Merging CryoSat-2 and ICESat-2 Retrievals to Advance Observations of Arctic Sea Ice

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Introduction

The Arctic Ocean experiences enhanced sensitivity to global warming due to the positive ice albedo feedback. This has resulted in an acceleration of warming - temperatures are now rising in the Arctic at rates 2-3x the global average. In turn, this has contributed to a downward trend in sea ice extent over the last 40 years. ***Sustained monitoring is required to constrain variability and trends, to better understand the processes driving loss and to improve model predictions.***

Snow on Sea Ice

- The high albedo and low thermal conductivity of snow on sea ice significantly impacts Earth's energy budget and regulates the flux of heat between the ocean and atmosphere in winter.
- Accumulation and redistribution of snow on sea ice is associated with synoptic weather events. Obtaining direct estimates of snow depth is useful for constraining precipitation over Arctic Ocean in winter (**Fig. 1**).
- Annual growth and retreat of sea ice influenced by snow accumulation, redistribution and melt. The depth and distribution of snow on sea ice influences the location of summer melt ponds and freshwater flux to the ocean.
- Information on the seasonal evolution of snow ice provides insights about changes in marine mammal habitat.
- ***Knowledge of snow loading is required to convert satellite altimeter measurements of freeboard to thickness (Fig. 3).***

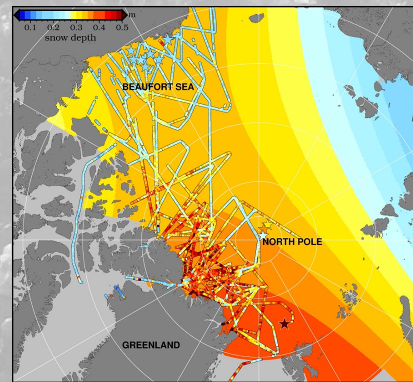

Figure 1. Snow depth on Arctic sea ice at the end of winter, prior to melt onset. *In situ* measurements of snow (stars) collected at a variety of field sites in winters 2015 and 2017. Airborne observations of snow depth (dots along multiple flight survey lines) obtained in March-May 2019-2012 and 2014-2015 (Newman et al., 2020). Both datasets are overlaid on the climatological mean snow depth for the months of March and April (adapted from *Warren et al.*, 1999). **Here, mean snow depths at the end of winter range ~0.05 m to 0.55 m**.

Figure credit: Arctic Report Card, *Perovich et al.*, 2017, https://www.arctic.noaa.gov/Report-Card/Report-Card-2017

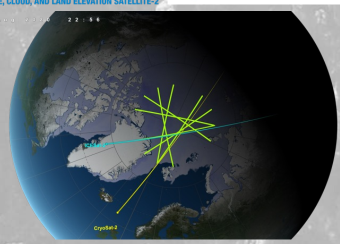

Figure 2. Cryo2Ice Coincident Data Explorer

Cryo2Ice

- In summer 2020, a successful spacecraft maneuver raised the semi-major axis of the CryoSat-2 orbit by ~900 m to align the orbits of CryoSat-2 and ICESat-2 every ~ 1.5 days.
- The longitude of CryoSat-2 and ICESat-2 satellites become periodically synchronized every 19th CryoSat-2 revolution and every 20th ICESat-2 revolution (**Fig. 2**).
- Cryo2Ice (https://cryo2ice.org) is a Coincident Data Explorer tool
- The Cryo2Ice tool (Alford et al., 2021) enables users to visualize spatial intersections between CryoSat-2 and ICESat-2 (**Fig. 2**) and download ESA & NASA data products.

Measurement Approaches

Snow depth on sea ice is typically measured by conducting direct, *in situ* surveys (e.g., *Warren et al.*, 1999; *Webster et al.*, 2014) or via autonomous ice sensors such as Ice Mass Balance Buoys or snow buoys. However, remote sensing observations from airborne snow radar systems (e.g., *Kurtz and Farrell*, 2011; *Newman et al.*, 2014), passive microwave radiometer observations (e.g., *Rostosky et al.*, 2018), global atmospheric reanalysis products and global climate models (e.g., *Blanchard-Wrigglesworth et al.*, 2015; 2018) also provide complimentary estimates of snow depth on Arctic sea ice, as shown in **Figure 1**.

LaRA freeboard = ICESat-2 laser fb (f_s) – CryoSat-2 radar fb (f_i^{CS2})

Snow depth = $h_s = f_s - f_i$ and thus, $h_s = \frac{f_s - f_i^{CS2}}{\eta_s}$ or $h_s = \frac{LaRA\ freeboard}{\eta_s}$

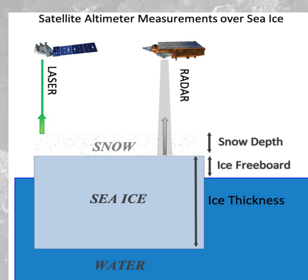

Figure 3. Coincident satellite laser and radar altimeter measurements over sea ice. In dry snow conditions, the ICESat-2 laser return originates from the air/snow interface, while the CryoSat-2 return originates from the snow/ice interface.

