Snow Depth Estimation on Lead-less Landfast ice using Cryo2Ice satellite observations

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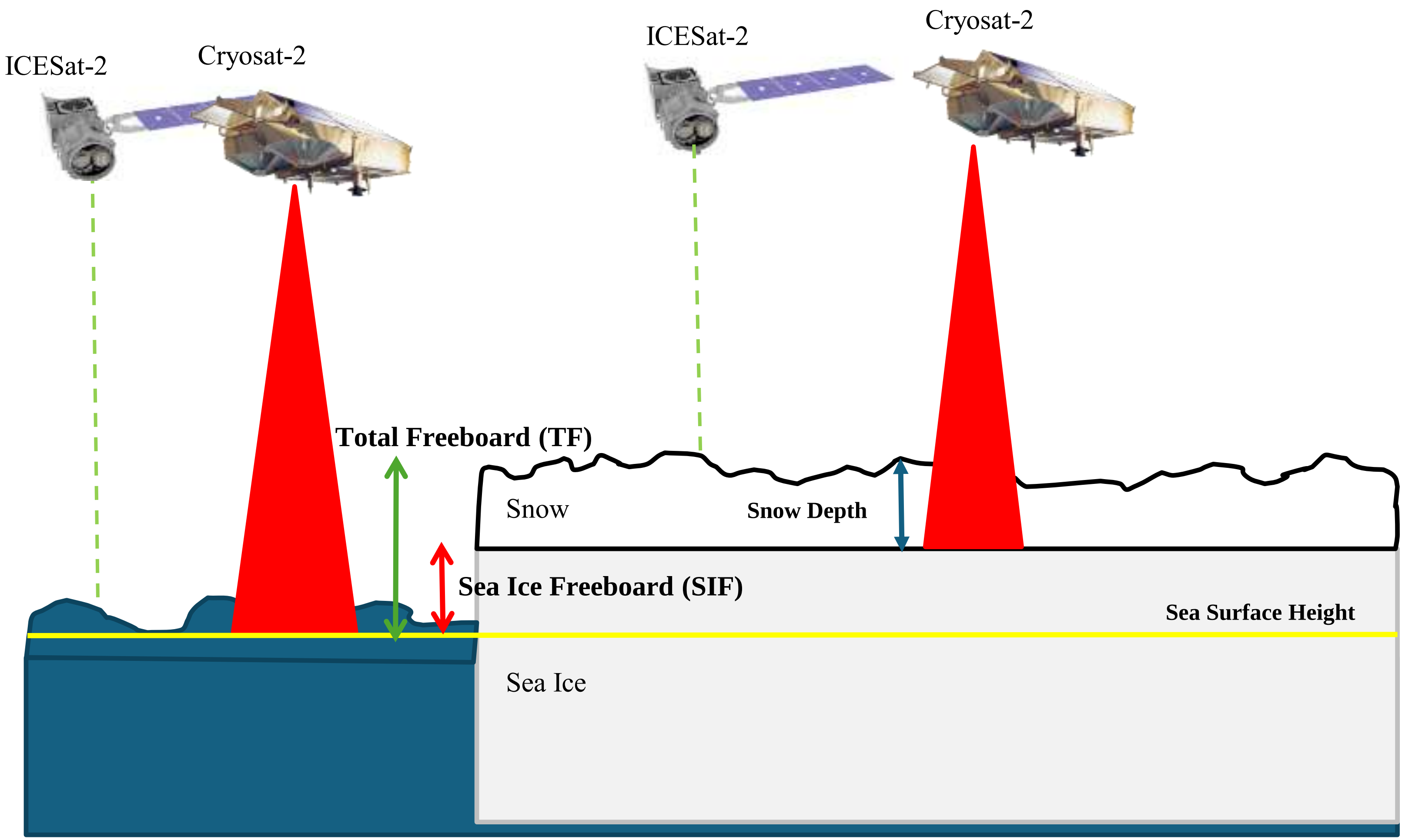

$$SD = \frac{\mathrm{TF} - SIF}{\eta s}$$

Kwok et al., 2020

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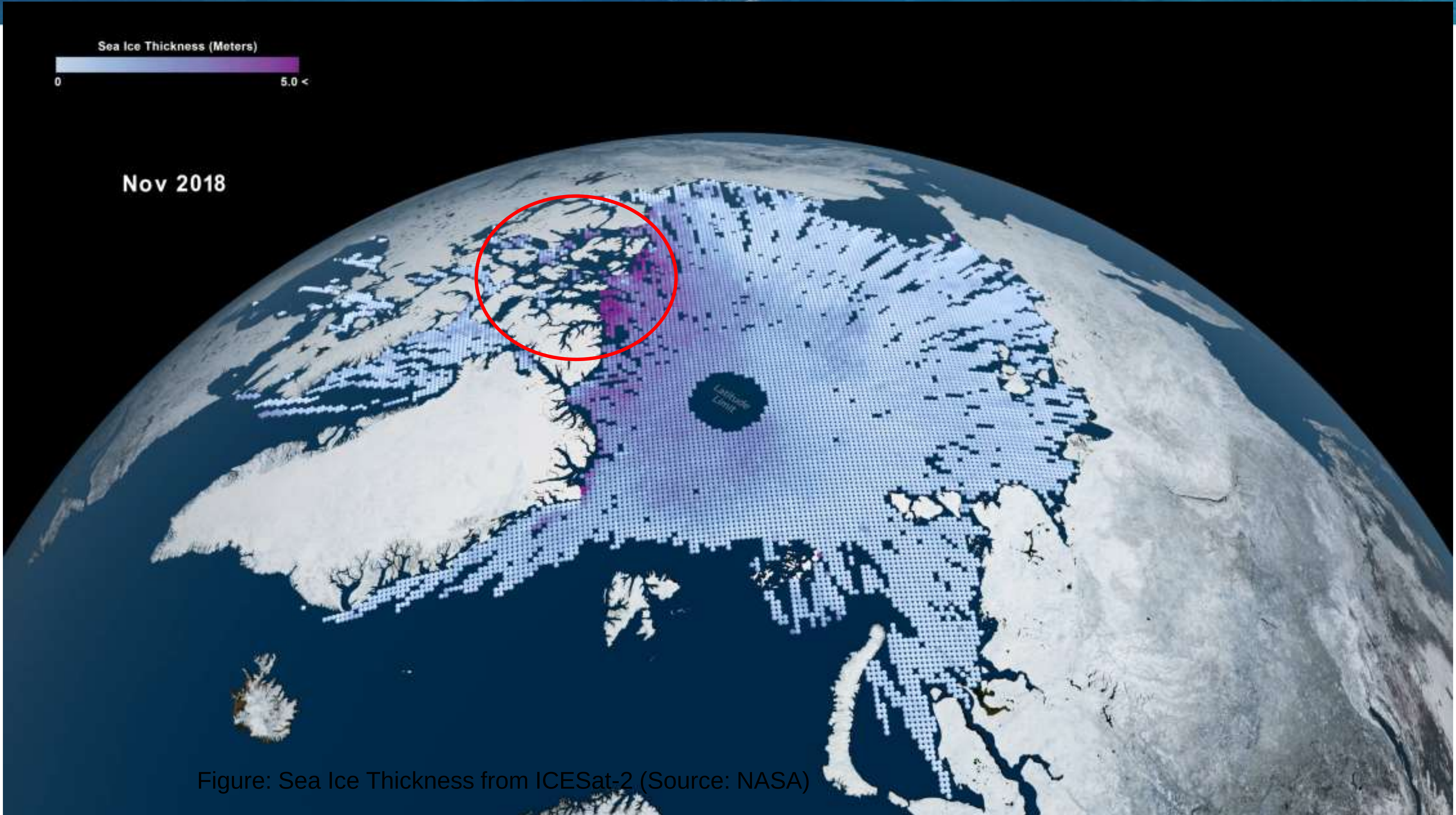

Figure: Sea Ice Thickness from ICESat-2 (Source: NASA)

