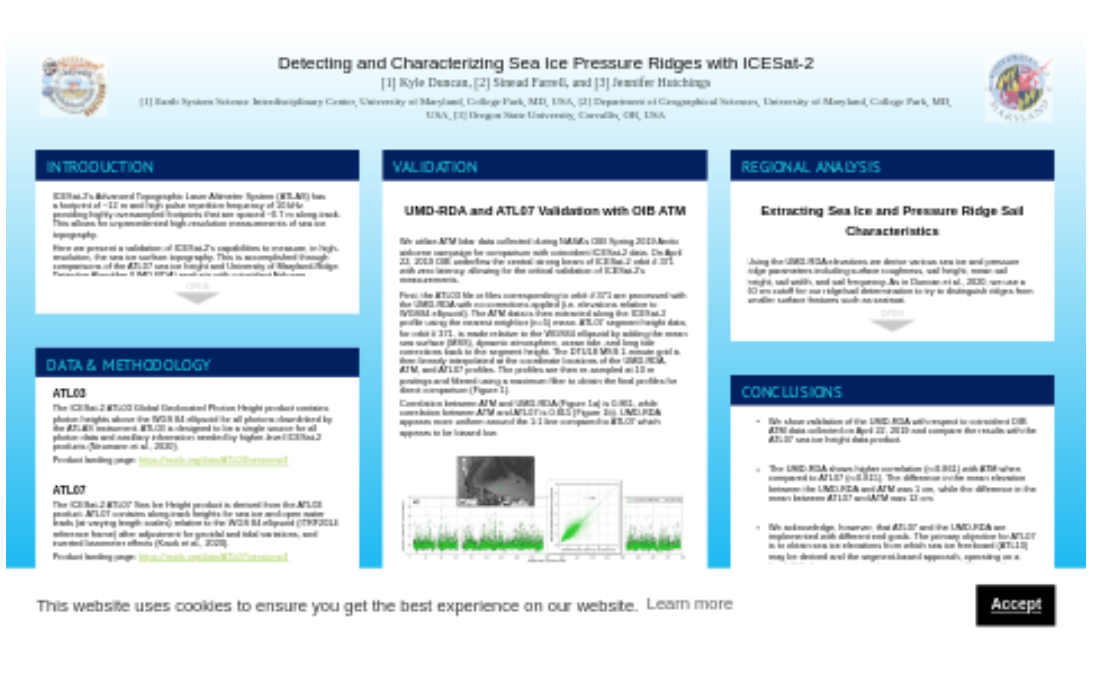
Detecting and Characterizing Sea Ice Pressure Ridges with ICESat-2



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INTRODUCTION

ICESat-2's Advanced Topographic Laser Altimeter System (ATLAS) has a footprint of ~12 m and high pulse repetition frequency of 10 kHz providing highly oversampled footprints that are spaced ~0.7 m along-track. This allows for unprecedented high-resolution measurements of sea ice topography.

Here we present a validation of ICESat-2's capabilities to measure, in high-resolution, the sea ice surface topography. This is accomplished through comparisons of the ATL07 sea ice height and University of Maryland-Ridge Detection Algorithm (UMD-RDA) products with coincident Airborne Topographic Mapper (ATM) lidar data collected during an under-flight of ICESat-2 on April 22, 2019 as part of NASA's annual Spring Operation IceBridge (OIB) airborne campaign (Figures 1, 2). We use these validation results to apply the UMD-RDA to the entire month of April 2019 (Figure 3). We analyze two distinct regions of varying ice type to calculate the annual variability in surface roughness, sail height, sail width, and sail frequency for the month of April, 2019-2021 (Figure 5).

DATA & METHODOLOGY

ATL03

The ICESat-2 ATL03 Global Geolocated Photon Height product contains photon heights above the WGS 84 ellipsoid for all photons downlinked by the ATLAS instrument. ATL03 is designed to be a single source for all photon data and ancillary information needed by higher-level ICESat-2 products (Neumann et al., 2020).

Product landing page: https://nsidc.org/data/ATL03/versions/4

ATL07

The ICESat-2 ATL07 Sea Ice Height product is derived from the ATL03 product. ATL07 contains along-track heights for sea ice and open water leads (at varying length scales) relative to the WGS 84 ellipsoid (ITRF2014 reference frame) after adjustment for geoidal and tidal variations, and inverted barometer effects (Kwok et al., 2020).

