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Observationally calibrating snow-on-sea-ice model free parameters and estimating uncertainties using a Markov Chain Monte Carlo method

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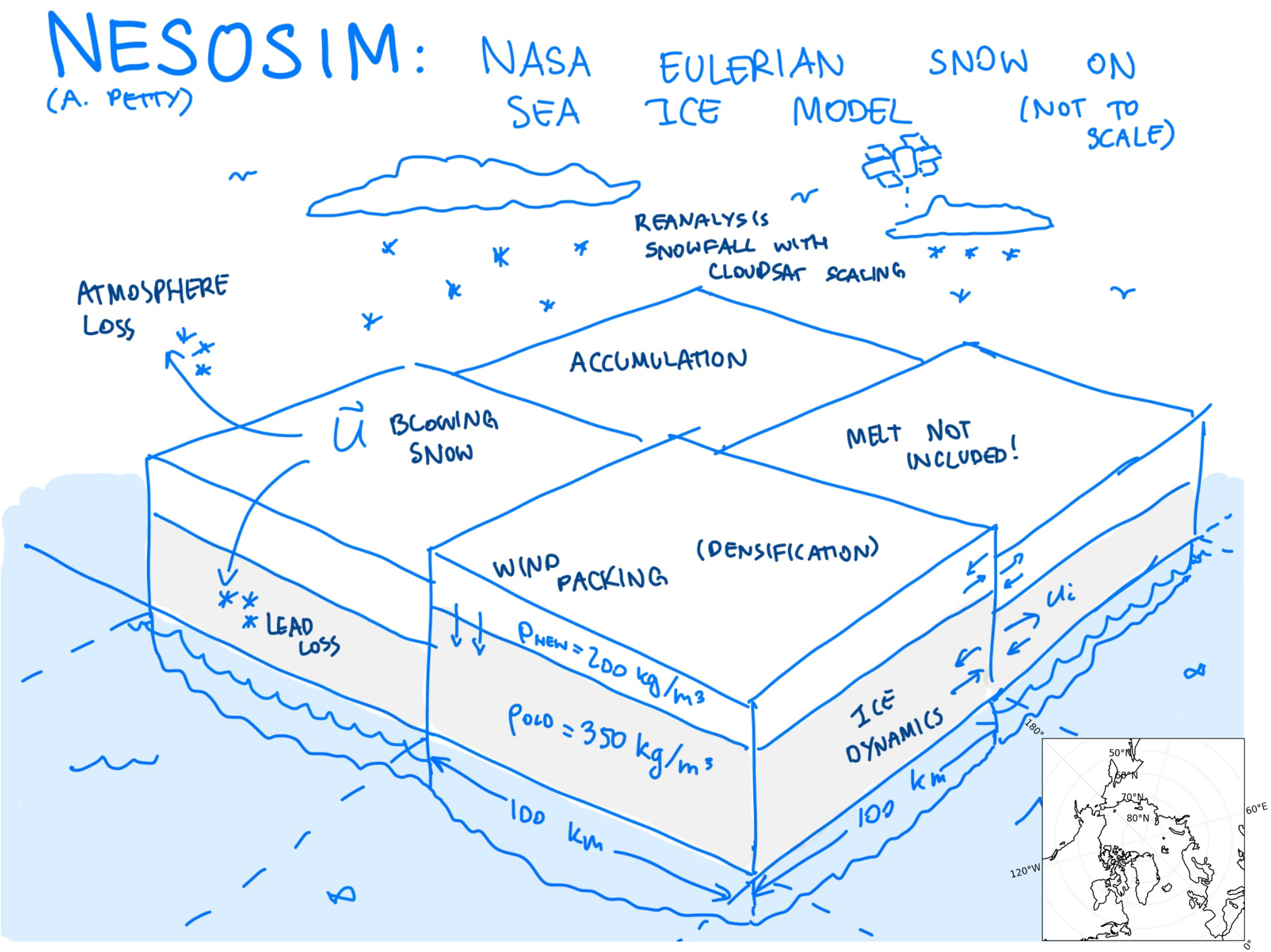
Background: Snow on Arctic sea ice poses many challenges

- Direct, in situ measurements tend to be infrequent and/or sparse
- Remote observations can be highly uncertain
- Warren (1999) climatology still commonly in use, but with a modification over first-year ice
- Models can help address the observation gap, but how can these models be calibrated to existing observations?



