Improved Bare Ice Albedo over the Greenland Ice Sheet using Physically Based Radiative Transfer Methods

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February 23, 2023

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NSF

Overview

Motivation

- The land components of E3SM (ELM) and CESM (CTSM) prescribe a constant bare ice albedo
- The Greenland Ice Sheet has a highly variable bare ice albedo and is a significant contributor to sea level rise

My work

- SNICAR-ADv4 - radiative transfer modeling of bare ice
- Incorporation of SNICAR-ADv4 into an Earth System Model (E3SM)
  - Methods
  - Results
- Future work – Glacier Algae

Motivation:
Current Model Representation of Bare Ice Albedo

- Within Earth System models, bare ice albedo is parameterized as constant over the visible and near-IR wavelengths

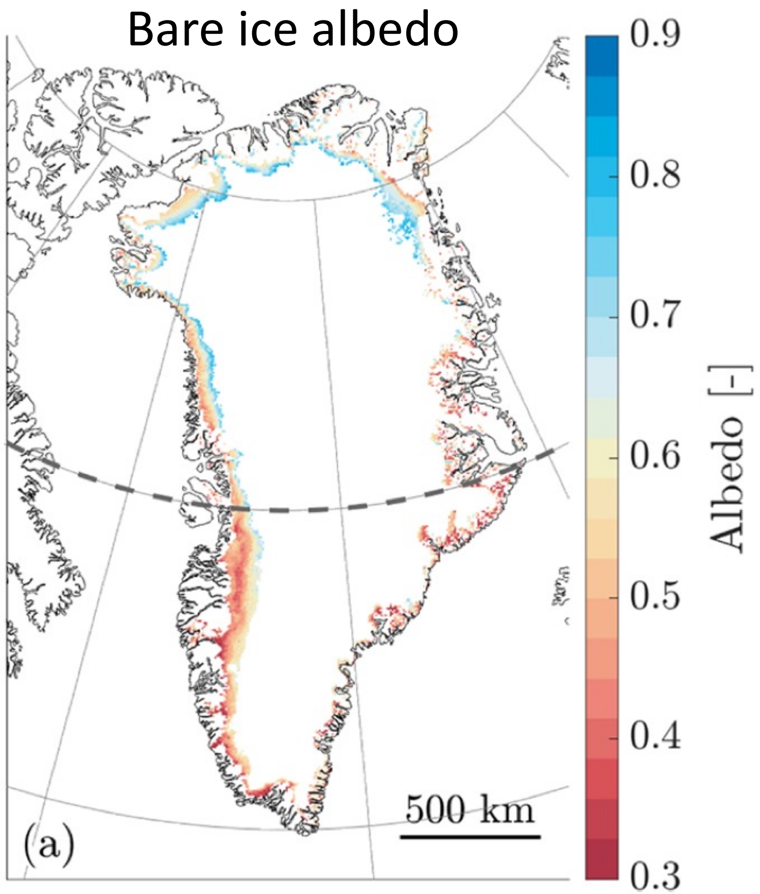
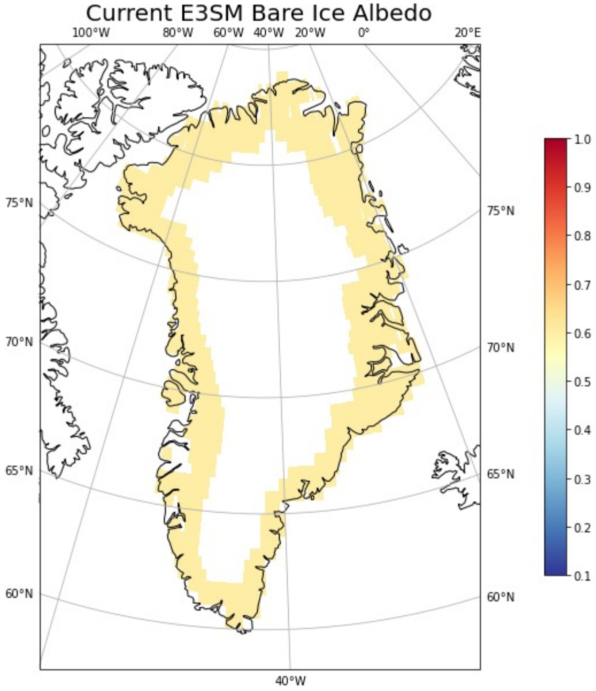


Figure: Antwerpen, et al. (2022)

E3SM Energy Exascale Earth System Model

- In ELM the albedo is 0.6 in the visible and 0.4 in the near-ir



NCAR | Community Earth System Model

- In CTSM the albedo is an adjustable constant ranging from 0.5-0.8 in the visible and 0.3-0.55 in the near-ir

