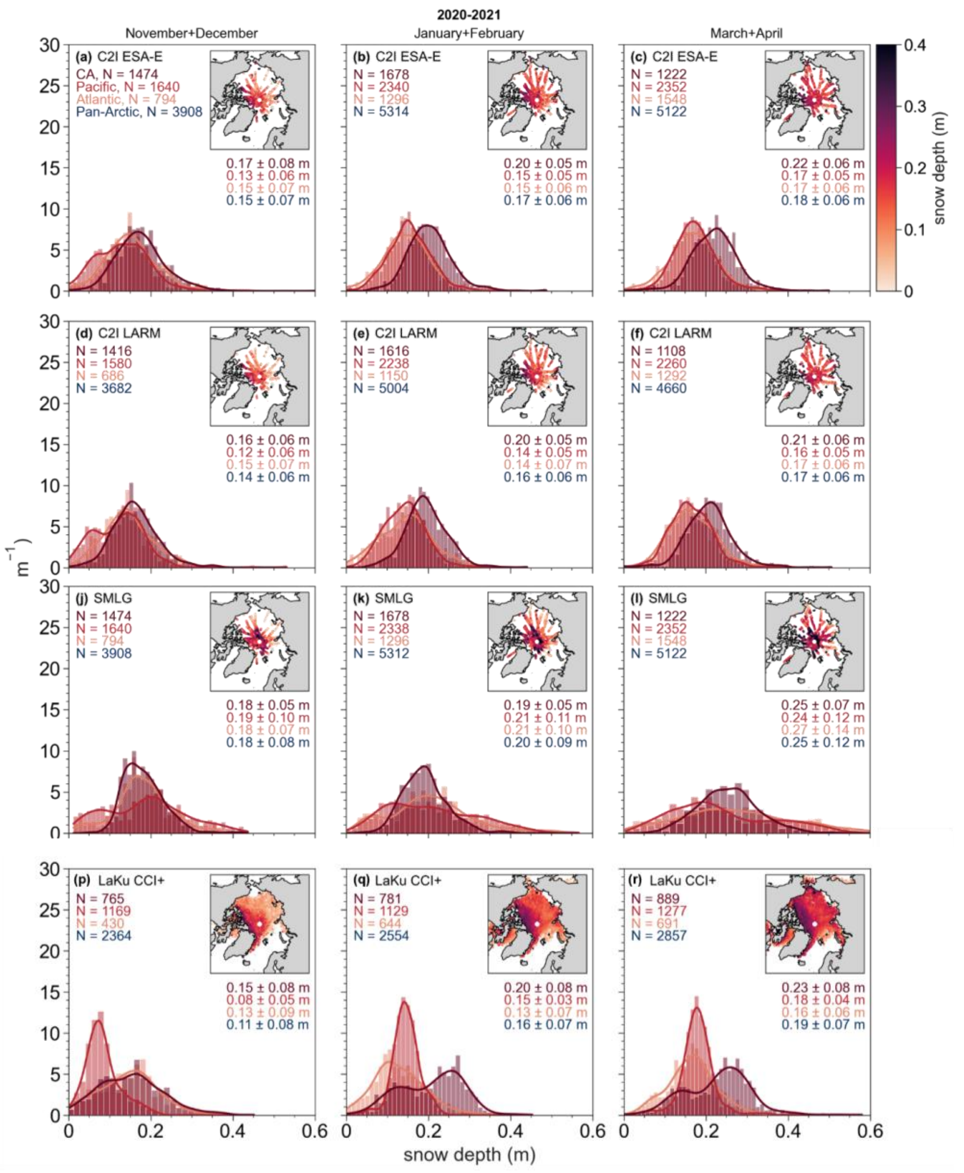
SMLG overestimates compared to CRYO2ICE with almost 20 cm

Key findings – **along-track examples**

- ICESat-2 generally **reflects above** CryoSat-2 (only 3% negative snow depths at CRYO2ICE resolution)
- Spatial **variability minimized** with the smoothing applied to CryoSat-2
- **More leads** observed in November compared to March
- Higher **snow depth variability** at CRYO2ICE than gridded estimates (at 12.5—25 km resolution)
- **Re-trackers most consistent** in January (not shown) covering first-year ice (impact of complex snow and ice cover)
- **AMSR2 compared well** over part of the ice cover (March), but **overestimates for others** (November) – **SMLG overestimates** in majority of cases by almost 10-20 cm during the season