- NESOSIM Version 1.1, https://zenodo.org/record/4448356
- Simple 2-layer model, 100x100 km resolution
- Designed for SIT retrievals from ICESat-2 lidar observations (Petty et al., 2020)
- ECMWF ERA5 reanalysis snowfall input constrained to CloudSat monthly climatology (Cabaj et al., 2020)
- Runs from Sept 1st to April 30th
- Goal: Calibrate wind packing and blowing snow parameters

Metropolis Markov Chain Monte Carlo (MCMC) algorithm

- **Goal: find parameter values *a* which maximize the (log-)likelihood function, *L***
- **Start with prior parameters and corresponding log-likelihood**
- **For each iteration :**
  - Obtain new parameters a small step from previous value
  - Calculate new log-likelihood function L_{i+1}
  - Accept new values if $L_{i+1} - L_i \geq U(0,1)$ (a log-uniform value; helps avoid local maxima)
- **The distribution of accepted parameters approximates the posterior distribution of *a***

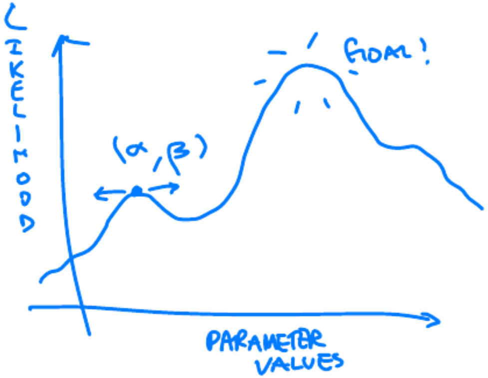
NESOSIM snow depth

Obs snow depth

$$L = -\frac{1}{2}\sum_{i=1}^{M}\frac{(h_{N,i} - h_{o,i})^2}{u_{h_o}^2}$$

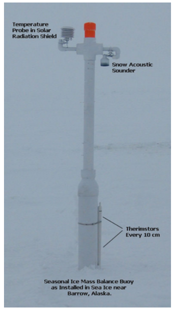
M: number of grid cells with obs

Obs uncertainty

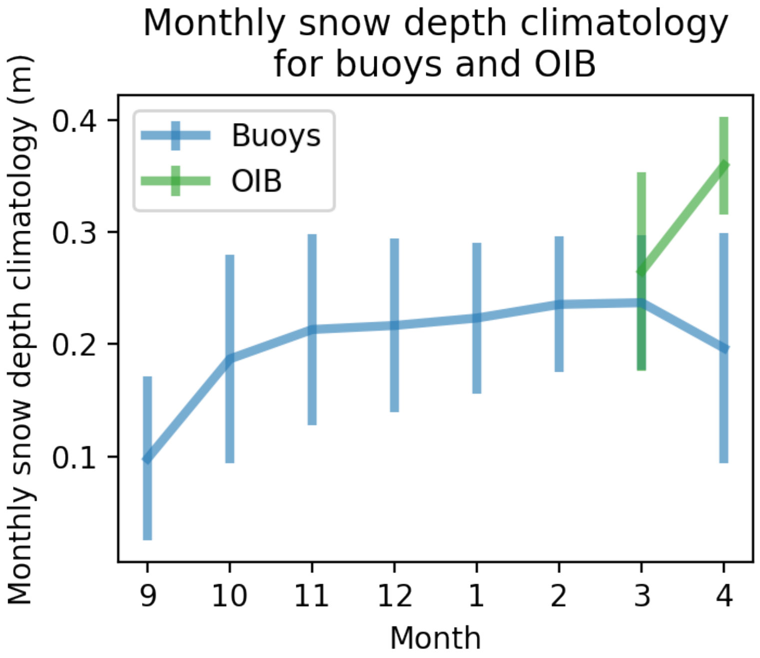


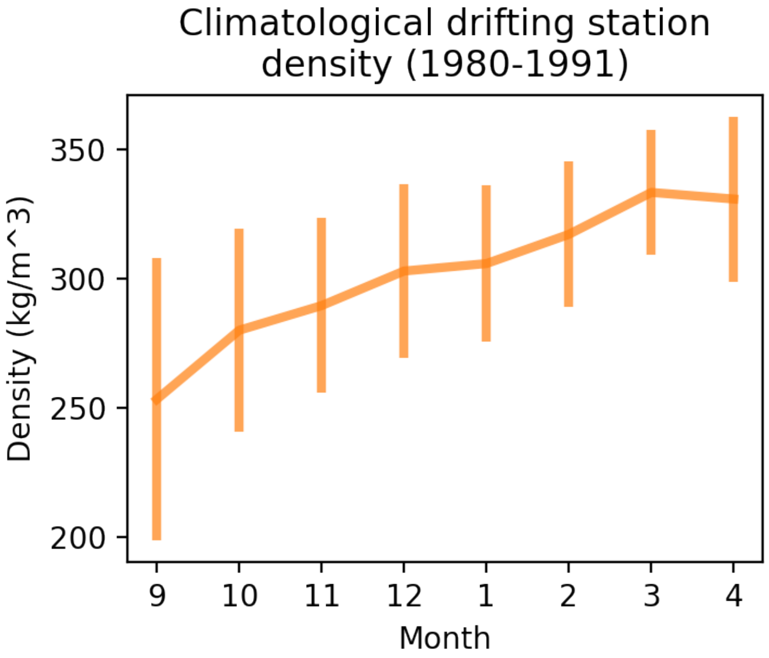
Measurements used for NESOSIM MCMC calibration

