Parameter calibration and uncertainty analysis for snow depths from the NASA Eulerian Snow On Sea Ice Model and derived sea ice thickness from ICESat-2

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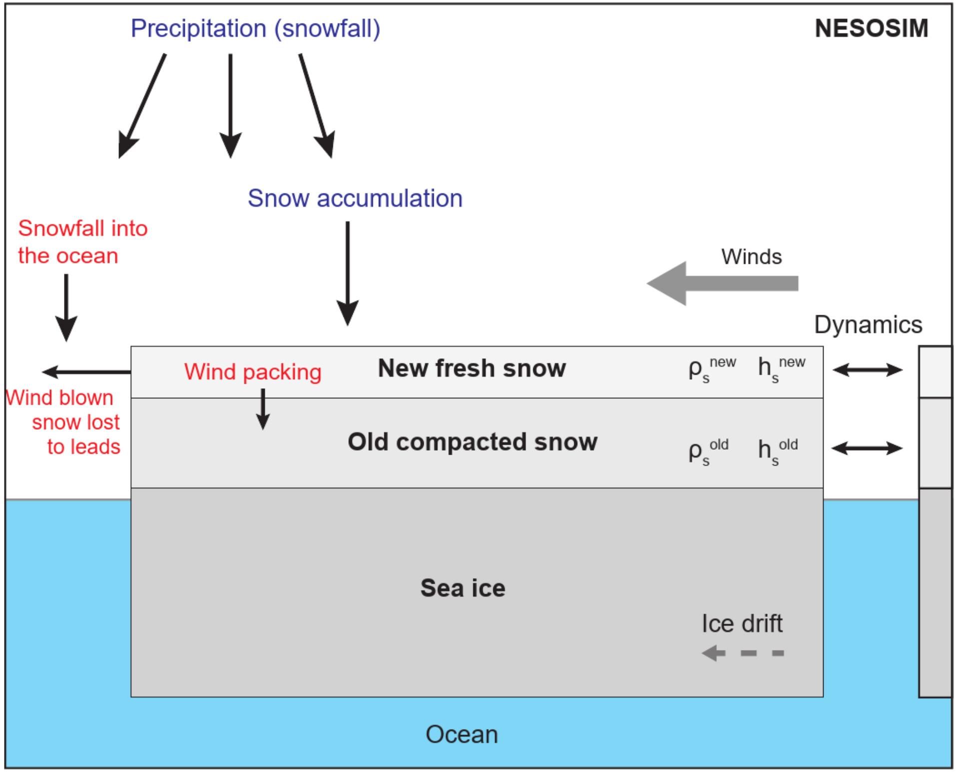
Background

- Snow on sea ice impacts the global climate in many, sometimes contrasting ways
- Also introduces uncertainty into sea ice thickness retrievals
- Direct, in-situ observations of snow on sea ice are infrequent and sparse
- Snow-on-sea-ice models can provide snow depth and density estimates for sea ice thickness retrieval; model uncertainty can contribute to sea ice thickness uncertainty
- How can we observationally constrain model free parameters? Can we estimate uncertainties in these parameters?