Product landing page: https://nsidc.org/data/ATL07/versions/4

ATM

The Airborne Topographic Mapper (ATM) is a conically scanning lidar used during the NASA Operation IceBridge (OIB) airborne campaigns in the polar regions (Studinger, 2020). ATM lidar data was specifically utilized in this study for validation of ICESat-2.

Product landing page: https://nsidc.org/data/ILATM1B/versions/2

DTU18 Mean Sea Surface

The Technical University of Denmark 2018 Mean Sea Surface (DTU18 MSS) is a mean sea surface model that includes the addition of 3 years of Sentinel-3A data as well as an improved 7 year record of CryoSat-2 LRM data (Andersen et al., 2018). The DTU18 MSS grids are available by ftp here: https://ftp.space.dtu.dk/pub/DTU18/

UMD-RDA

The UMD-RDA is a surface retracker designed to extract sea ice surface height. The UMD-RDA is applied to the ATL03 product and processed on a per-shot basis. Photons are first filtered by removing photons outside of the 15th to 85th percentiles. A 5 shot aggregate (~3.5 m) is then used to calculate the 99th percentile of the photon height distribution. This aggregate is applied on a per-shot basis which allows for the maximum along-track resolution of ~0.7 m. Atmospheric, tidal, and mean sea surface corrections are applied to the photon heights which results in corrected elevations relative to the DTU18 MSS (Farrell et al., 2020; Duncan et al., *in prep.*).

VALIDATION

UMD-RDA and ATL07 Validation with OIB ATM

We utilize ATM lidar data collected during NASA's OIB Spring 2019 Arctic airborne campaign for comparison with coincident ICESat-2 data. On April 22, 2019 OIB underflew the central strong beam of ICESat-2 orbit # 371 with zero latency, allowing for the critical validation of ICESat-2's measurements.

First, the ATL03 file or files corresponding to orbit # 371 are processed with the UMD-RDA with no corrections applied (i.e. elevations relative to WGS84 ellipsoid). The ATM data is then extracted along the ICESat-2 profile using the nearest neighbor (n=5) mean. ATL07 segment height data, for orbit # 371, is made relative to the WGS84 ellipsoid by adding the mean sea surface (MSS), dynamic atmosphere, ocean tide, and long tide corrections back to the segment height. The DTU18 MSS 1-minute grid is then linearly interpolated at the coordinate locations of the UMD-RDA, ATM, and ATL07 profiles. The profiles are then re-sampled at 10 m postings and filtered using a maximum filter to obtain the final profiles for direct comparison (Figure 1).

Correlation between ATM and UMD-RDA (Figure 1a) is 0.861, while correlation between ATM and ATL07 is 0.815 (Figure 1b). UMD-RDA appears more uniform around the 1:1 line compared to ATL07 which appears to be biased low.