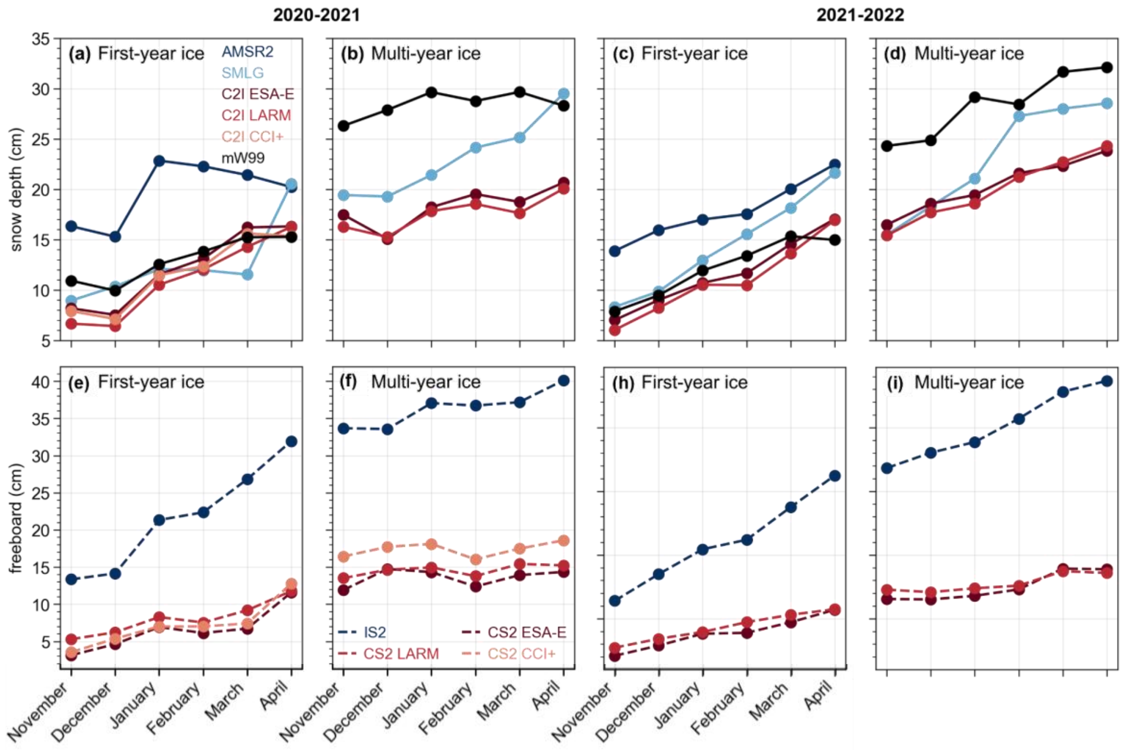
Variations across winter season 2020—2022

- Bi-monthly distributions **largest discrepancies** with model over Pacific and Atlantic Arctic
- CRYO2ICE observes **thickest snow over Canadian Arctic**, whereas SMLG observes this over Pacific and Atlantic Arctic
- Comparison with AWI buoys was inconclusive
- **SIMBA buoy** showed highest correlation (0.66—0.71) with CRYO2ICE albeit higher in magnitude
- Difference in **spatial coverage** limits the snow depth coverage to **central Arctic** → important to accumulation rates/distributions



Accumulation rates across 2020—2022

- Over first-year ice, **CRYO2ICE accumulates with similar rate and magnitude** as other composites
- Over multi-year ice, **similar snow depth in beginning as SMLG,** underestimates by 0.1 m by end of season
- ICESat-2 **total freeboard** increases by 0.20 m and 0.07 m over first-year and multi-year ice:
  - **Need to thicken** by double the amount over FYI (or CryoSat-2 decrease by 0.05 m) to follow SMLG
- CryoSat-2 radar freeboards **increase during season** – thickening or incomplete penetration, impact of complex snow and/or synoptic events
- Uncertainty (cross-over analysis) in the order of **10—11 ± 2—3 cm per** 7-km segments
  - CRISTAL requires 5 cm for 25-km segments or shorter
  - To align: La/Ka penetration dissimilarities, impact of footprints, and temporal lag are key here!



Key **take-aways**

- A method to **align CRYO2ICE observations** over drifting sea ice to derive snow depth has been proposed
- Comparison with other snow depth composites shows **similarities and discrepancies – snow is complex**!
- Comparison with SIMBA buoy (deployed on level ice) drifting in the Fram Strait showed most favorable statistics with **CRYO2ICE** at these scales! *However, in situ and satellite comparison is challenging …*
- **Understanding** the limitations and impact of difference in footprints, spatial coverage, and scattering at different spatial scales is key!
- Finally, *CRYO2ICE is not directly comparable to CRISTAL* … We need to understand more about Ka-band and Ku-band **COMBINED**!

Thank you!

If you have any questions, feel free to reach out either at the Symposium, or via rmfha@space.dtu.dk. Interested in reading the paper? **See here!**