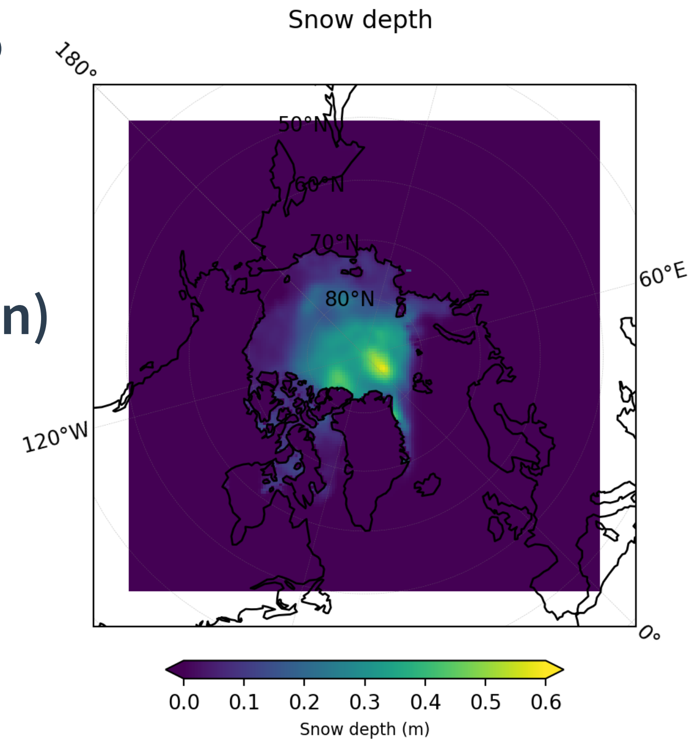
NESOSIM: Snow on sea ice modelling

- NASA Eulerian Snow On Sea Ice Model (Petty et al, 2018)
  v 1.1, https://github.com/akpetty/NESOSIM
- Simple 2-layer model, up to 50x50 km resolution, designed for use with sea ice thickness retrievals from lidar observations from ICESat-2
- Processes:
  - Snow accumulation from reanalysis snowfall products
  - Redistribution of snow due to sea ice drift (from observations)
  - Wind packing (transfers snow between layers, reanalysis wind)
  - Blowing snow lost to leads and atmosphere (sea ice concentration from observations)



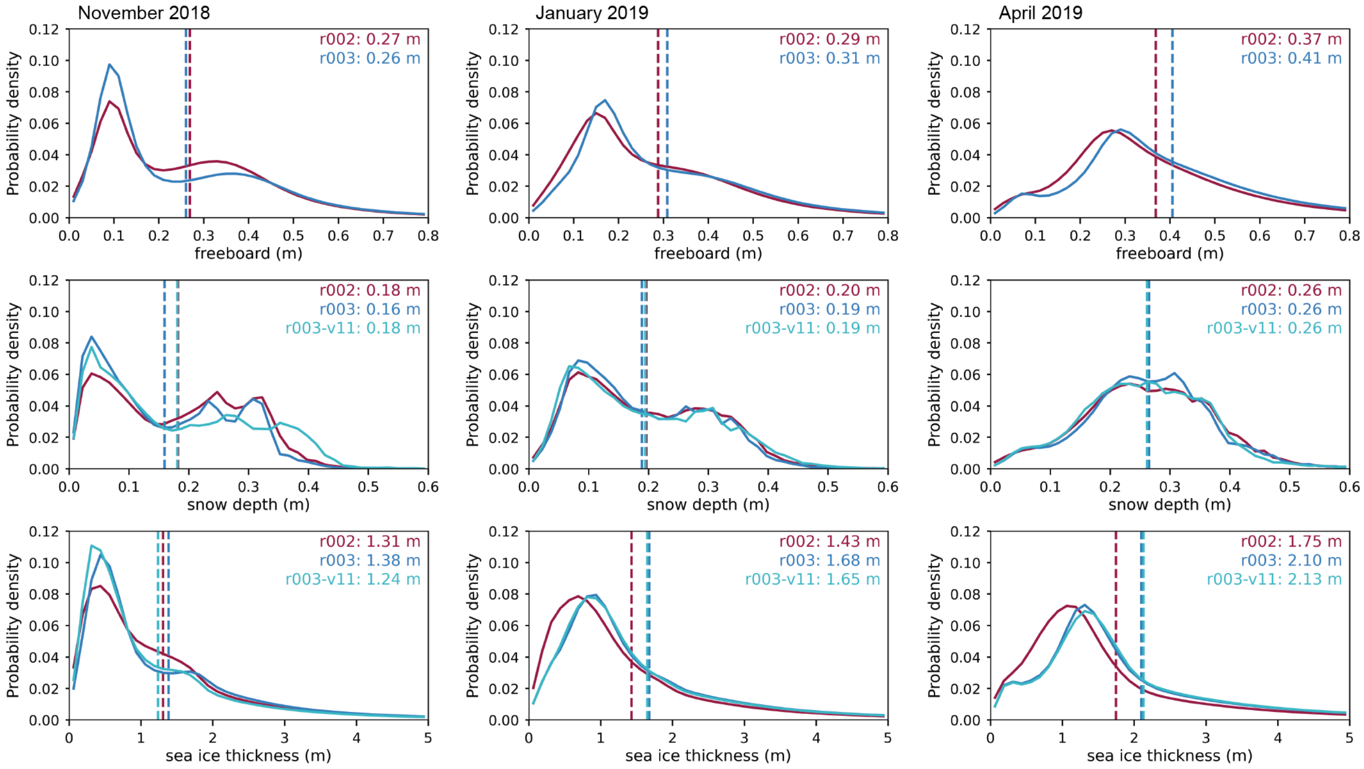
NESOSIM was recently updated to version 1.1