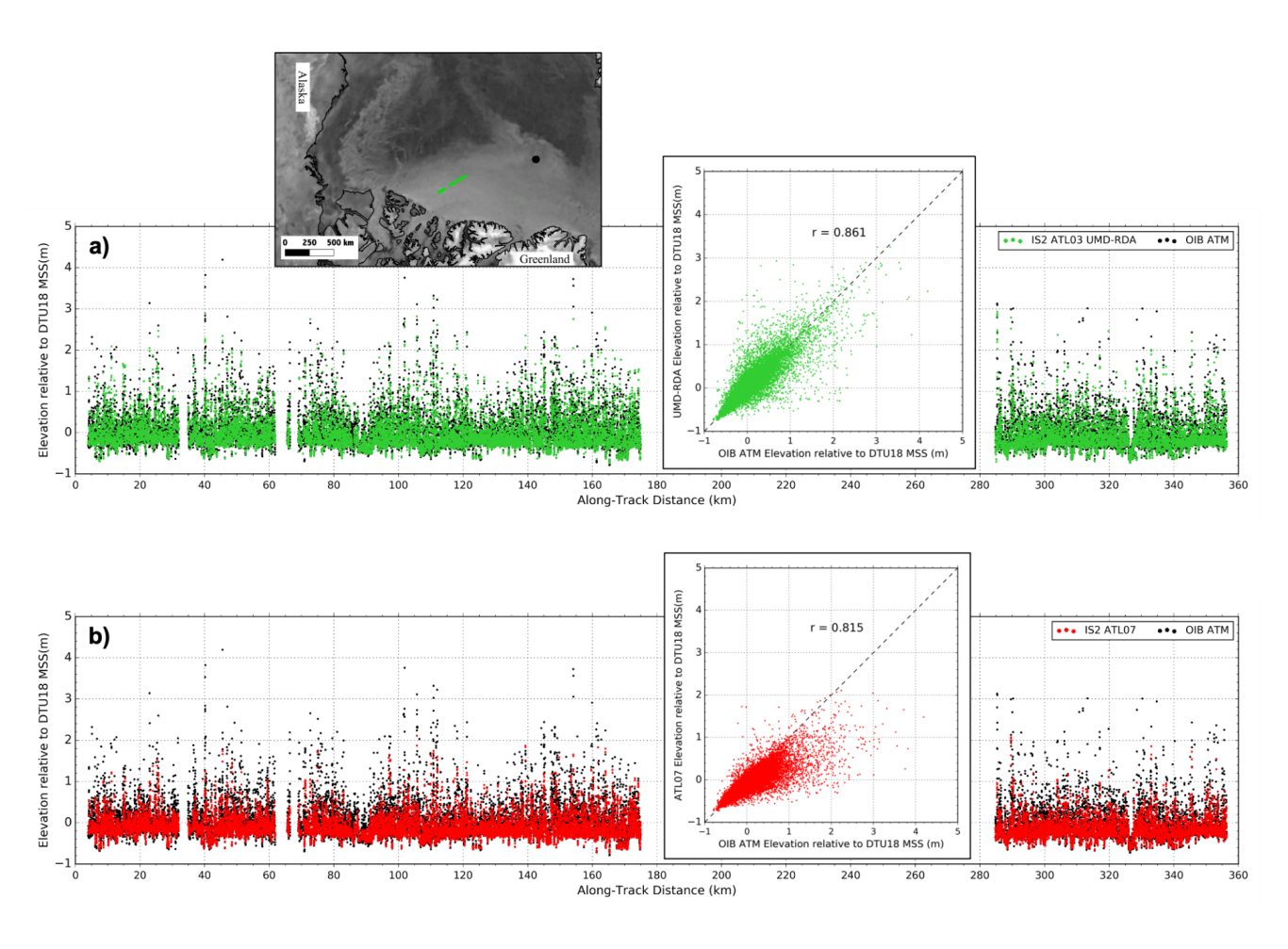

Figure 1. (a) Map of ASCAT backscatter for April 22, 2019. Green line shows where the coincident ICESat-2 (RGT# 371) and OIB ATM data were used in this analysis. Elevation profile of coincident OIB ATM (black dots) and ICESat-2 UMD-RDA (green dots) data, with correlation scatter plot. (b) Same as in (a) but for coincident OIB ATM and ICESat-2 ATL07 (red dots) data.

Further examination of the lowest elevation areas (i.e. leads) for each of the three profiles also provides critical validation (Figure 2a,b). Comparisons of the elevations at and below the approximate 5th percentile of the data (-0.55 m and less) shows excellent agreement between the three datasets (Figure 2c). ATL07 shows the highest quantity of data over these lower elevations with 499 total measurements, compared to 467 from UMD-RDA, and 452 from ATM. All three share the same modal elevation of -0.6125 m. Overall, UMD-RDA and ATM share the same statistics while ATL07 only differs in the mean, median, and standard deviation by 1 cm, respectively. The differences in the elevation distributions for the three profiles become clearer when the entire ~233 km of data is considered (Figure 2d). While all three profiles share the same modal value of -0.25 m, ATL07 differs from ATM's mean, median, and standard deviation by 12 cm, 6 cm, and 15 cm, respectively. UMD-RDA differs from ATM's mean, median, and standard deviation by 1 cm, 1 cm, and 2 cm, respectively.