Data source	Data used	Years used	Notes	References
NASA Operation IceBridge (OIB)	Snow depth on sea ice from airborne snow radar	2010-2015	Median of SRLD, GSFC, and JPL products used Only available in March and April	Koenig et al., 2016; Kurtz et al., 2013; Kwok et al., 2017
Soviet drifting stations	Snow density on sea ice from in situ obs	1980-1991	Historical measurements; monthly climatology used	Radionov et al., 1997
CRREL-Dartmouth snow buoys	Snow depth on sea ice from acoustic sounders	2010-2013	Using monthly climatology of daily-averaged measurements	Perovich et al, 2021



Measurements used for NESOSIM MCMC calibration: plots

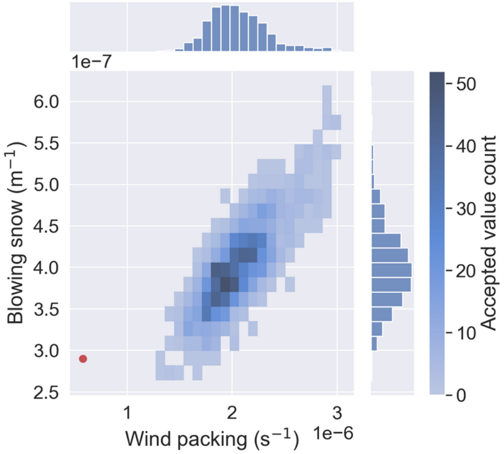


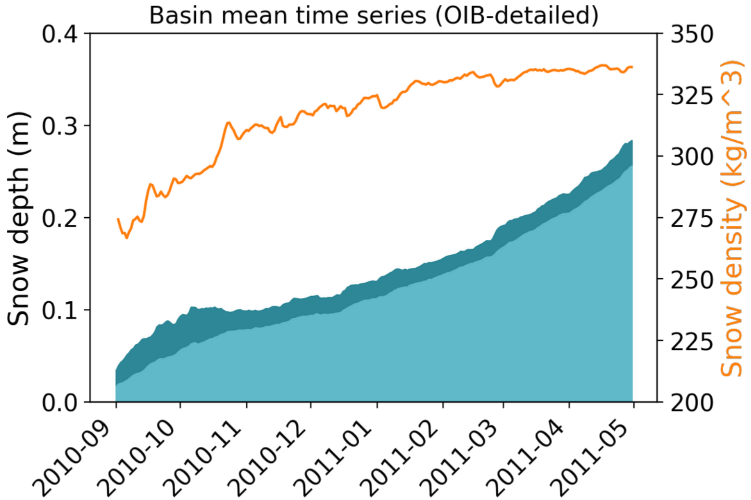


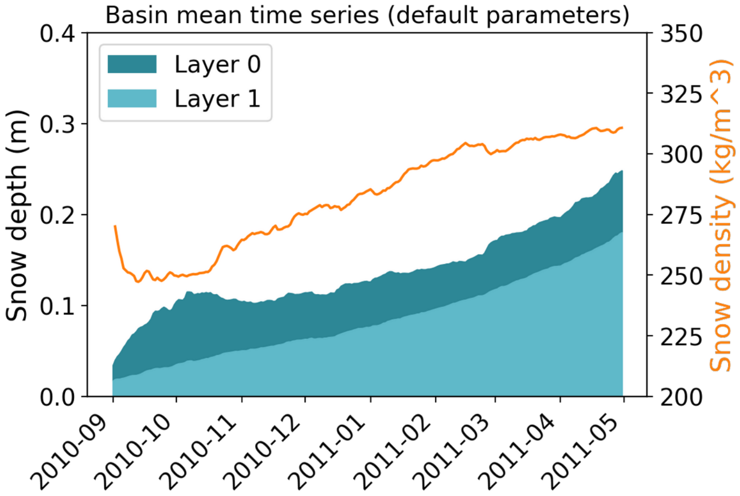
MCMC optimization results: similar depth, higher density

OIB gridded depth | Drifting station density climatology | Snow buoy depth climatology