- Snowfall input (from reanalysis products) scaled to CloudSat observations, as per Cabaj et al. 2020
- Additional loss term introduced: atmospheric loss (blowing snow independent of sea ice concentration)
- Extended model domain, covers peripheral seas
- Other bug fixes
- More information: https://zenodo.org/record/4448356



NESOSIM v1.1 impact on sea ice thickness from ICESat-2

- Freeboard, NESOSIM-derived snow depth, and corresponding sea ice thickness from ICESat-2
- r002/r003 refers to ICESat-2 freeboard product releases, r003-v11 is derived using NESOSIM v1.1 (r003 and r002 use NESOSIM 1.0)



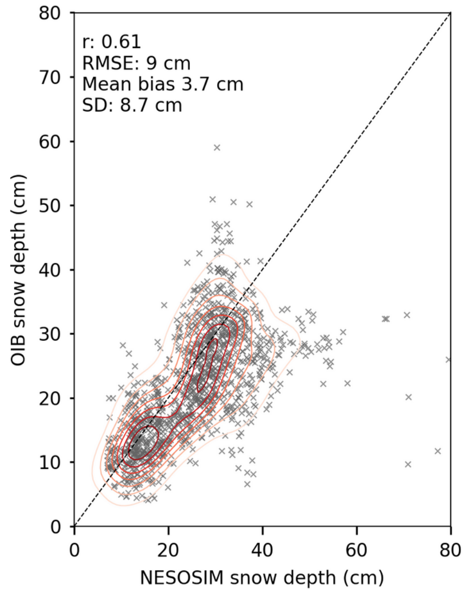
Plot: A. Petty (2020)

Current work: free parameter calibration

- **Wind packing factor**
  - How much snow is transferred between layers
  - Impacts snow depth and density; $\rho_{fresh} = 200\ kg/m^3$, $\rho_{old} = 350\ kg/m^3$
- **Blowing snow factor (atmospheric + lead loss)**
  - How much snow is lost to wind, depends linearly on wind speed (above a threshold of 5 m/s)
  - 2 terms: lead loss (depends on sea ice concentration) and atmospheric loss (independent of SIC)

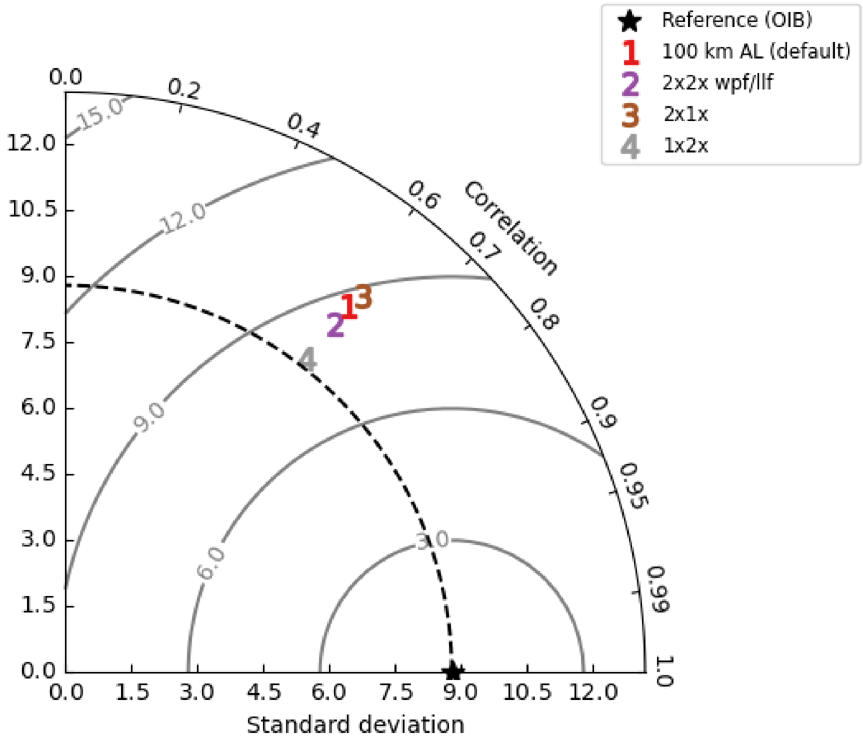
Calibration with respect to Operation IceBridge measurements