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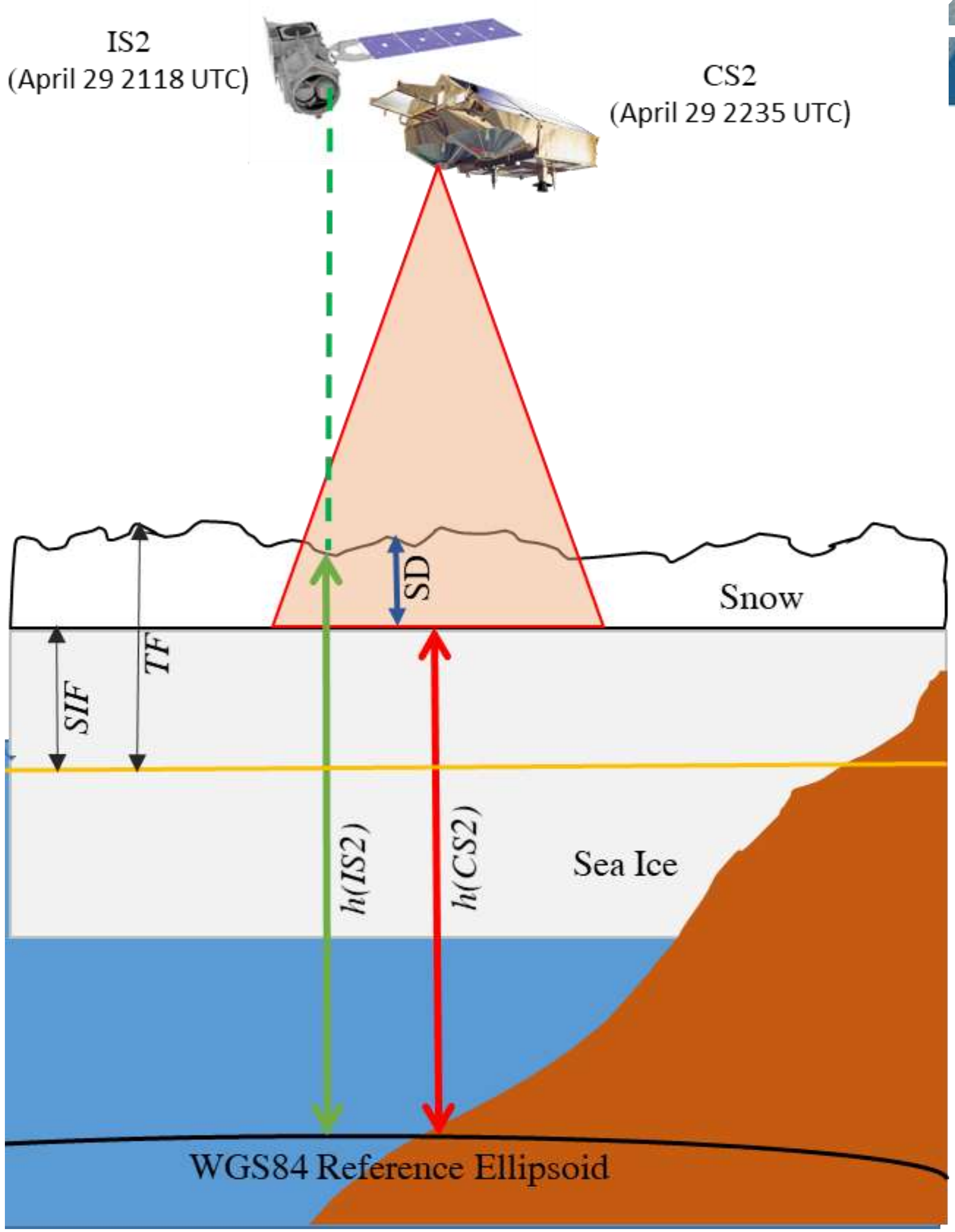
Dease Strait, Cambridge Bay, Nunavut
April, 2022

Sea ice in the CAA is landfast ice for the majority of the year (6 to 8 months) (Melling, 2002), and exhibits minimal ice drift (Galley et al., 2012), making it easier to match up IS2 and CS2 tracks.



Snow Depth on Land-fast Lead-less Sea Ice

$$SD = \frac{\mathrm{TF} - SIF}{\eta s}$$ Kwok et al., (2020)

$$SD = \frac{h_{IS2} - h_{CS2}}{\eta s}$$

$\eta s =$ (1+0.51ρs)1.5

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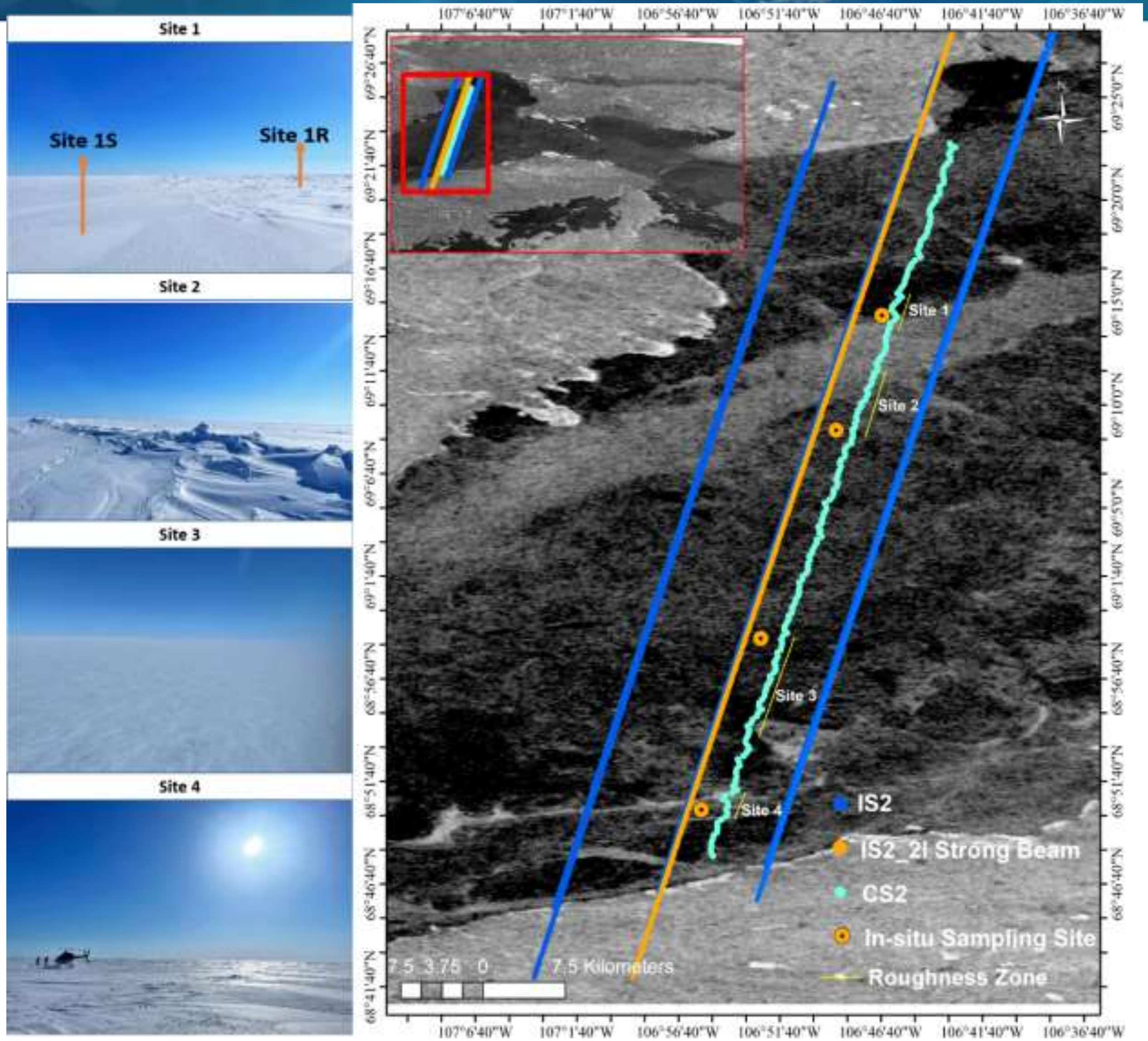

Figure 1 Map shows the Cryosat-2 Points of Closest Approach (POCA) locations, IS2 2l Strong Beam and other IS2 beam, in-situ sampling locations and identified roughness zones. The background contains Sentinel-1 HH-pol SAR imagery. Site photos show the variation in snow roughness.