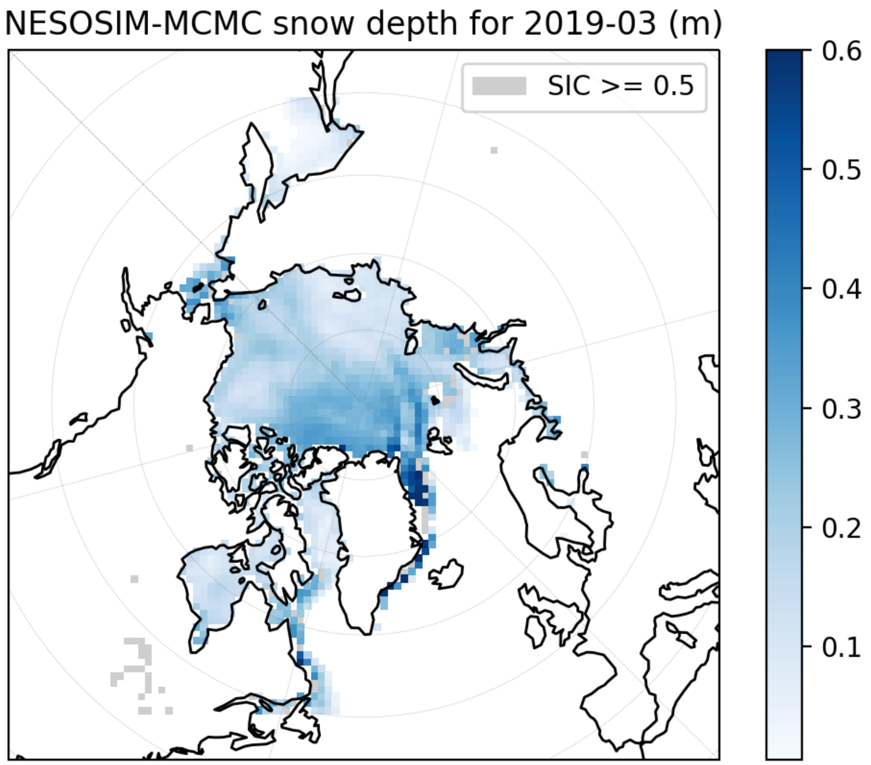
$$L_{grid} = -\frac{1}{2}\sum_{i=1}^{M}\frac{(h_{N,i}-h_{o,i})^2}{u_{h_o}^2} - \frac{1}{2}\sum_{j=1}^{8}\frac{(\langle\rho_{N,j}\rangle-\langle\rho_{d,j}\rangle)^2}{\langle u_{\rho_d,j}\rangle^2} - \frac{1}{2}\sum_{k=1}^{8}\frac{(\langle h_{N,k}\rangle-\langle h_{b,k}\rangle)^2}{\langle u_{h_b,k}\rangle^2}$$