- Airborne snow depth measurements, available from 2009-2019, generally in March and April
- Previously used to validate NESOSIM v 1.0
- Currently using the GSFC (Kurtz et al., 2013) product for calibration, 2010-2015, as well as the median of GSFC, JPL (Kwok and Maksym, 2014), and SRLD (Koenig et al., 2016) products



What is the impact of varying wind packing and blowing snow factors?

- **Parameter doubling test:**
  - Best results from 2x blowing snow, 1x wind packing
  - Doubling wind packing while keeping 1x blowing snow worsens agreement
- **How can we determine optimal parameter values? → Markov Chain Monte Carlo approaches**

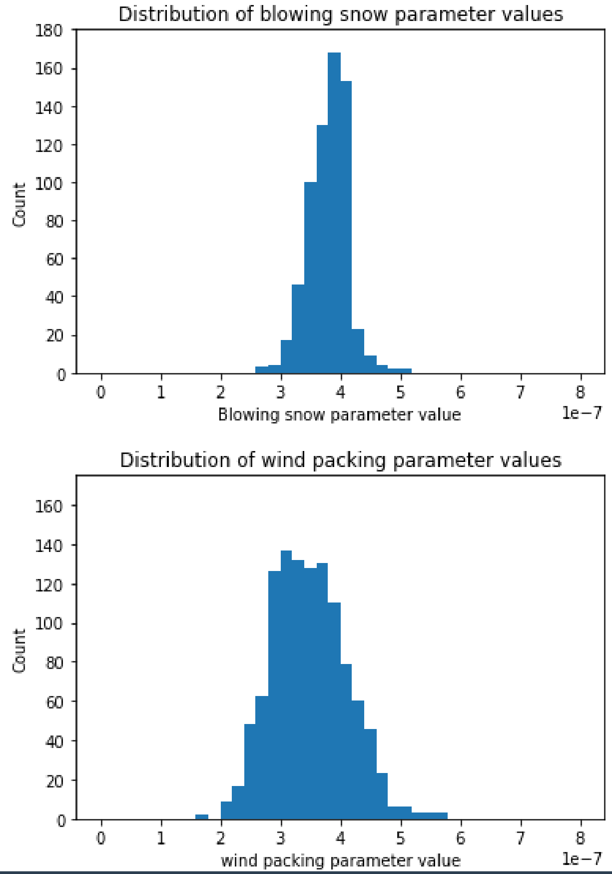


Markov Chain Monte Carlo (MCMC) algorithm

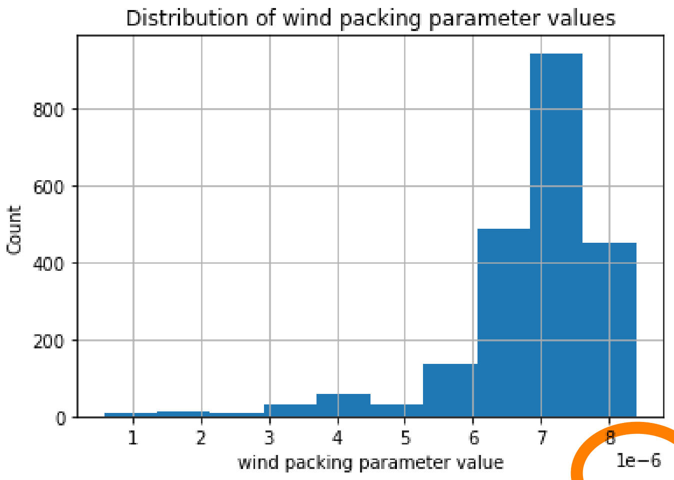
- **Goal: maximize likelihood (a measure of the difference between NESOSIM snow depth and OIB observations)**
- **Start with a prior parameter value and its corresponding likelihood**
- **For each iteration**
  - Randomly generate a new set of parameters a small step away from the previous parameter value (step size based on prior parameter uncertainty)
  - Calculate the likelihood function (difference between modelled and observed values, weighted by uncertainty)
  - Examine the ratio of likelihood functions between the new and previous parameter values; accept if the ratio is greater than a value chosen from a uniform distribution
- **This favours higher likelihoods but allows for some variation so that we don't get stuck in a local maximum**