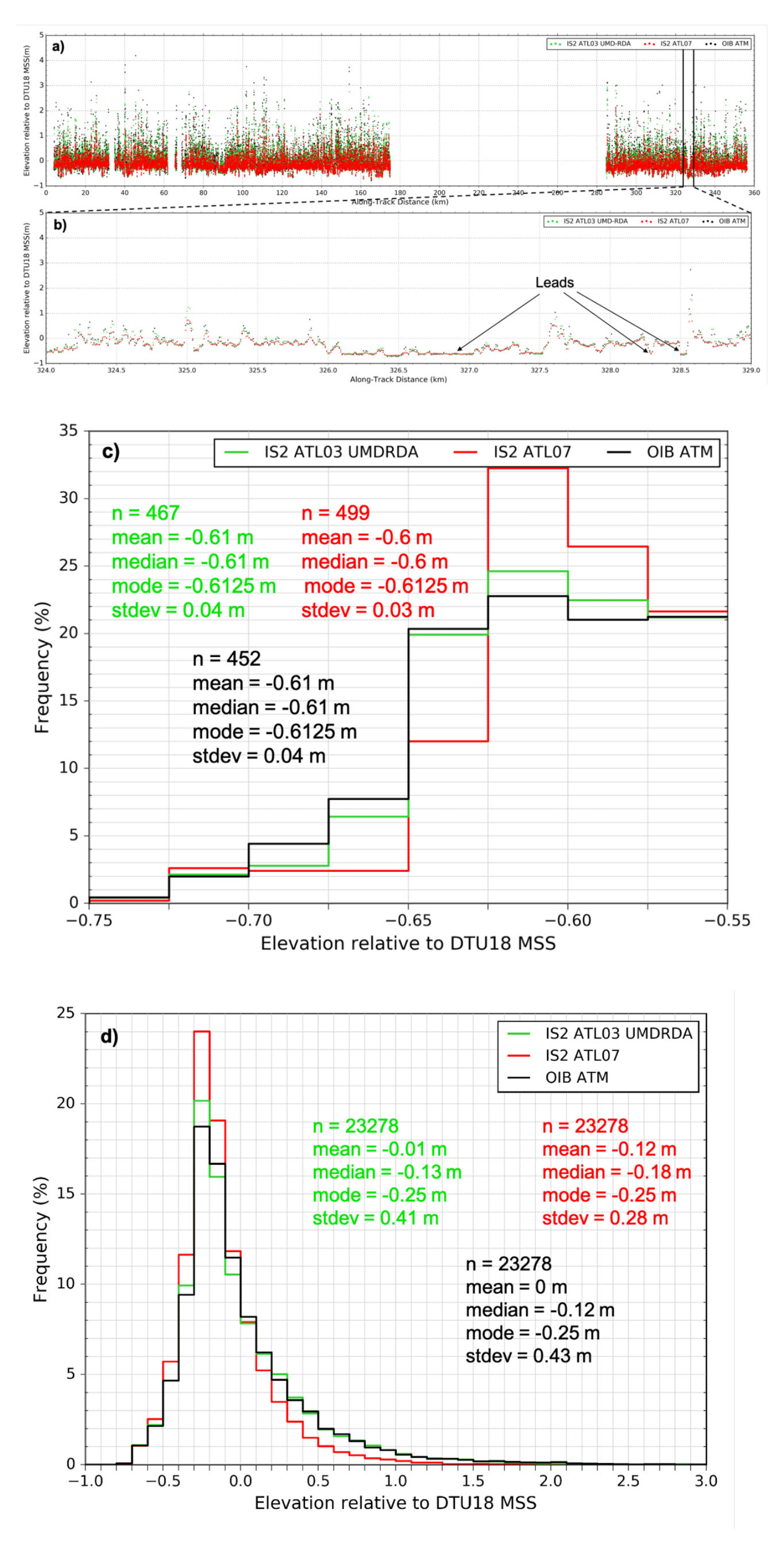

Figure 2. (a) Elevation profiles of OIB ATM (black dots), UMD-RDA (green dots), and ATL07 (red dots) for the April 22, 2019 coincident data collection. (b) A 5 km close-up of profile shown in (a) focusing on areas of low elevation (marked as "leads") for comparison of the three datasets. (c) Histograms and statistics of elevations less than -0.55 m over the entire ~233 km transect for all three profiles. (d) Histograms and statistics of elevation for the entire ~233 km of data for all three profiles.

The UMD-RDA is extended to the entire month of April 2019 based on the above validation results. From the surface elevations derived from the UMD-RDA we calculate the 25 km standard deviation of elevation (Figure 3a) which serves as a measure of sea ice surface roughness. We also calculate the 25 km standard deviation of elevation from the ATL07 data product and map the difference of ATL07 from UMD-RDA (Figure 3b). We choose two regions representing varying ice types. Region A is located north of the Canadian Archipelago, within predominantly multiyear ice, while Region B is located in the Beaufort Sea, within predominantly first-year ice. We find that the greatest differences in sea ice surface roughness between the ATL07 and UMD-RDA products occurs in the roughest sea ice of Region A (Figure 3c). The mean, median, and modal differences of ATL07 - UMD-RDA in Region A were -0.11 m, -0.1 m, and -0.09 m, respectively, while in Region B the differences were -0.06 m, -0.06 m, and -0.05 m, respectively.