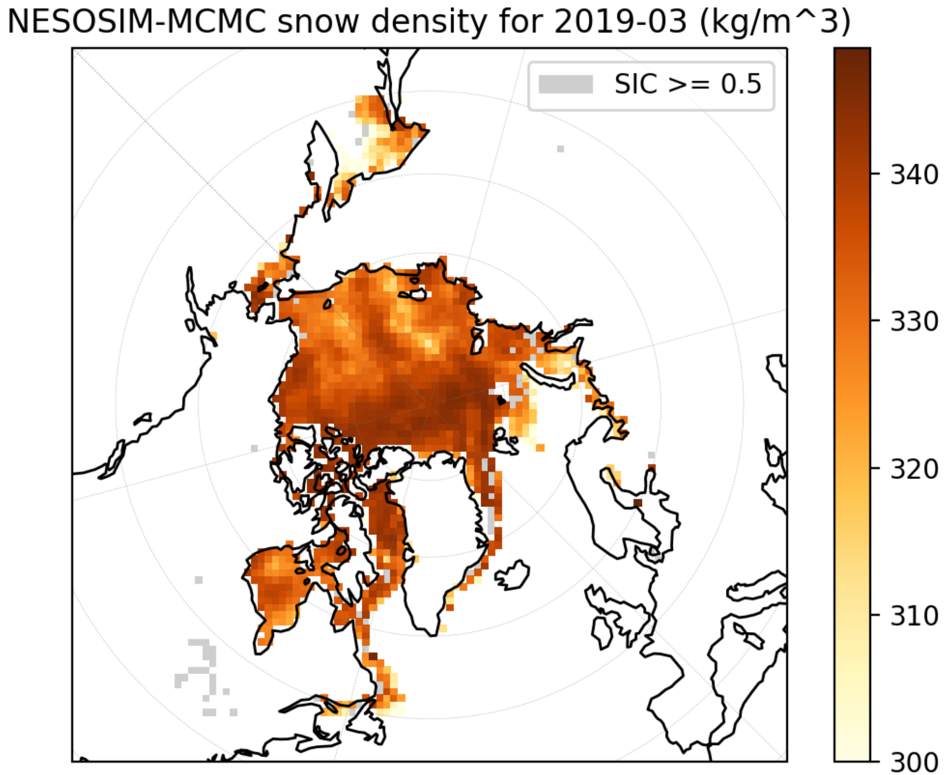




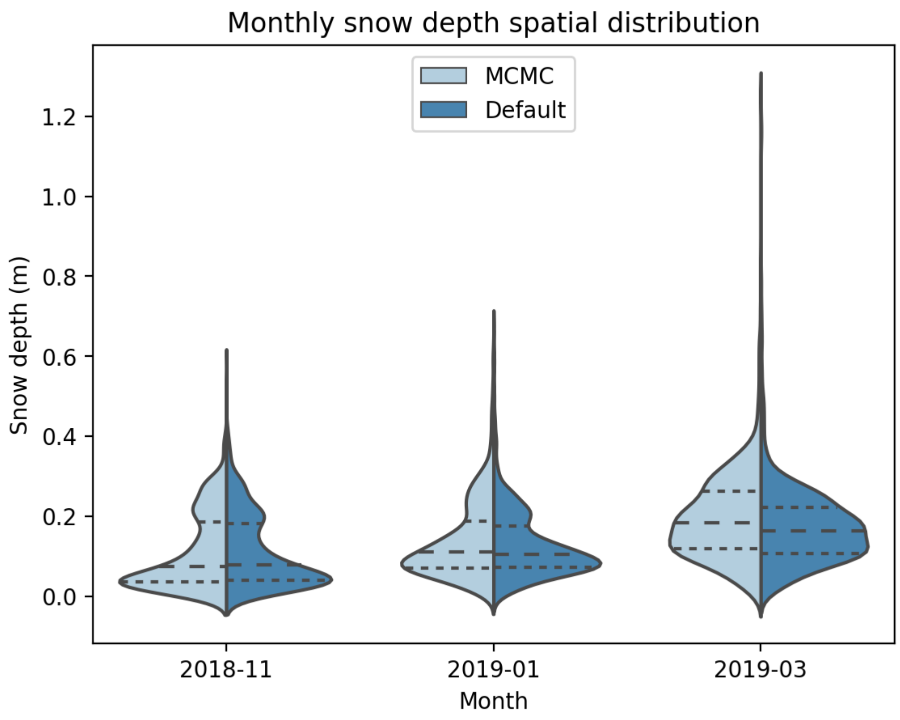


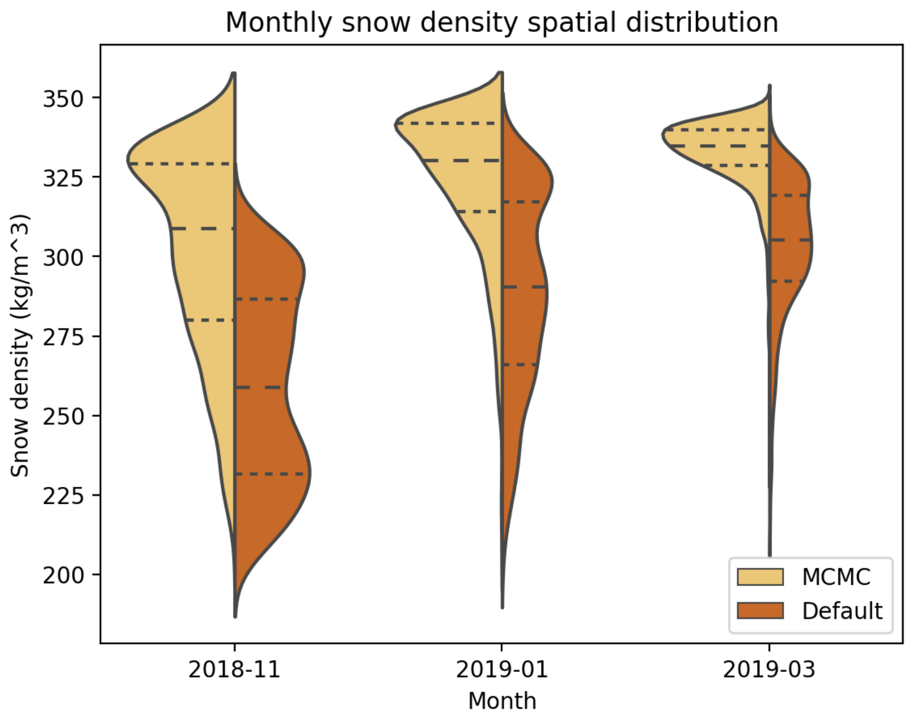
Snow depth and density maps for MCMC-optimized configuration