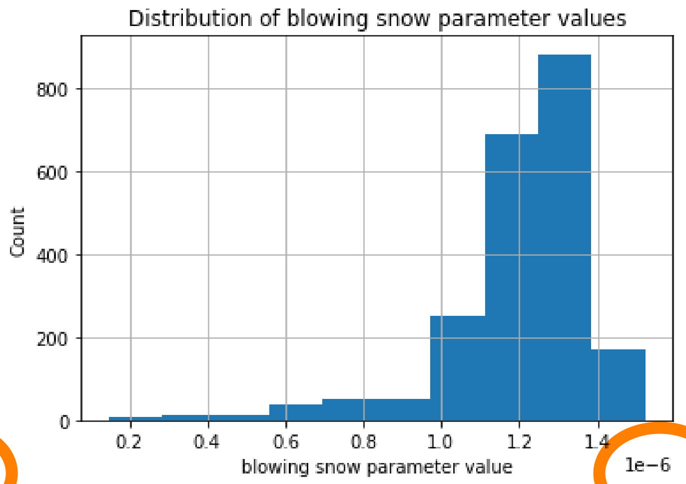
Single parameter MCMC calibration for blowing snow and wind packing

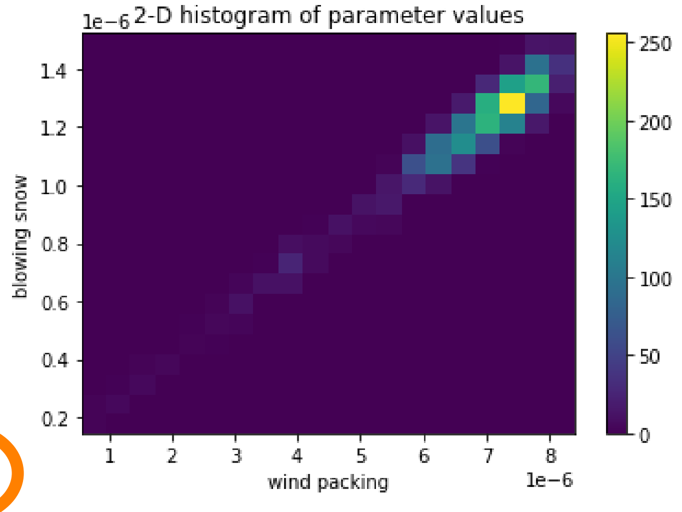
- Single-parameter optimization with respect to OIB observations, GSFC algorithm (2010-2015), 1000 iterations
- Parameters calibrated: blowing snow (both atmospheric and lead loss simultaneously); wind packing
- Prior parameter values of 2.9e-7 for blowing snow and 5.8e-7 for wind packing, optimal values as suggested by MCMC: 3.96e-7, 3.32e-7 (respectively)
- Larger spread in wind packing parameter distribution compared to blowing snow