Satellite Altimeter Estimates of Snow Depth

Here, we describe a novel technique to directly estimate snow depth using observations from two satellite altimeters: ICESat-2 and CryoSat-2. We exploit the Cryo2Ice orbit resonance (**Fig. 2**) to obtain sea ice height at two electromagnetic frequencies. Using Cryo2Ice data we difference satellite laser and radar altimeter (LaRA) freeboard observations to estimate the seasonal evolution of snow depth on sea ice (**Fig. 5**). To do this we take advantage of the difference in radar and laser penetration depths into the snow pack (**Fig. 3**). Typically, in dry snow conditions, the laser return from ICESat-2 originates from the air/snow interface, while the return from CryoSat-2 is from the snow/ice interface. We combine freeboard measurements retrieved from different scattering horizons to directly estimate snow depth (**Fig. 4**).

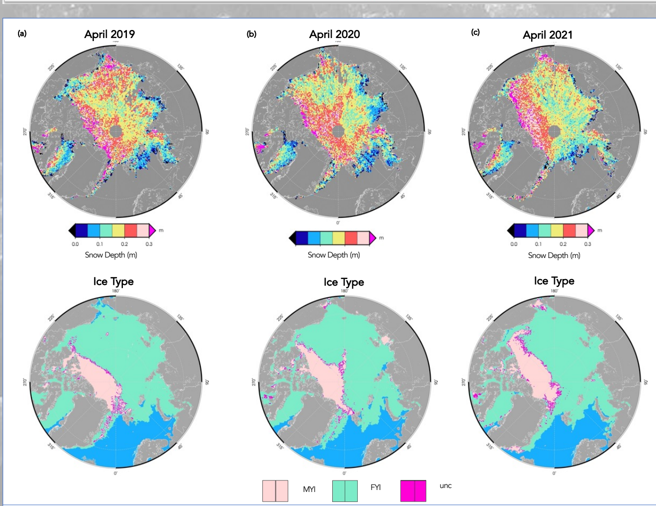

Figure 4. Altimeter-derived snow depth estimates. Arctic snow depth (top row) and sea ice type (bottom row) for April (a) 2019, (b) 2020 and (c) 2021. Multiyear ice (MYI, pink), first-year ice (FYI, green) and unclassified pixels (unc, magenta).

Evolution of LaRA freeboard with time

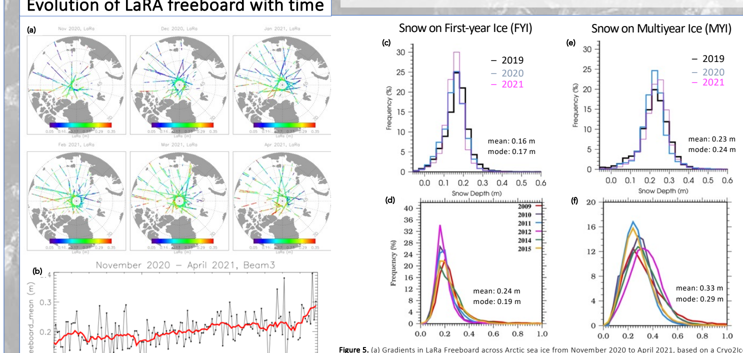

Figure 5. (a) Gradients in LaRa Freeboard across Arctic sea ice from November 2020 to April 2021, based on a Cryo2Ice search with an overlapping distance of 2 minutes, a maximum separation between CryoSat-2 and ICESat-2 tracks of 5 km, and a temporal offset of <3 hours. (b) Increase in LaRa freeboard with time between Nov. 2020 and April 2021 indicating snow accumulation on sea ice. (c) Distribution of snow depth on first-year sea ice estimated from LaRa freeboard for April 2019, 2020 and 2021. (d) Snow depth on first-year sea ice estimated from airborne snow radar data using the wavelet-based algorithm (Newman et al., 2020) for April 2009 – 2015. (e) Same as in (c) except for snow on multiyear ice. (f) Same as in (d) except for snow on multiyear ice.

Results show that (i) there are distinct snow depth distributions dependent on ice type, (ii) that snow depth on first year sea ice is ~ 75 % that of snow on multiyear sea ice, and (iii) snow depth derived using the LaRa freeboard technique is an underestimate compared to airborne data.

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