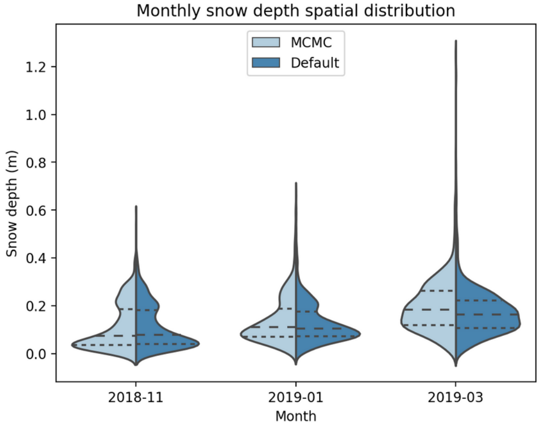


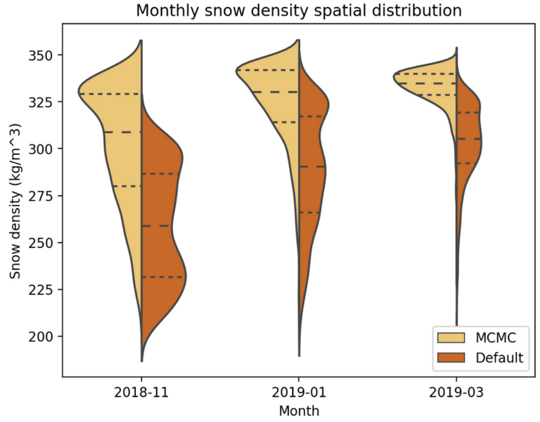
Some differences in snow depth, large differences in density relative to model default



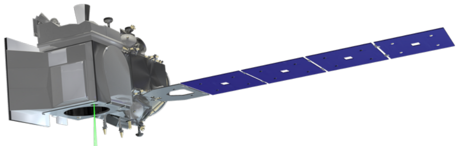


Despite differences in snow loading, resulting ice thickness distributions broadly agree