2-parameter MCMC optimization for blowing snow and wind packing, simultaneously

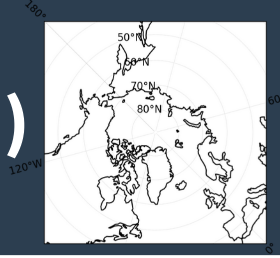




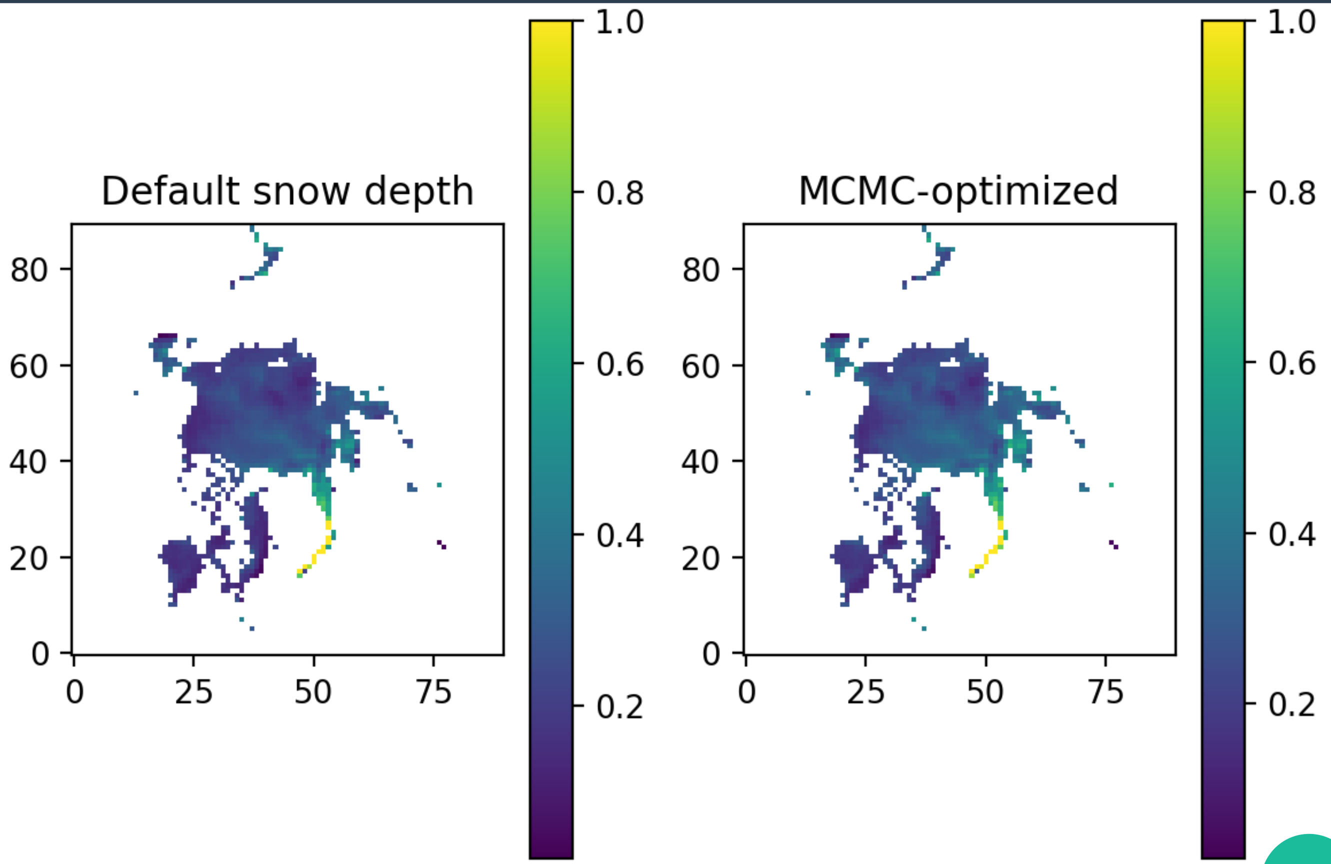


- Optimal parameter values are much larger than from the single-parameter calibration (showing results using multi-product median OIB, but similar result for GSFC product): Prior values of O(1e-7), posterior parameter values on the order of 1e-6 (calculated with 3000 iterations)
- Next step: investigate how this looks in the NESOSIM model output

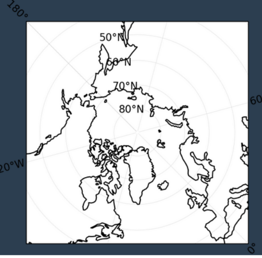
Snow depth with default and optimized parameters (m)