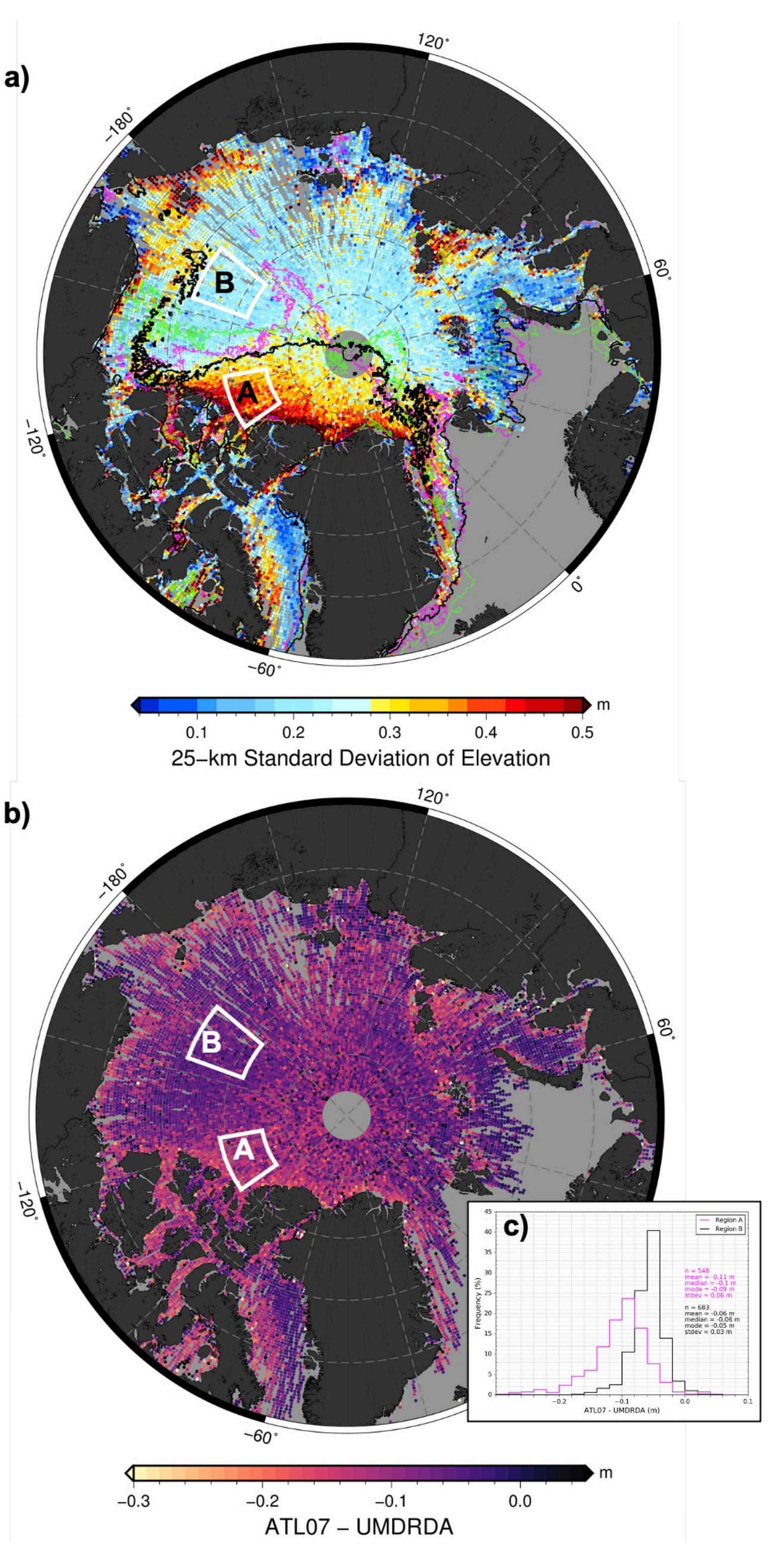

Figure 3. (a) 25-km standard deviation of elevation in April 2019 derived from ICESat-2 ATL03, using the University of Maryland-Ridge Detection Algorithm, mapped at 1/4 degree. A and B denote regions of analysis depicted in this poster. Contours differentiate the ice type extent in 2019 (black line), 2020 (green line), and 2021 (magenta line). (b) Map of the difference between ATL07 and UMD-RDA 25-km standard deviation of elevation for April 2019, mapped at 1/4 degree. (c) Histograms and statistics of difference shown in (b) for Regions A and B.