Motivation:
A warming climate and increasing sea levels

- The Greenland Ice Sheet is the largest cryospheric contributor to sea level rise
- The majority of mass loss from the GrIS in the last decade has been attributed to surface melt

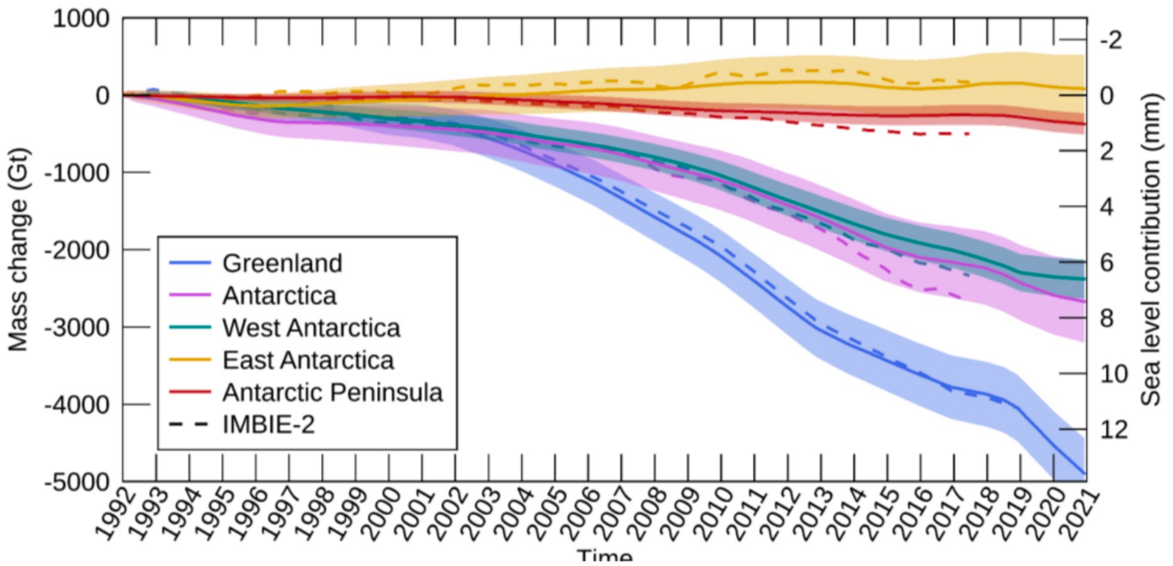


Figure: Otosaka, In Review

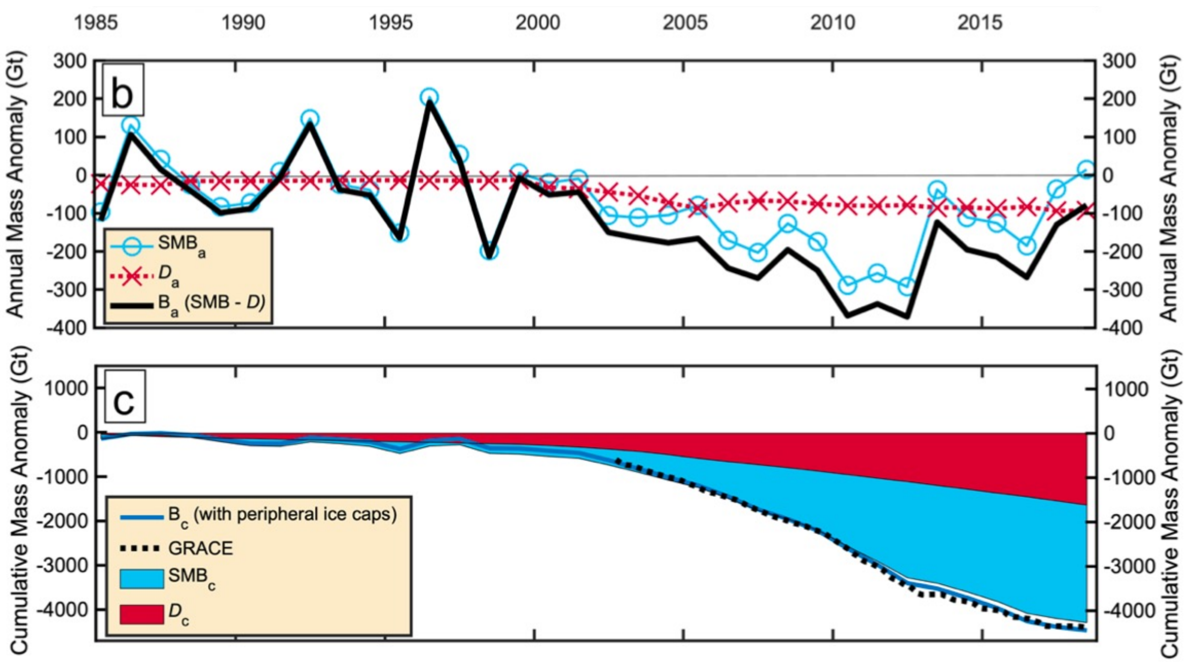


Figure: King et al. (2020)

