C-ICESat-2

a constrained estimate of global sea ice thickness from laser altimeter freeboard observations

Molly M. Wieringa | NSF NCAR ASP CESM Polar Climate Working Group 10 June 2025 When run in an unconstrained^{*} fashion, CICE exhibits biases in sea ice thickness relative to current observational estimates.



- Estimated from Cryosat-2 radar altimeter observations + DL model
- 80km north polar stereographic grid

- 30-member ensemble mean
- Data atmosphere, slab ocean, 1° res.

2.70

2.25

1.80

1.35 (1.35 -1.35 thickness

0.45

0.00

• Tuned following Kay et al. (2022)

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- Estimated from Cryosat-2 radar altimeter
 observations + waveform model
 - NSIDC 25km polar stereographic grid

- 30-member ensemble mean
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sea ice thickness (SIT)

- available from derived *in situ* and satellite products
- intermittent, relatively short satellite records (~2003-present)
- shown to improve state estimates and predictions of SIT and SIC (Lisaeter et al., 2007; Fritzner et al., 2018; Xie et al., 2016; Zhang et al., 2018).



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sea ice freeboard (FB)

- can be used as a proxy for SIT
- available from recent satellite missions (Cryosat-2 and ICESat-2)
- not commonly assimilated; multiple types

Laser altimeter freeboard observations are available at unprecedented density from ICESat-2.



ICESat-2 freeboard observations can be aggregated into gridded, along-track estimates accompanied by well-defined^{*} uncertainties.



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Assimilating ICESat-2 freeboard observations reduces error in the model estimates of freeboard.



*monthly model ensemble mean compared to monthly gridded freeboard product

Assimilating ICESat-2 freeboard observations does not always improve model estimates of SIT.



*monthly model ensemble mean compared to monthly SIT estimates from Cryosat-2

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Validation and constrained thicknesses look more similar here!

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Why did the assimilation act to thin ice in a region where the model and validation agree?



Validation and unconstrained model look more similar!

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Where the constrained model overestimates snow depths, ice thickness is underestimated.



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Pattern adjustment is reasonable, consistent differences in magnitude (~1m)

Current status...

- 1. Generally, ICESat-2 freeboards improve model representations of freeboard, ice thickness, and snow depth in the Arctic.
 - improve model estimates of total sea ice volume
 - mixed seasonal effect on modeled sea ice cover
- 2. As currently represented in the C-ICESat-2 assimilation framework, laser altimeter freeboard observations demonstrate some limitations when constraining both sea ice and snow in the Northern Hemisphere.
- 3. Validation in the Southern Hemisphere is very limited.

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How have our assimilation configuration choices and the observational network impacted the analysis?

Thanks! Questions?



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Modern satellite estimates of thickness are derived from measurements of sea ice freeboard.



Radar altimeter freeboard observations target the snow-ice interface.

$$\sim 0.1 \qquad \sim 0.3$$
$$FB_{R} = h_{i} \left(1 - \frac{\rho_{i}}{\rho_{w}} \right) - h_{s} \frac{\rho_{s}}{\rho_{w}}$$



 FB_R has a **positive** relationship with thickness and a **negative** relationship with snow depth

 $\rho_i \cong 917.0 \ kg/m^3$ $\rho_s \cong 330.0 \ kg/m^3$ $\rho_w \cong 1026.0 \ kg/m^3$ Radar altimeter freeboard observations target the snow-ice interface.

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Laser altimeter freeboard observations target the top of the snow/ice surface.

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$$\boldsymbol{FB}_{\boldsymbol{L}} = h_i \left(1 - \frac{\rho_i}{\rho_w} \right) + h_s \left(1 - \frac{\rho_s}{\rho_w} \right)$$



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Observation density is reduced and observation error quantified by aggregating the ICESat-2 data product on the model grid.



C-ICESat-2 Process Diagram





Beaufort Gyre Exploration Project (BGEP) moorings







C-ICESat-2 Northern Hemisphere SIA/SIV



C-ICESat-2 SIT Variability



C-ICESat-2 sea ice coverage biases



C-ICESat-2 Integrated Ice Edge Error