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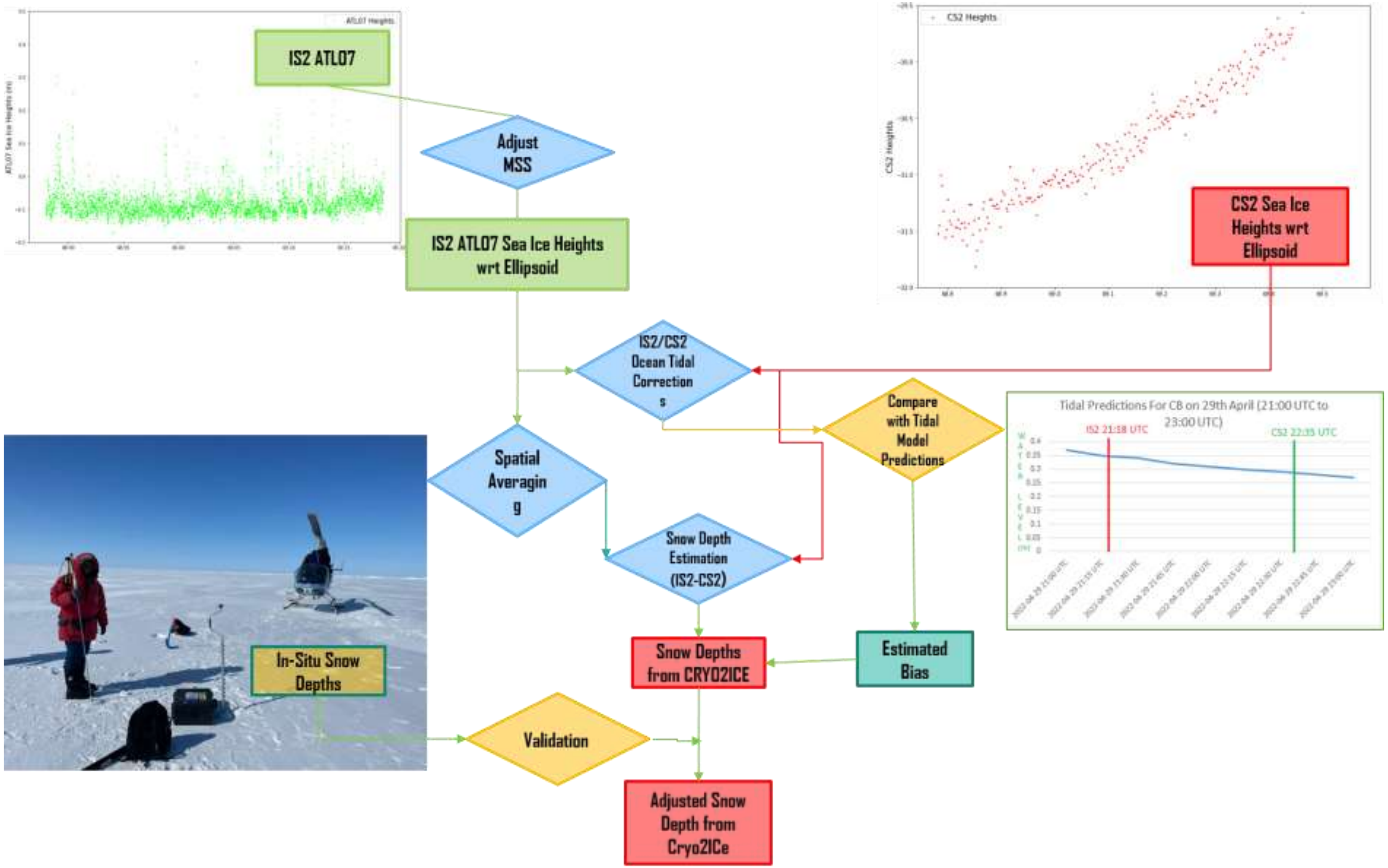

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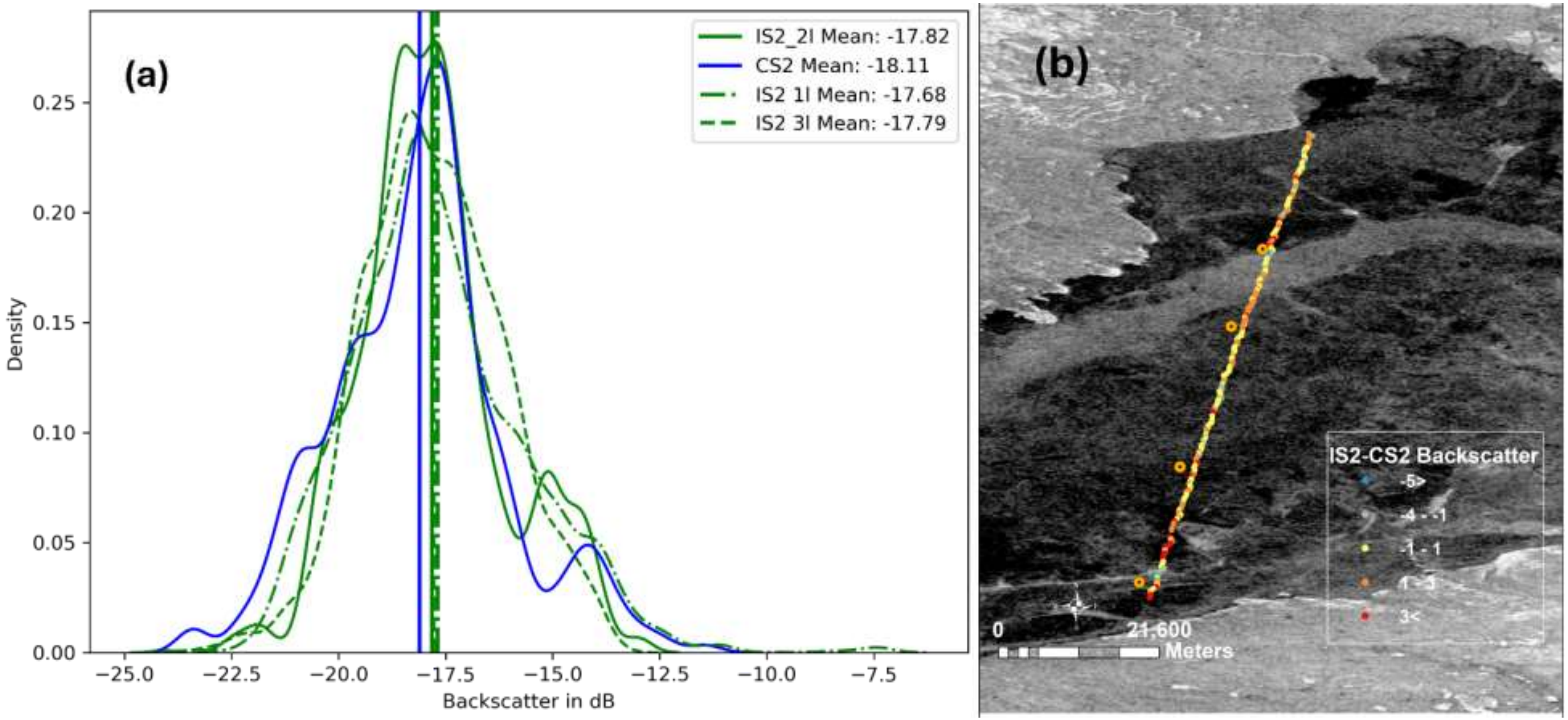

The mean difference in SAR backscatter was -0.3 dB, less than 1 standard deviation of the backscatter of each track

Figure (a) Sentinel-1 Backscatter in dB obtained from all the strong beams of IS2 (IS2 1l, 2l and 3l) and CS2 track locations.
The Sentinel-1 VH backscatter from 05-05-2022 is used for extracting backscatter along both the tracks to assess whether the observed snow distribution is similar
(b) Spatial Distribution of the Sentinel-1 backscatter between IS2 and CS2 tracks, shown differences in backscatter between IS2 and CS2 on retrieved from collocated Sentinel-1 image from 5th May 2023 .