Motivation:
Greenland Ice Sheet surface melt and albedo

- Mass loss on the surface is modulated by the albedo of the surface, which declines as the winter snowpack melts off
- Significant surface melt has been attributed to bare ice exposure, which has been increasing spatially and temporally

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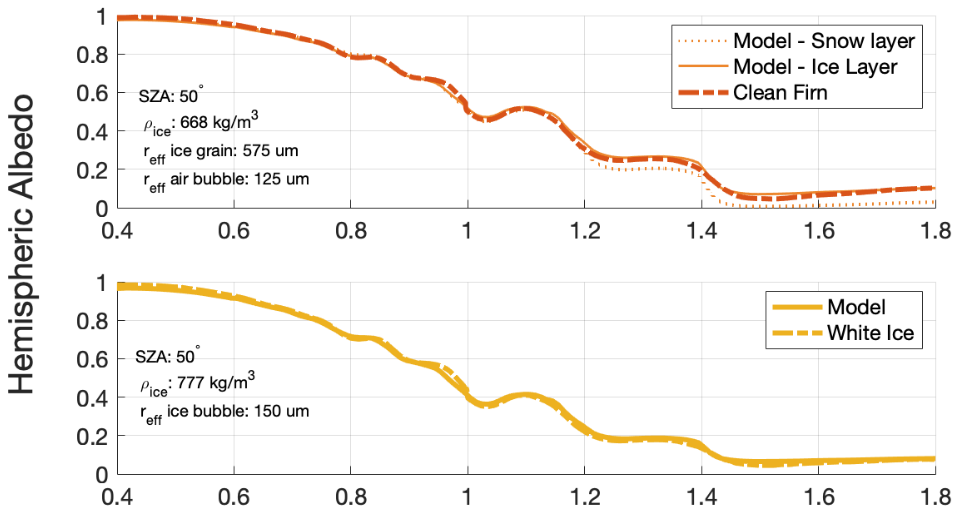
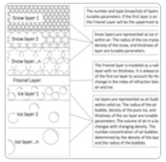
SNICAR-ADv4

The Snow, Ice, and Aerosol Radiative (SNICAR) model Adding-Doubling version 4

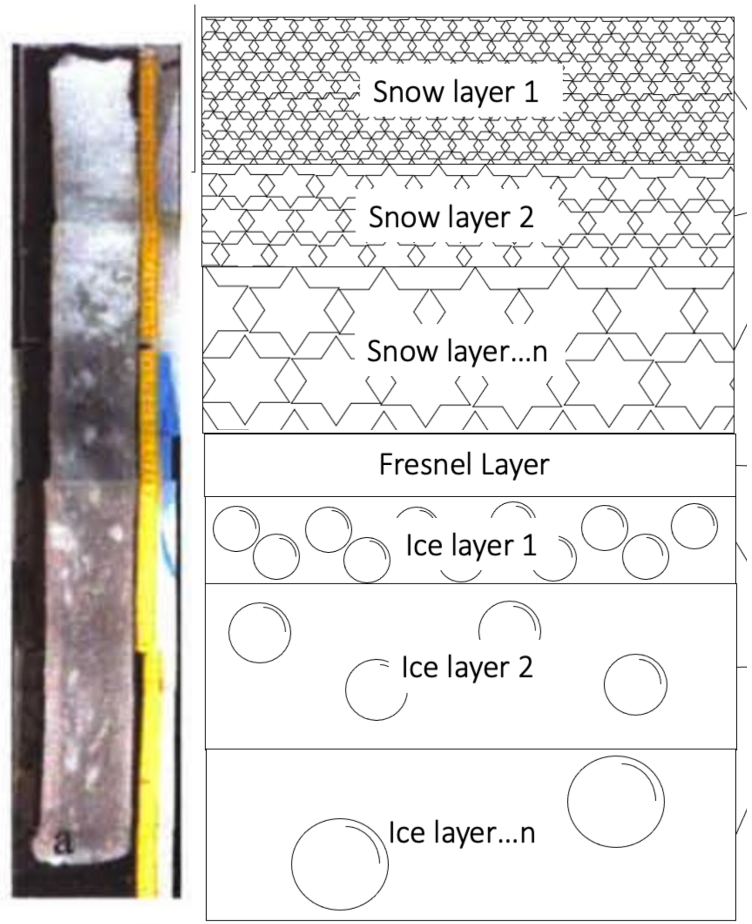
- SNICAR-ADv4
  - Calculates albedo for multi-layer cryospheric columns (needs ice physical properties as inputs)
  - Includes the influence of 9 abiotic LAC and 2 biotic LAC
  - Reproduces measurements from varying locations and conditions accurately