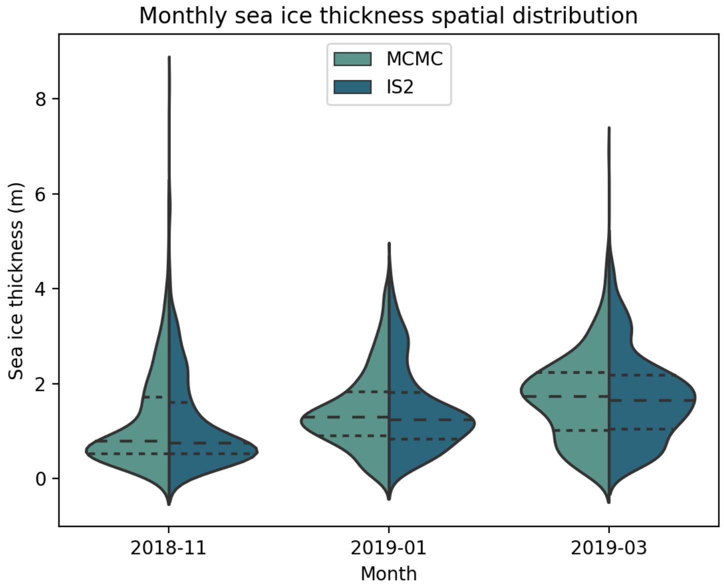




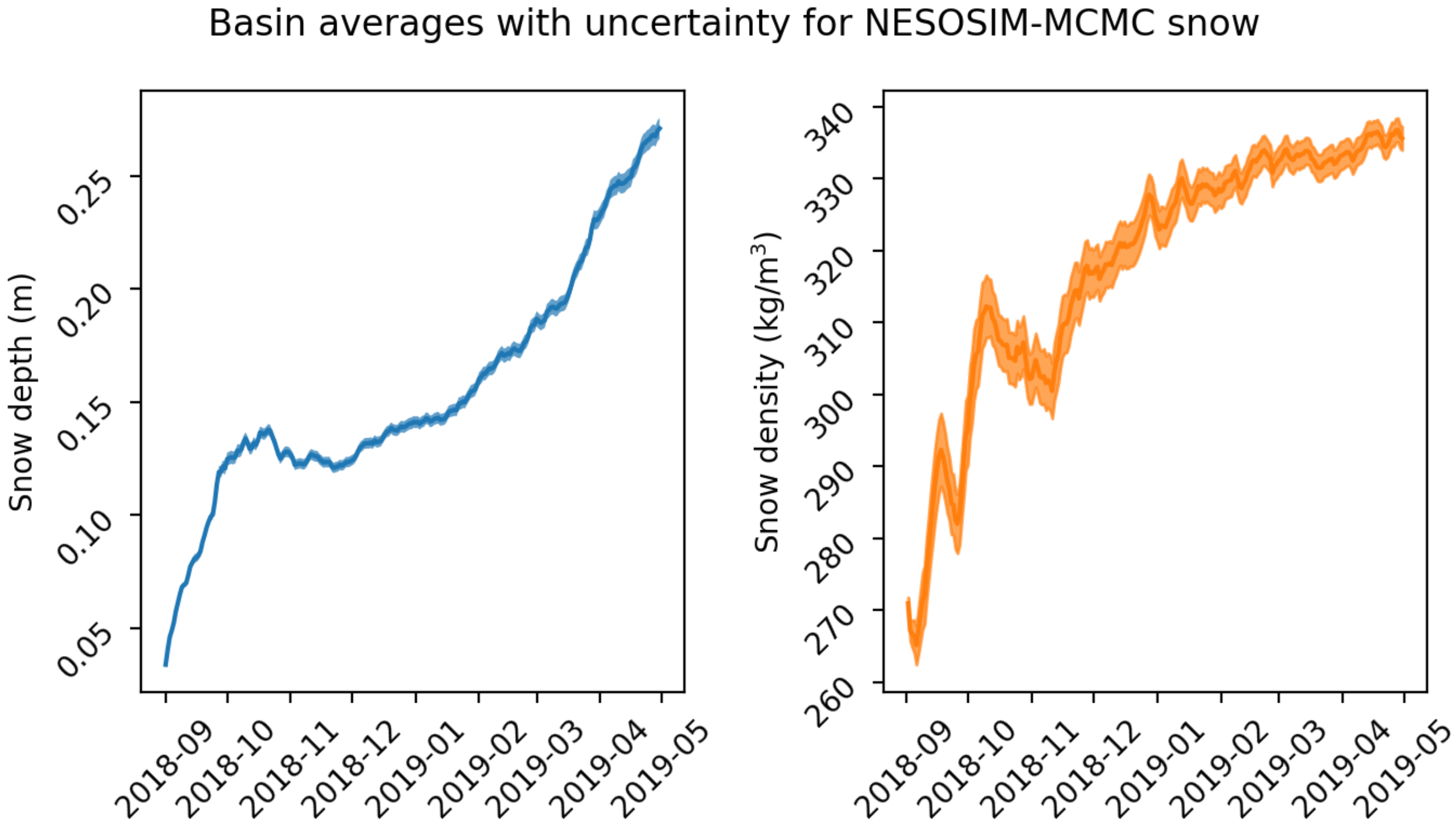
NASA ICESat-2



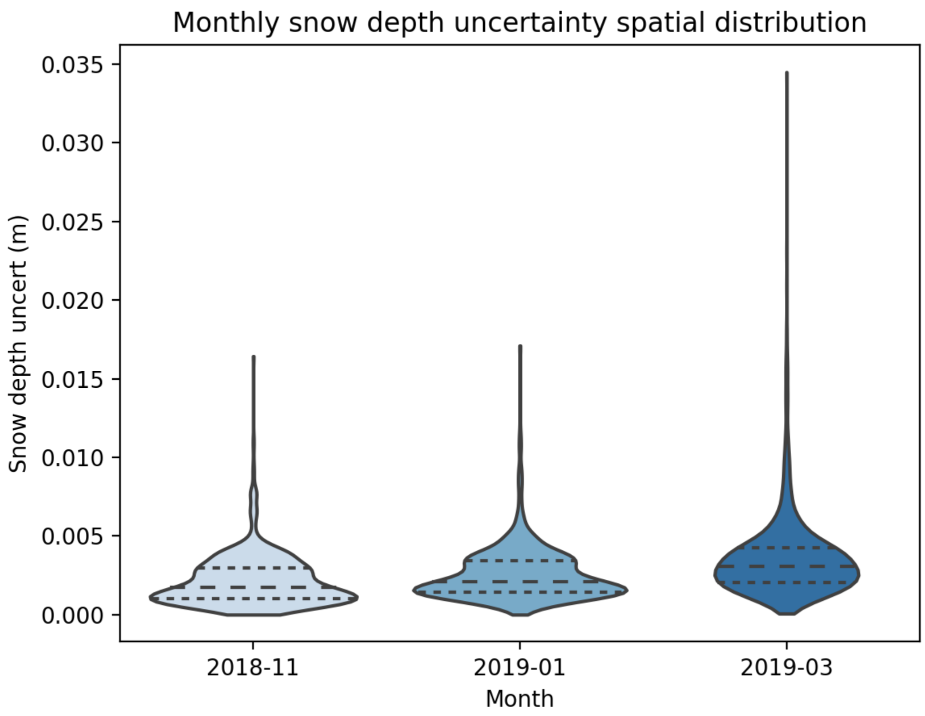
$$h_i = \frac{h_f \rho_w}{\rho_w - \rho_i} + \frac{h_s(\rho_s - \rho_w)}{\rho_w - \rho_i}$$