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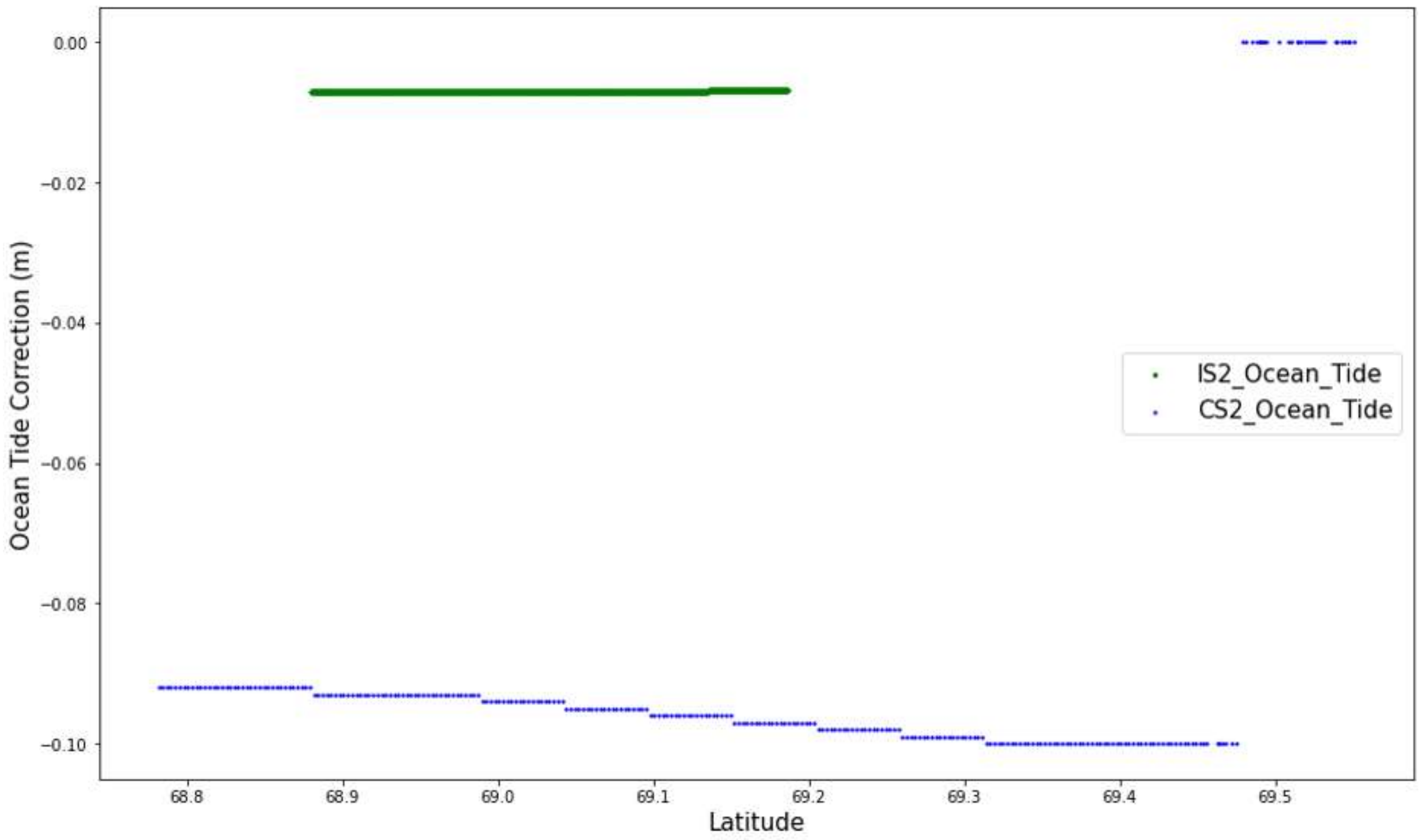

Figure: Ocean tidal correction used in the IS2 and CS2 tracks. The IS2 ocean tide corrections are shown in green while the CS2 ocean tide corrections are shown in blue.

- According to the Canadian Hydrological Survey predictions, the water level was 6 cm higher for the IS2 pass at 21:18 UTC than for the CS2 pass at 22:35 UTC.
- The difference between IS2 heights and CS2 heights was increased by 7.9 cm due to the ocean tide correction adjustment but the CHS predictions suggest it should have been only 6.0 cm
- This 1.9 cm difference would introduce a **25.5 %** bias in retrieved snow depths, given the approx. mean snow depths we measured in-situ.
- This error could be attributed to the ocean tide corrections used in IS2 and CS2 originating from two different models i.e. **GOT 4.8 (IS2) and FES 2004** (CS2)
- Past CS2 and IS2 coincident tracks from **15-04-2021 and 14-05-2021** were also analysed. We found a bias of **2 to 5 cm** when compared with the CHS dataset, meaning that we can expect ~15-40% systematic uncertainty

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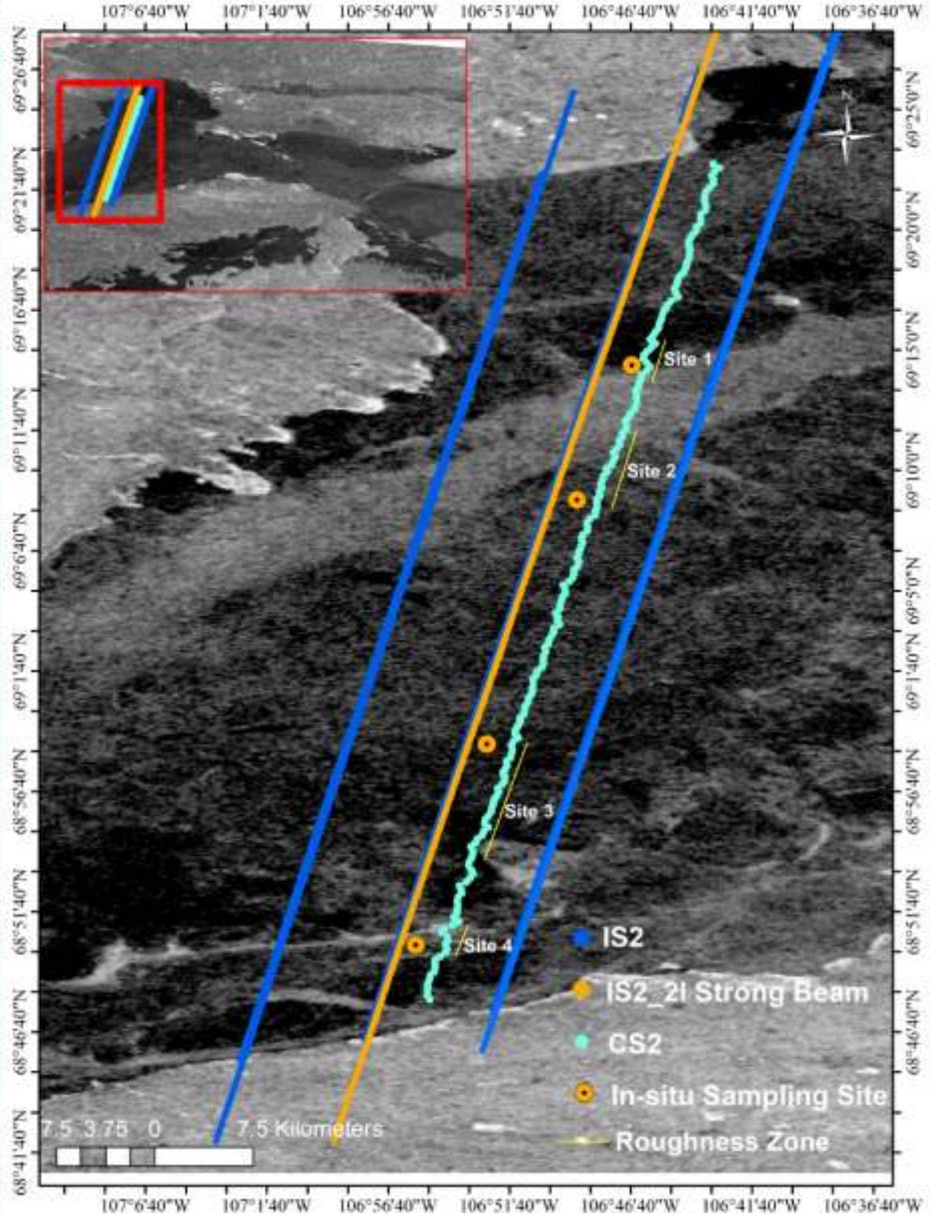