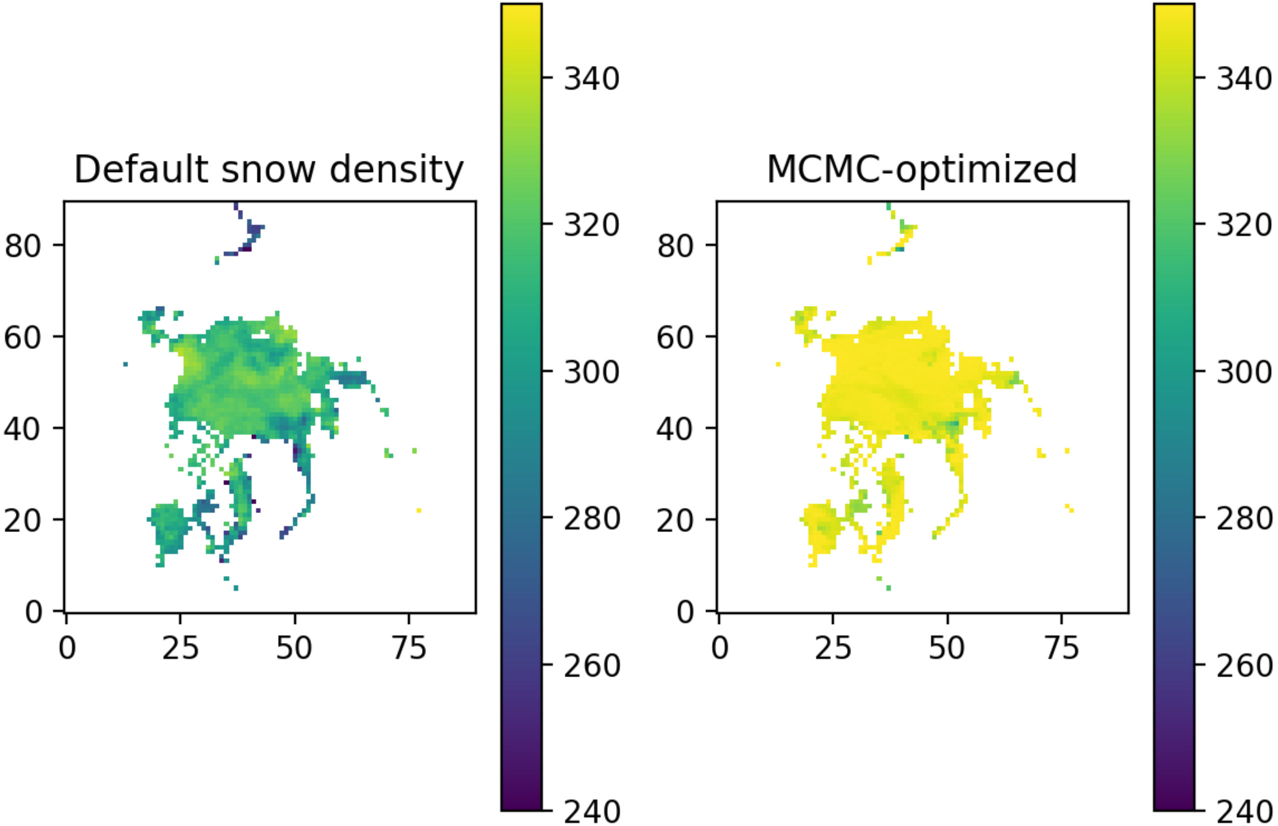
- End-of-season snow depth for 1 year shown (polar view)
- Very little difference in snow depth, despite vast difference in parameters