REGIONAL ANALYSIS

Extracting Sea Ice and Pressure Ridge Sail Characteristics

Using the UMD-RDA elevations we derive various sea ice and pressure ridge parameters including surface roughness, sail height, mean sail height, sail width, and sail frequency. As in Duncan et al., 2020, we use a 60 cm cutoff for our ridge/sail determination to try to distinguish ridges from smaller surface features such as sastrugi.

Sail height is calculated by first finding the modal elevation of 25 km along-track segments and using that modal value as the local level surface. This level surface is used as the zero elevation from which sail height can be calculated (Figure 4b). Any peak occurring above the 60 cm cutoff is therefore determined to be a ridge sail from which a sail width can be calculated at the 60 cm cutoff (Figure 4b).

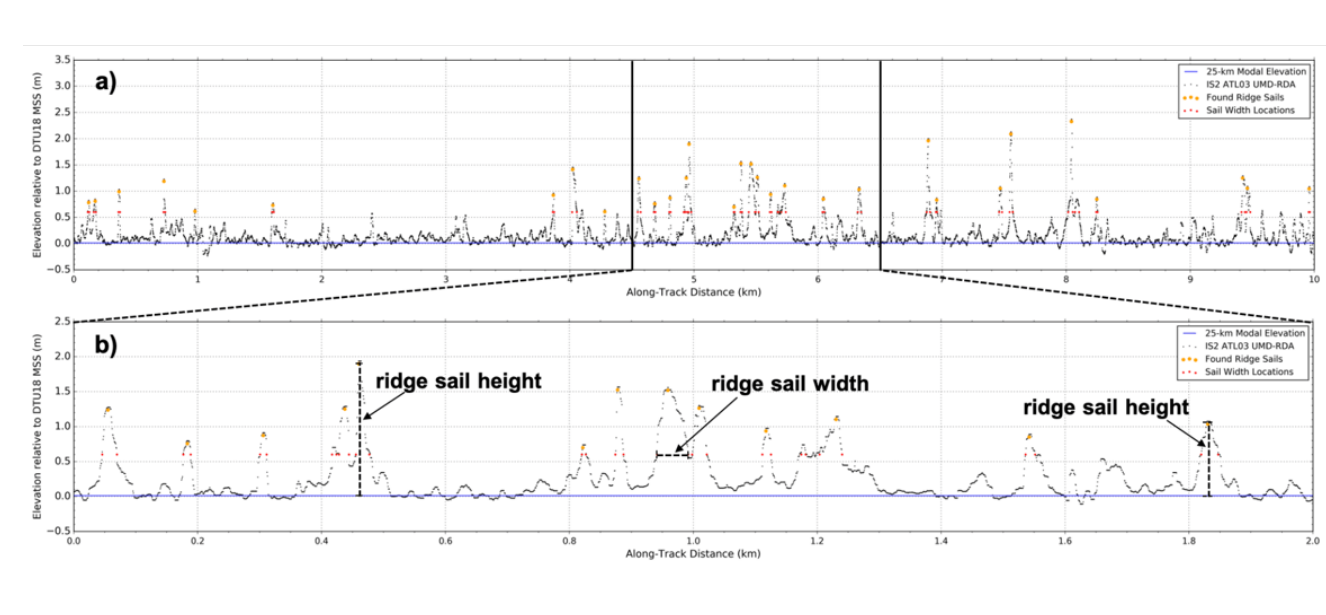

Figure 4. (a) 10 km segment of UMD-RDA derived elevations (black dots) for April 22, 2019. Found ridge sails are denoted by orange dots while locations for calculating sail width are denoted by red dots. Modal elevation for this segment (blue line) is used as the local level surface and a base for extracting numerous sea ice parameters. (b) 2 km close-up view of profile from (a) defining how we're measuring sail height and sail width.

Here, we build upon Farrell et al., 2020, and extend the regional analysis of Regions A and B to April 2020 and 2021. We show the annual variability of surface roughness, sail height, mean sail height, sail width, and sail frequency with respect to varying ice type for the month of April, 2019-2021.