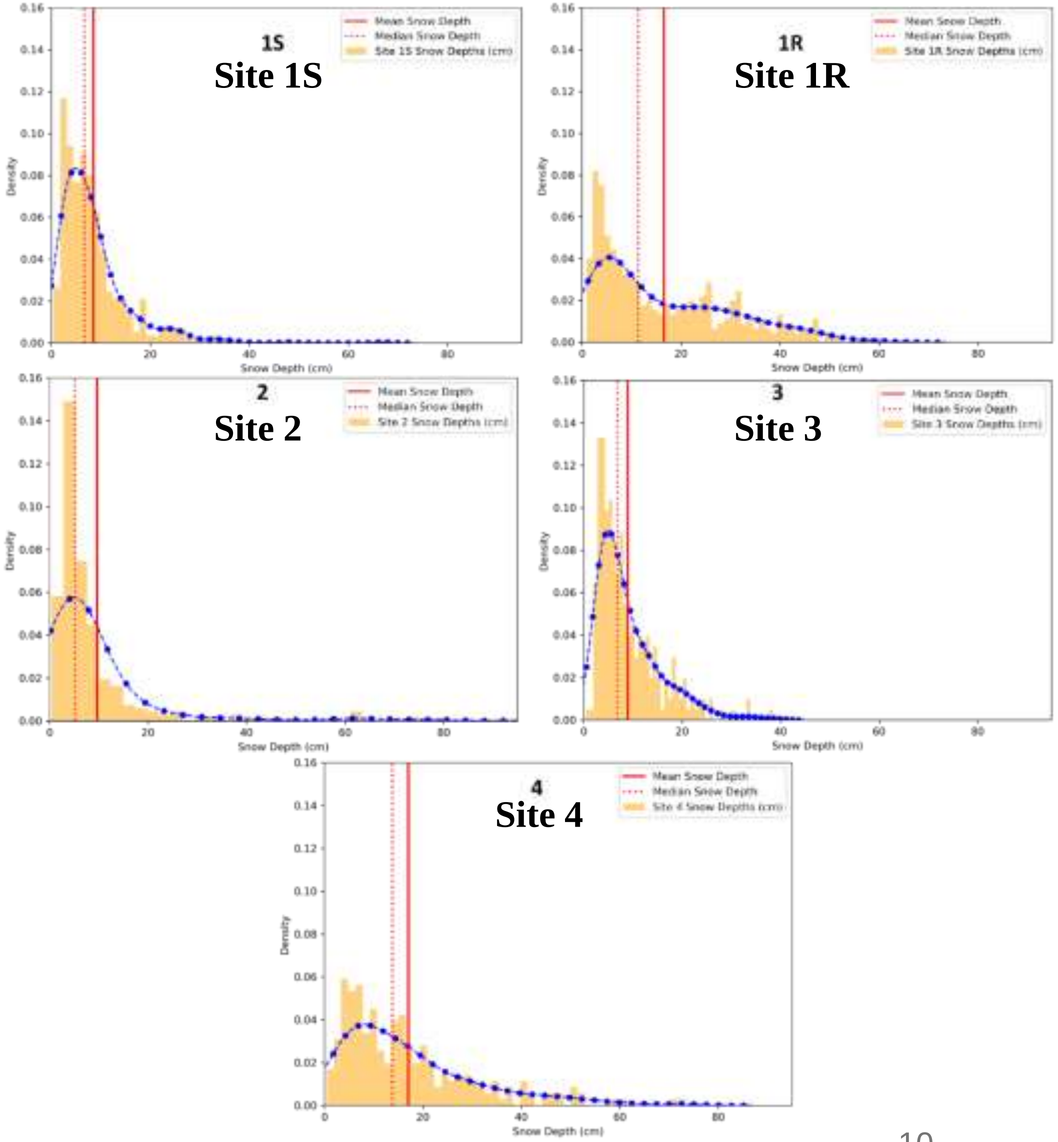

Figure 5 Snow depth distributions from the four in-situ measurement sites along the Cryo2Ice transect. The density distribution curve is shown in blue.

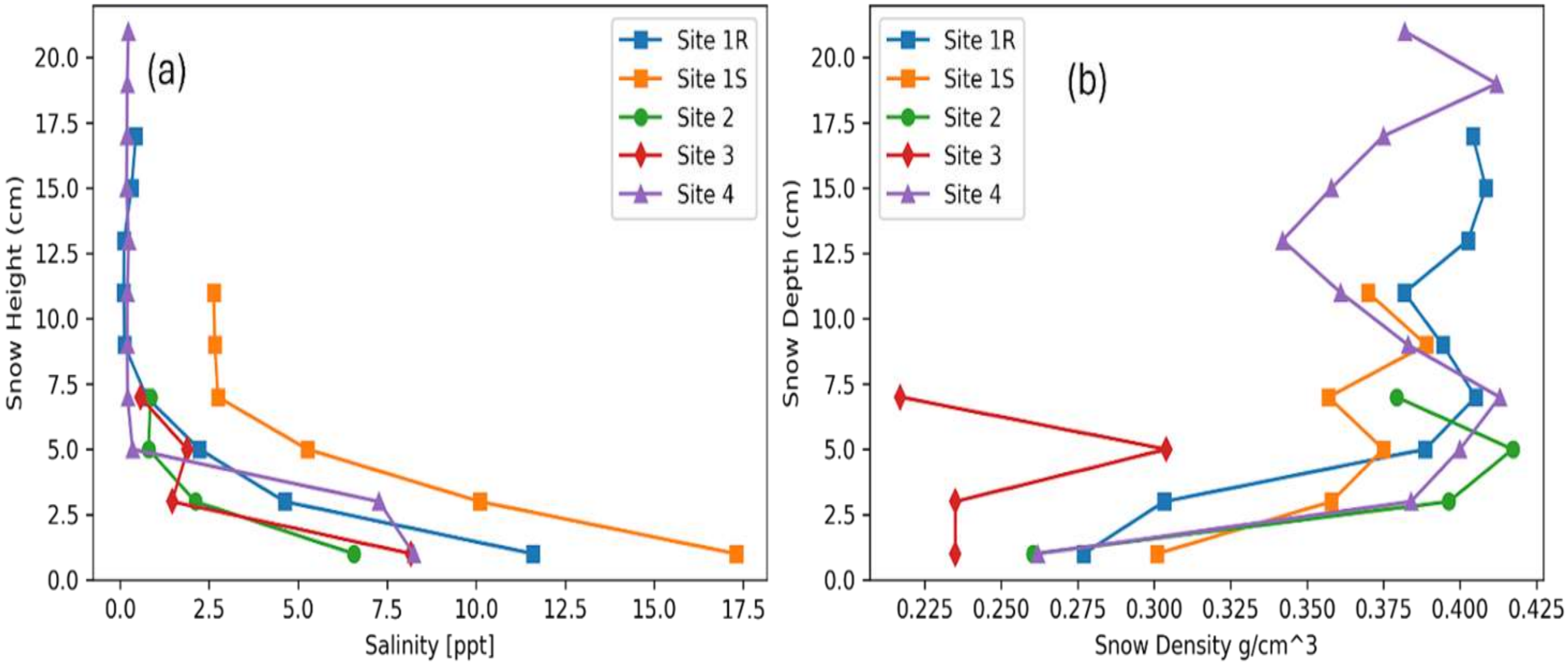

Figure (a) Snow salinity and (b) Snow density change by snow pack depth at the four snow sampling sites. Zero snow depth in both plots represents the snow-ice interface.

- Mean snow salinity varies between 1.5 to 3.0 ppt for Sites 1R, 2, 3 and 4, whereas at Site 1S the snow salinity is 6.78 ppt.
- The mean snow bulk density varies between 0.358 and 0.374 g/cm3 in all sites except Site 3 where the mean snow density is 0.248 g/cm3.