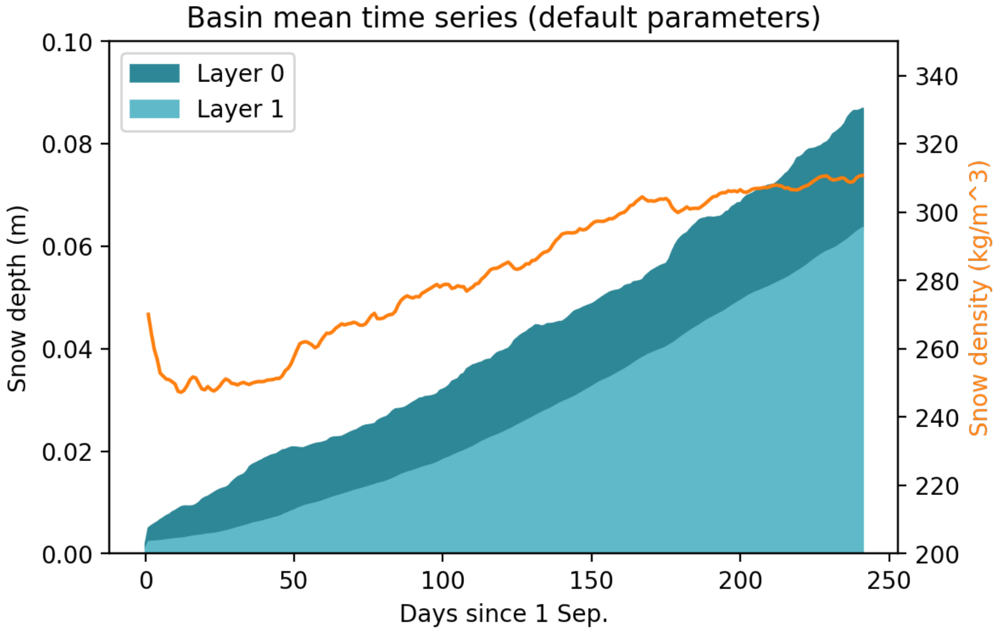
Snow density (kg/m³) is more impacted

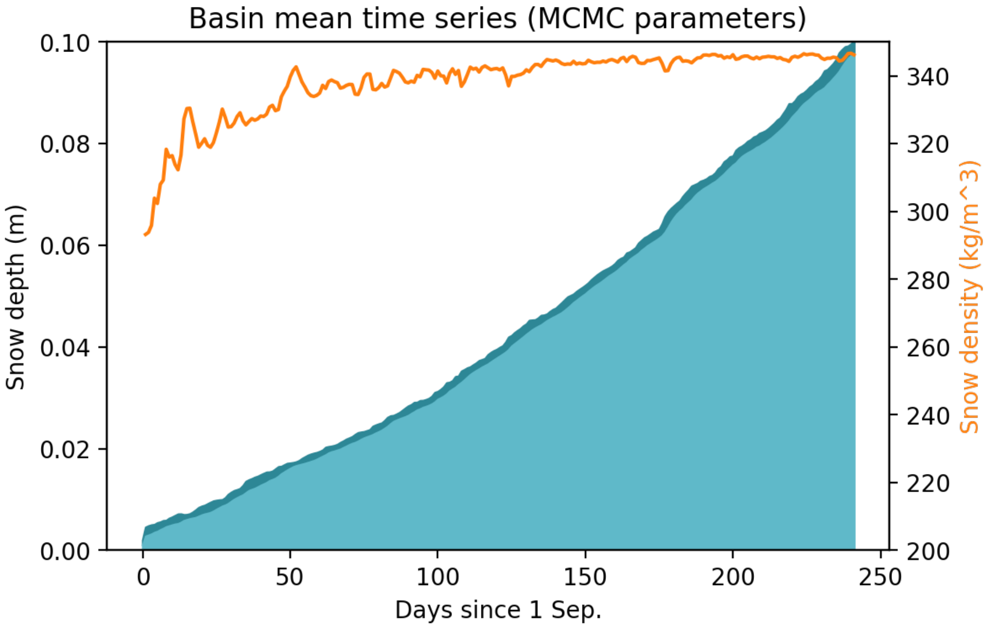


- End-of-season snow density for 1 year shown (polar view)
- MCMC-optimized snow density is close to lower layer prescribed density (350 kg/m³)
- Overall density high compared to historical Soviet drifting station obs; expect average of ~320 kg/m³ at end of season



Snow depth (layer by layer) and density time series





- Almost all of the snow is transferred to the lower layer; the blowing snow parameter is tuned very high to compensate
- The overall density is too high (as compared to drifting station climatologies): further constraints on density are needed

Next steps

- Continue with parameter optimization
- Introduce observation-based density constraints (from historical drifting station observations; Radionov et al., 1997) to better constrain wind packing
- Snow depth validation against later years of OIB
- Estimation of snow depth uncertainty derived from parameter uncertainty estimates; corresponding sea ice thickness uncertainty estimates

Summary

- NESOSIM updated to version 1.1, but the free parameters remain difficult to constrain
- Single parameter calibration using Markov Chain Monte Carlo: blowing snow (atmospheric + lead loss) is better constrained than wind packing
- 2-parameter MCMC calibration: produces similar snow depth, but much higher snow density, needs further constraints

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