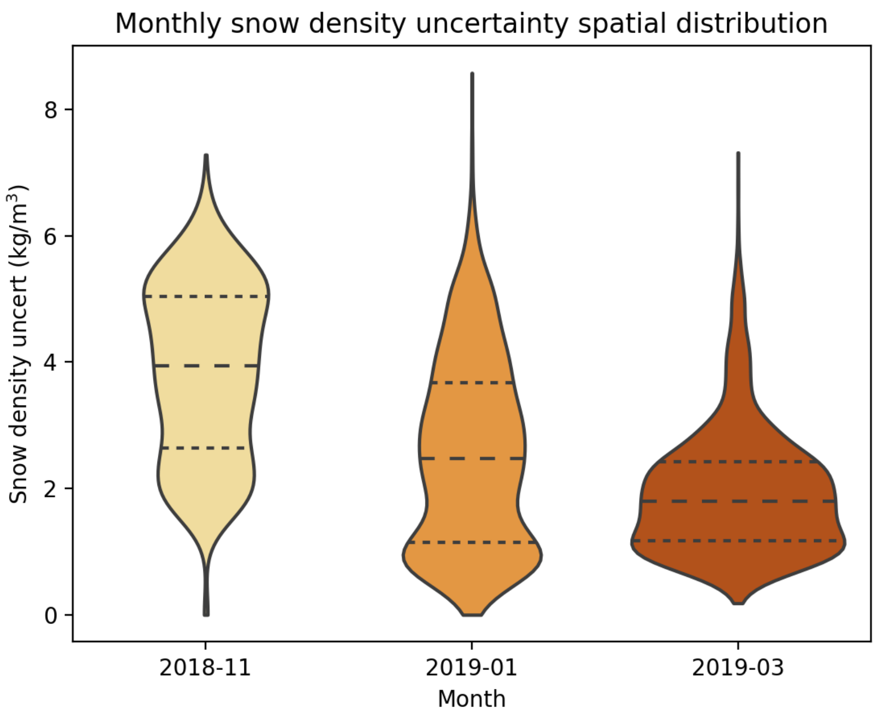


Uncertainties in snow depth and density due to parameter uncertainties are relatively small



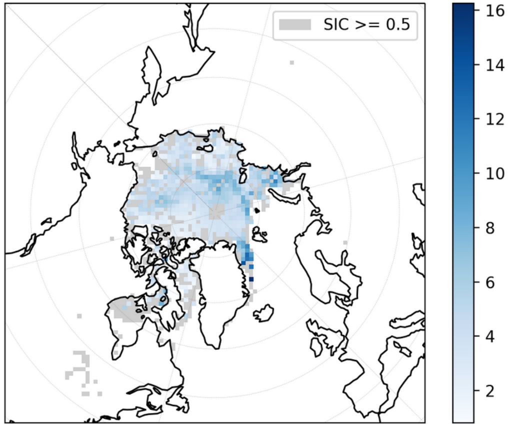
Over the course of a season: increasing snow depth uncertainty, decreasing snow density uncertainty



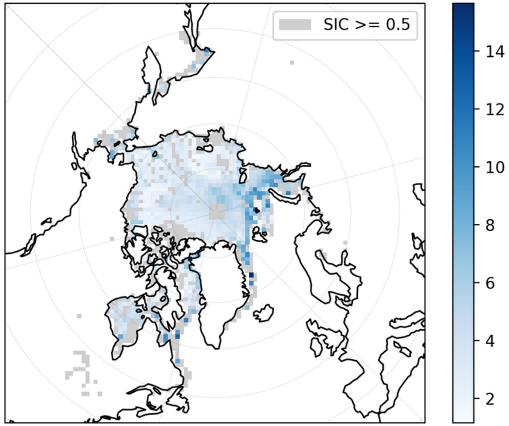


The MCMC snow uncertainty contribution to ice thickness uncertainty is up to 16% of total ice thickness uncertainty

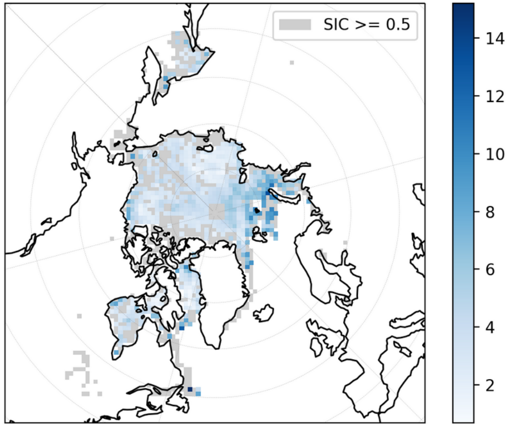
Snow uncertainty contribution to total uncertainty (%) for 2018-11



Snow uncertainty contribution to total uncertainty (%) for 2019-01



Snow uncertainty contribution to total uncertainty (%) for 2019-03



(Basin average: 3-4%)

Summary

- NESOSIM free parameters were calibrated to airborne and in situ measurements using a Markov Chain Monte Carlo process
- Produces estimates of snow depth and density uncertainties due to parameter uncertainty
- Small snow uncertainties can contribute to a considerable fraction of ice thickness uncertainty
- More widespread snow-on-sea-ice measurements needed, especially for density

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