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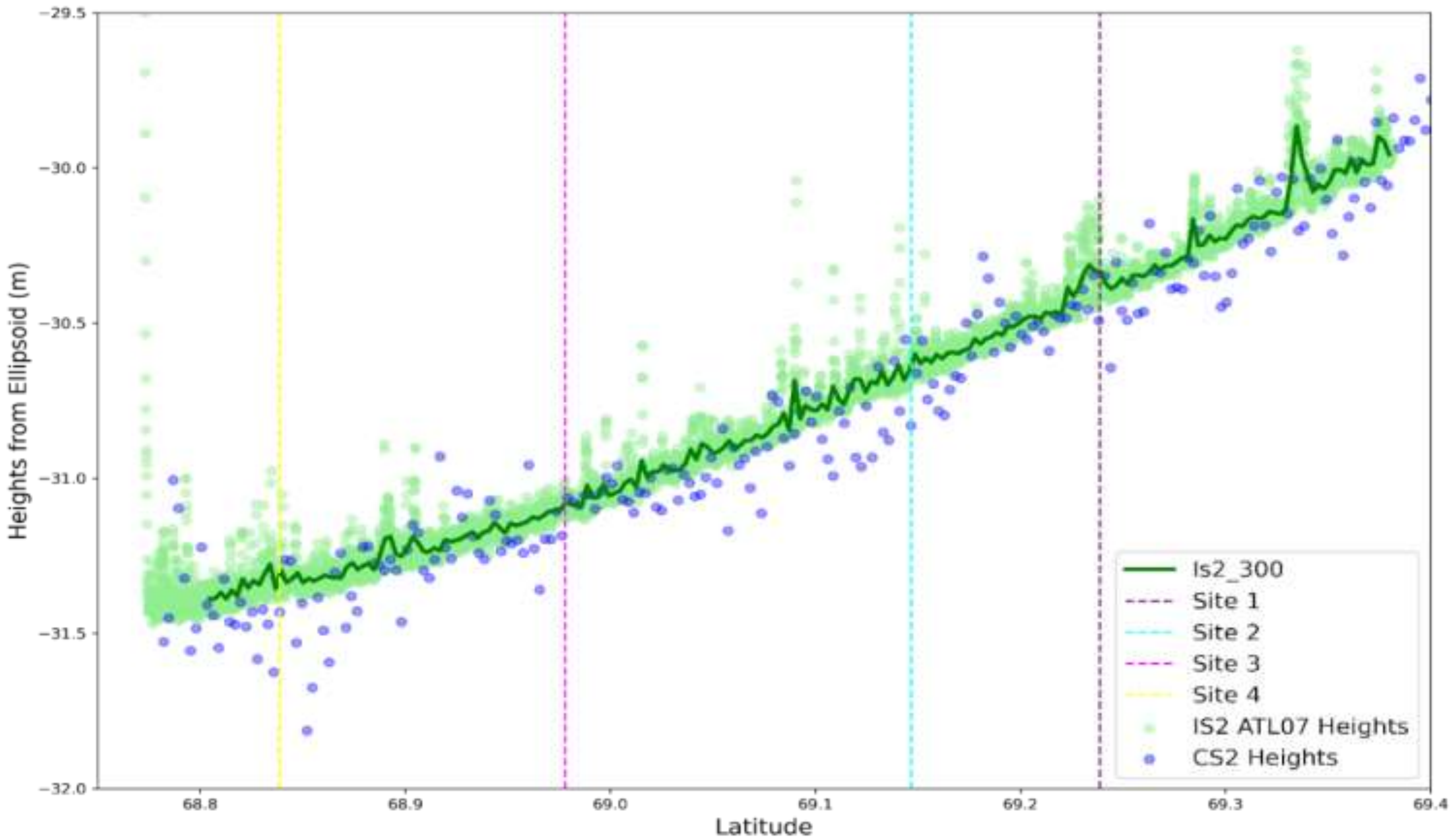

Figure IS2 ATL07 sea ice heights plotted along with CS2 surface heights. The light green color indicates the raw ATL07 heights (IS2 ATL07 Heights). The solid green line indicates the aggregated ATL07 heights aggregated every 300 meters (IS2_300). The purple color indicates the CS2 Heights.

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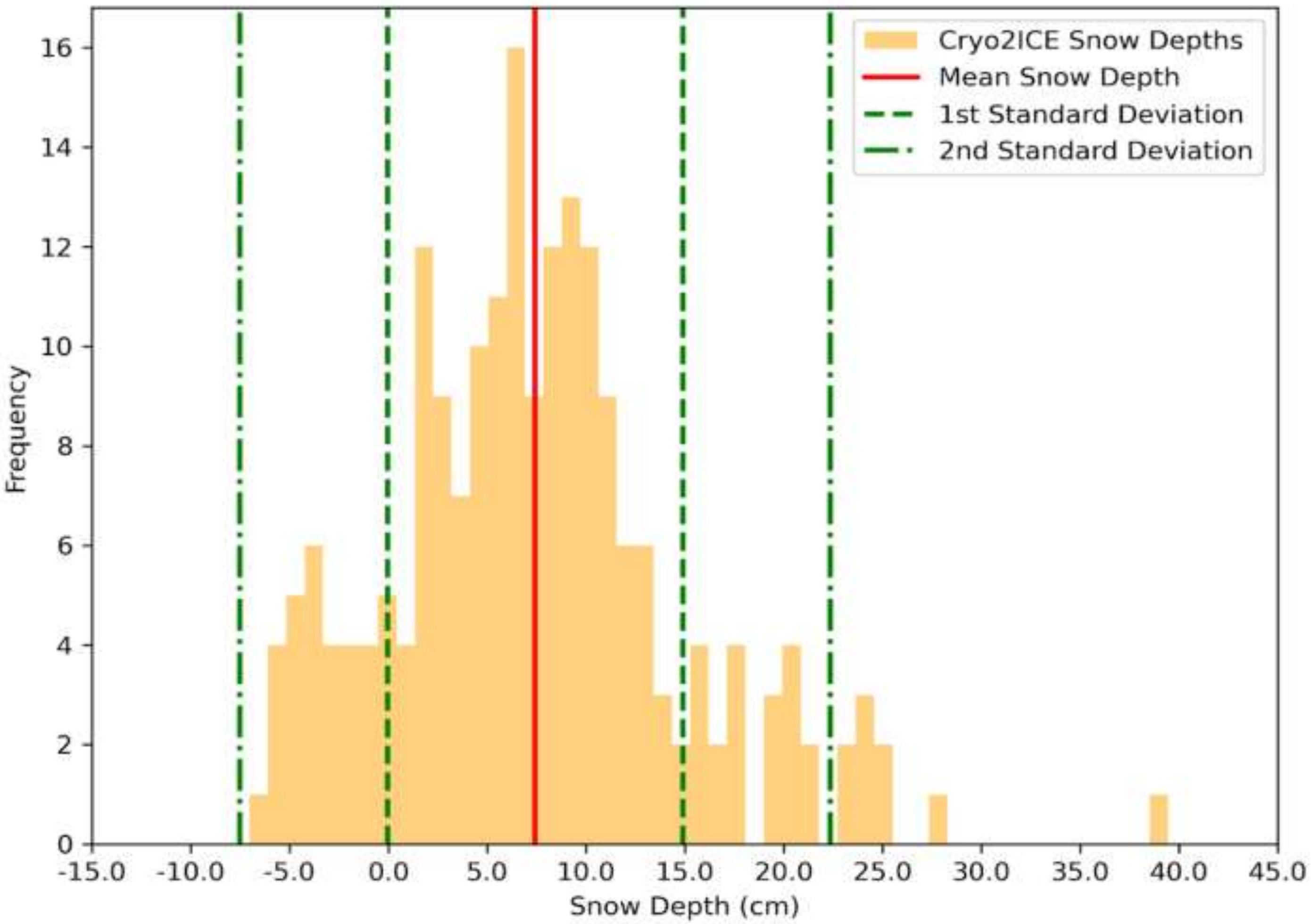
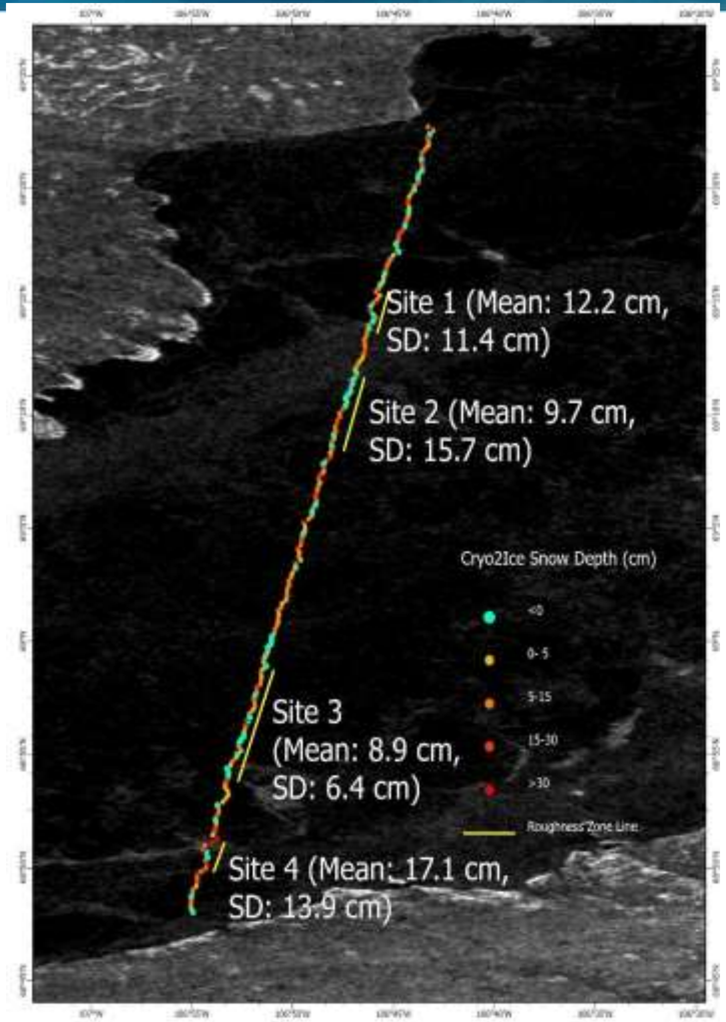


Figure Histogram showing the density distribution of the retrieved snow depth in the native 300 m resolution along the Cryo2Ice track with the mean and the median snow depths. Negative snow depths greater than 2 standard deviations from the mean snow depth were removed to reduce the impact of CS2 noise.