All parameters were larger in the predominantly multiyear ice of Region A when compared to that of Region B. The mean surface roughness of Region A from 2019-2021 was roughly constant at 0.42-0.43 m, which was approximately double that of Region B at 0.22-0.23 m. The mean sail height of Region A ranged from 1.24-1.3 m while Region B ranged from 0.95-1.03 m. Sail width in Region A ranged from 31.1-38.1 m while Region B ranged from 18.9-25.9 m. Sail frequency in Region A ranged from 3.3-4.1 km^{-1} while Region B ranged from 1.5-1.8 km^{-1}.

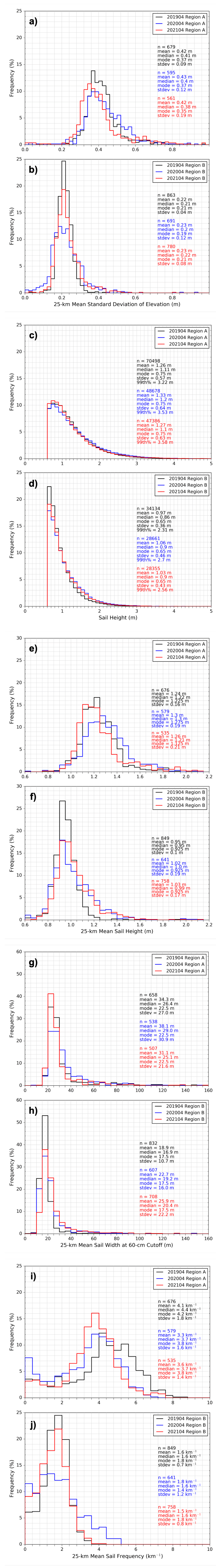

Figure 5. (a) Histograms and statistics for sea ice surface roughness in Region A for 2019 (black line), 2020 (blue line), and 2021 (red line). (b) Same as in (a) but for Region B. (c) Histograms and statistics for sail height in Region A for 2019 (black line), 2020 (blue line), and 2021 (red line). (d) Same as in (c) but for Region B. (e) Histograms and statistics for mean sail height in Region A for 2019 (black line), 2020 (blue line), and 2021 (red line). (f) Same as in (e) but for Region B. (g) Histograms and statistics for sail width in Region A for 2019 (black line), 2020 (blue line), and 2021 (red line). (h) Same as in (g) but for Region B. (i) Histograms and statistics for sail frequency in Region A for 2019 (black line), 2020 (blue line), and 2021 (red line). (j) Same as in (i) but for Region B.

CONCLUSIONS

- We show validation of the UMD-RDA with respect to coincident OIB ATM data collected on April 22, 2019 and compare the results with the ATL07 sea ice height data product.
- The UMD-RDA shows higher correlation (r=0.861) with ATM when compared to ATL07 (r=0.815). The difference in the mean elevation between the UMD-RDA and ATM was 1 cm, while the difference in the mean between ATL07 and ATM was 12 cm.
- We acknowledge, however, that ATL07 and the UMD-RDA are implemented with different end goals. The primary objective for ATL07 is to obtain sea ice elevations from which sea ice freeboard (ATL10) may be derived and the segment-based approach, operating on a fixed 150-photon count, tends to act as a low-pass filter over the roughest sea ice. On the other hand, the aim of the UMD-RDA is to accurately detect and measure the height and frequency of features formed through sea ice deformation, which are defined as elevation anomalies about the level ice surface.
- We apply the UMD-RDA to the entire month of April 2019 and within Regions A and B for April 2020 and 2021. We show the annual variability, by region, for sea ice surface roughness, sail height, mean sail height, sail width, and sail frequency.
- Surface roughness, mean sail height, and sail frequency, in Region A (Region B), from 2019 through 2021, had mean values ranging from 0.42-0.43 m (0.22-0.23 m), 1.24-1.3 m (0.95-1.03 m), and 3.3-4.1 km^{-1} (1.5-1.8 km^{-1}), respectively.
- We aim to apply the UMD-RDA to the entire ATL03 dataset to produce data products that can be utilized by the broader sea ice community and assimilated into high-resolution sea ice models.

DISCLOSURES

This study is supported under NASA Cryosphere Program Grant: 80NSSC20K0966 (ICESat-2 Science Team)

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