- 20% of the calculated differences are negative which are distributed randomly along the track

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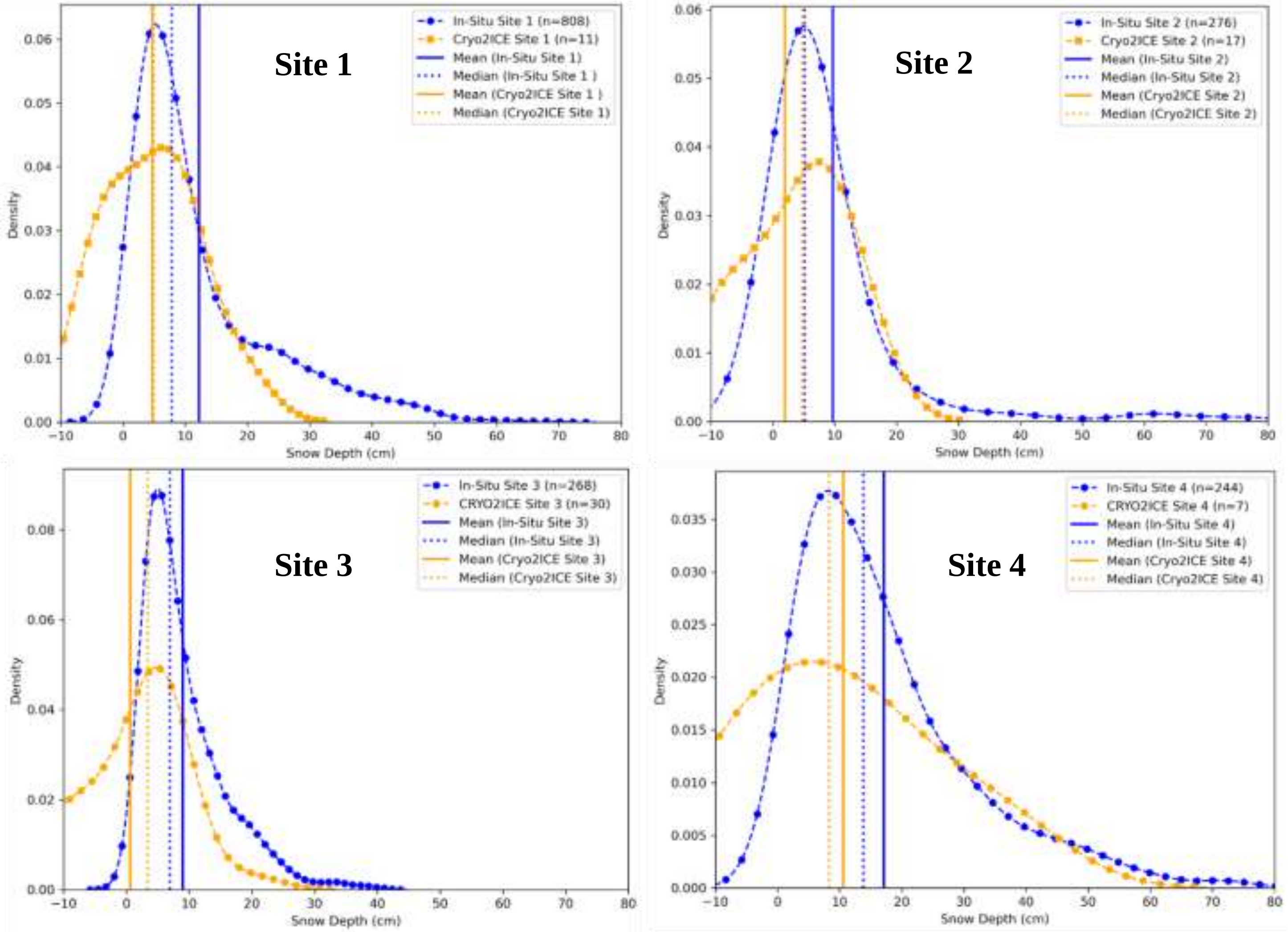

Figure Probability Density plots comparing In-Situ snow depths to Cryo2Ice retrieved snow depths along with the median and mean values. Different snow bulk densities were used to calculate the refractive index and subsequently Cryo2Ice snow depths for each site (Site 1-0.399 g/cm^3, Site 2- 0.398 g/cm^3, Site 3- 0.217 g/cm^3, Site 4-0.381 g/cm^3).

- The thinnest (Site 3) and thickest (Site 4) mean snow depths found in the in-situ measurements are corroborated with Cryo2Ice snow depths
- Cryo2Ice snow depths are on average **3.07 cm** thinner than the in-situ data
- Cryo2Ice snow depths are consistently truncated at the thick end of the distribution, with at least some portion of the in-situ distributions above **~30-50 cm seemingly unresolved from space**
- Cryo2Ice snow depth distributions are generally **wider** than in-situ due to the impact of negative snow depths which reflects the difference in footprint size between CS2 and IS2

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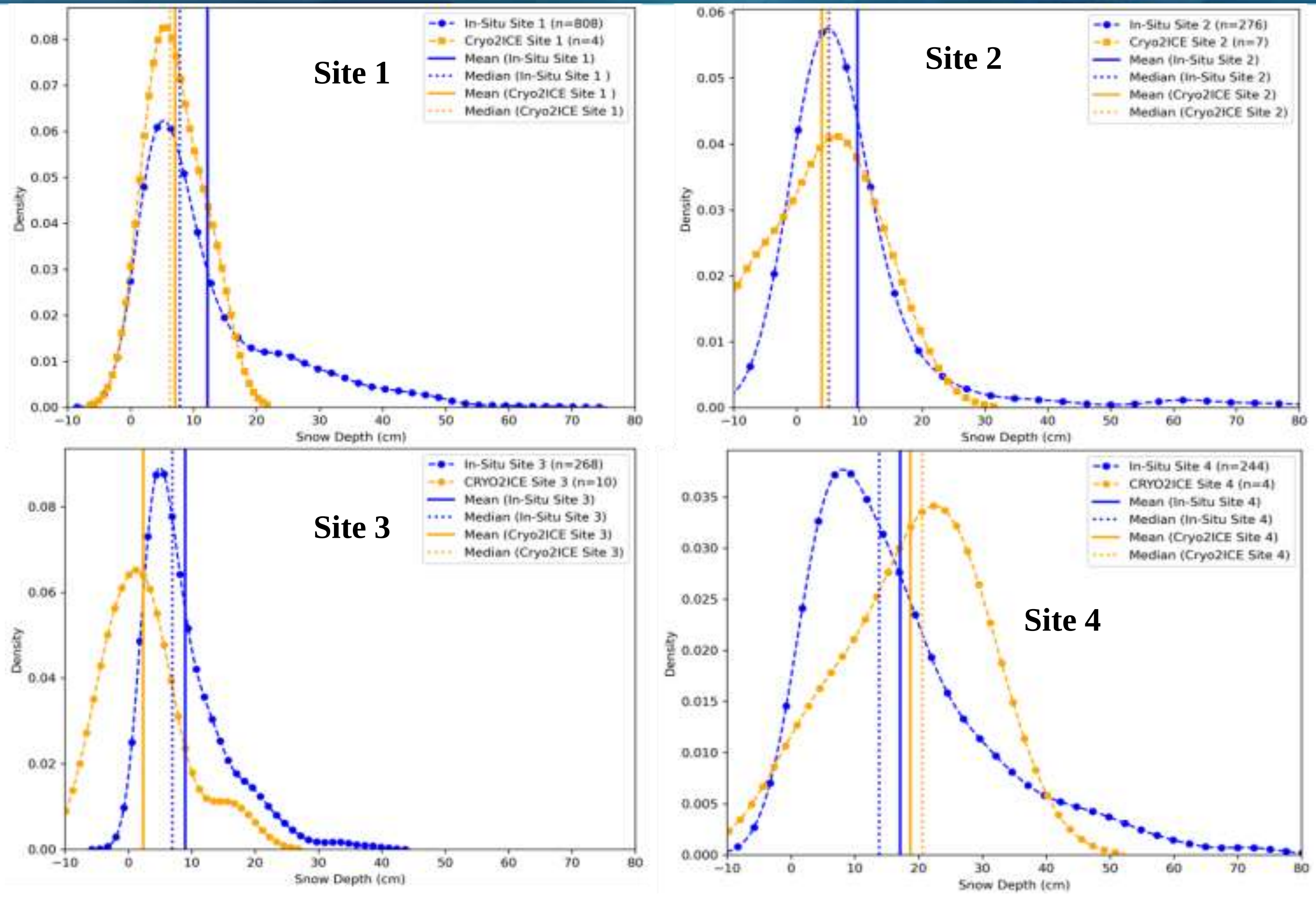

Figure Probability Density plots comparing In-Situ snow depths to Cryo2Ice retrieved snow depths retrieved from 1-km averaged CS2 and IS2 heights along with the median and mean snow depth values. Different snow bulk densities were used to calculate the refractive index and subsequently Cryo2Ice snow depths for each site (Site 1-0.399 g/cm^3, Site 2- 0.398 g/cm^3, Site 3- 0.217 g/cm^3, Site 4-0.381 g/cm^3)

- While averaging the CS2 and IS2 over 1-km causes some of the prominent roughness features such as ridges to be missed by Cryo2Ice
- The average snow depth retrieved from the 1-km averaged product is 7.80 cm which is slightly higher than the 300-meter averaged product presented.
- The 1-km averaged snow depth was slightly underestimated three out of four sites compared to in-situ measurements; however the median biases compared to in-situ are less than 5 cm.
- The peaks align well in Sites 1 and 2 compared to Sites 3 and 4

Identified Bias

- **Snow Salinity**

This phenomenon of snow depth underestimation was evident in Sites 1 and 2 potentially because of the sharp increase in snow salinity within the first 5 cm (from the air-snow interface) of the snowpack (Figure 6) and may have contributed to ~ 2 cm underestimation of Cryo2Ice snow depths

- **Presence of Wind Slab Layers**

The impact of snow bulk density on the Cryo2Ice retrievals was less likely except for the presence of wind-slab layers. The presence of wind slabs where the snow density is 0.425 g/cm3 compared to 0.358 to 0.374 g/cm3 on average throughout the snow-pack which may have caused hindrance to Ku-band penetration.

- **Tidal Corrections**

2 to 5 cm bias meaning that we can expect **~15-40%** systematic uncertainty in Cryo2Ice retrieved snow depths owing to the uncertainty in tidal differences between satellite passes.

- **Surface Roughness**

Site 4 had the highest mean surface roughness (4.58 cm) whereas the other sites had roughness ranging between 2.4-2.7 cm. Therefore, we notice that Cryo2Ice performs poorly in regions with relatively high surface roughness. The presence of isolated ridges and the deeper snow accumulated around them may have been missed by the CryoSat-2 radar given the larger impact of level ice versus ridges on the backscattered power which may explain the underestimation in Sites 1 and 2.

- **Use of Different CS2 Retrackers**

There are uncertainties such as the use of a fixed threshold retracker in CS2 which is not tuned for the landfast sea ice and uncertainties associated with the IS2 fine- tracker that may also contribute significantly to the snow depth retrievals

Conclusion

- We note that while Cryo2Ice generally underestimates snow depths by 2 to 4 cm compared to in-situ, the 1-km averaged snow depths also show the possibility of overestimation over significantly rough ice.
- The site-wise comparison between in-situ snow depths and Cryo2Ice snow depths show that Cryo2Ice performs well in regions with moderately thin and smooth snow on sea ice i.e. ranging between 5 to 20 cm while it struggles to pick up snow depths greater than 30 cm irrespective of the roughness characteristics.
- Difficult to determine given the few centimeters of bias to snow geophysical process, surface roughness and/or errors in the altimeters' tidal corrections given that a lot of these uncertainties are inter-related and are highly variable among different length scales.
- Findings from this study are encouraging for estimating snow depth on land-fast sea ice in lead-less regions using Cryo2Ice and for future coincident laser-radar or dual-frequency altimeter missions

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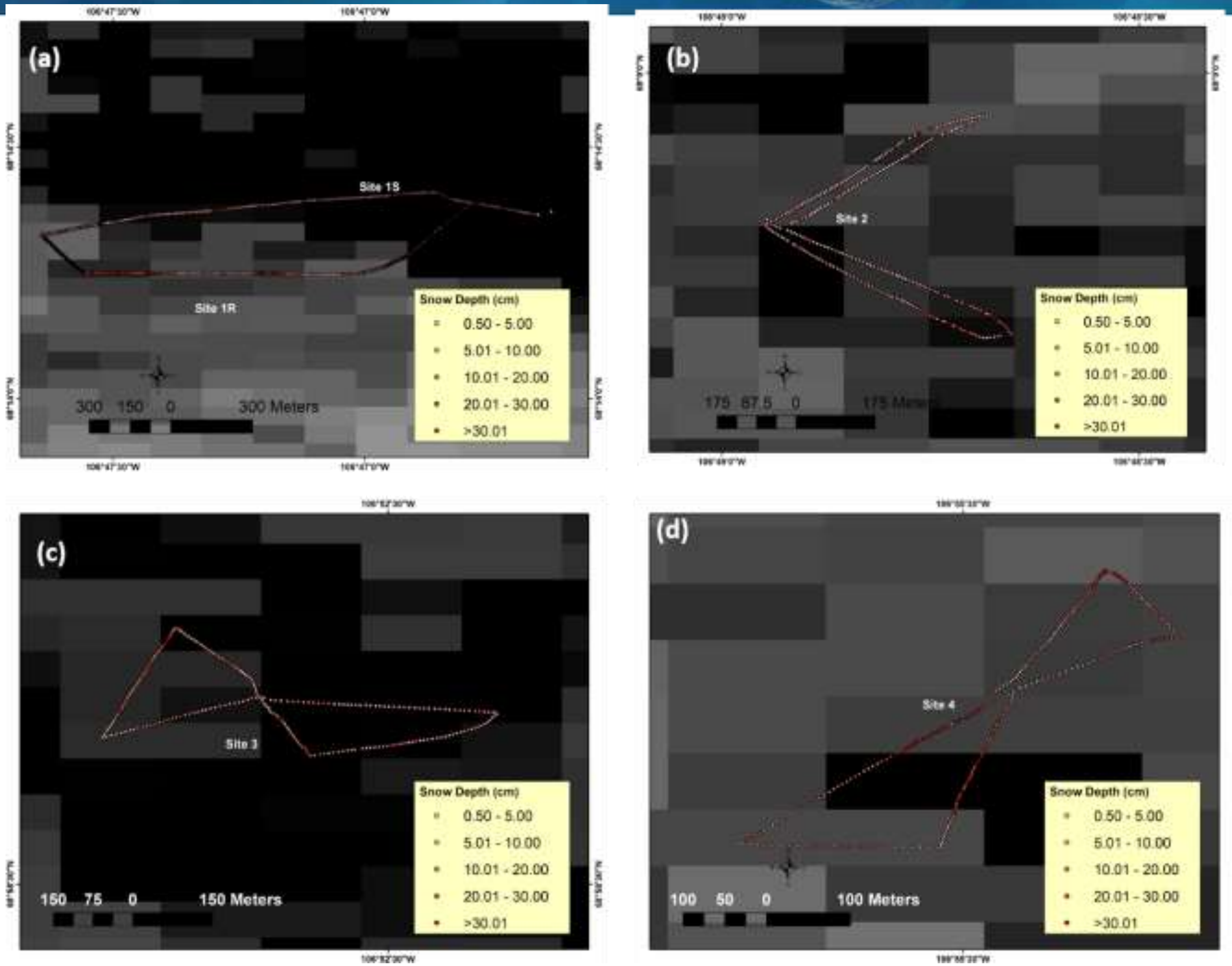

Figure D1: The in-situ snow depth transects conducted in (a) Site 1 (b) Site 2 (c) Site 3 and (d) Site 4. The spatial distribution of the snow depths are included for each site.

Table F1 In-situ versus Cryo2Ice snow depth distribution statistics retrieved using 300 meter averaged IS2 and CS2 height

		Mean (cm)	Median (cm)	Lower Quartile (cm)	Upper Quartile (cm)	Inter-quartile range (cm)
Site 1	In-Situ	12.2	7.8	4.1	16.3	12.2
	Cryo2Ice	4.7	4.9	-1.8	9.8	11.6
Site 2	In-Situ	9.7	5.2	3.7	9.2	5.5
	Cryo2Ice	1.9	4.8	-5.9	8.5	14.4
Site 3	In-Situ	8.9	6.9	4.2	11.9	7.7
	Cryo2Ice	0.61	3.4	-5.4	5.8	11.2
Site 4	In-Situ	17.1	13.8	6.7	22.4	15.7
	Cryo2Ice	10.6	8.3	-0.6	18.5	19.1