SNICAR-ADv4: a physically based radiative transfer model to represent the spectral albedo of glacier ice



Chloe A. Whicker[1], Mark G. Flanner[1], Cheng Dang[2], Charles S. Zender[3], Joseph M. Cook[4], and Alex S. Gardner[5]



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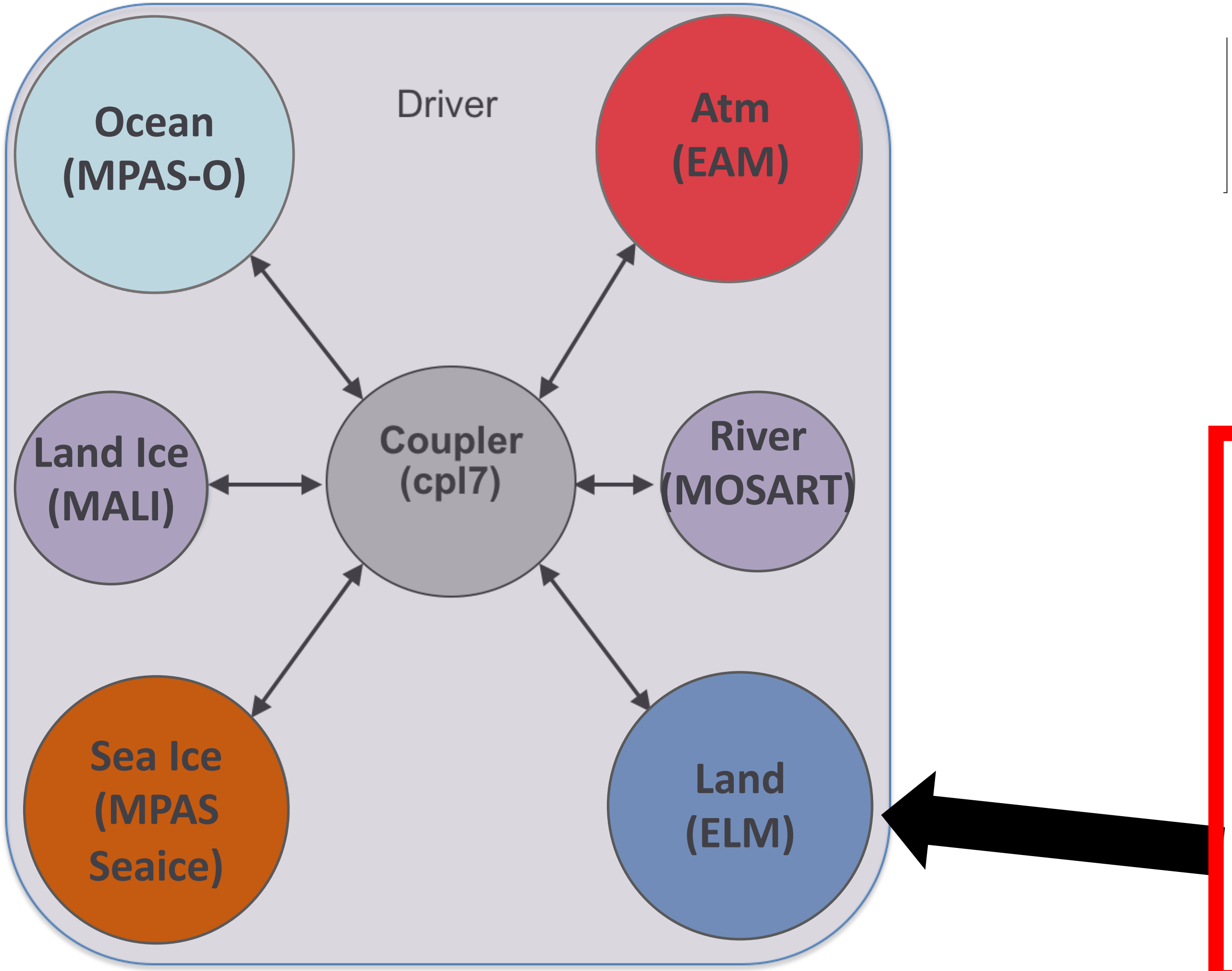
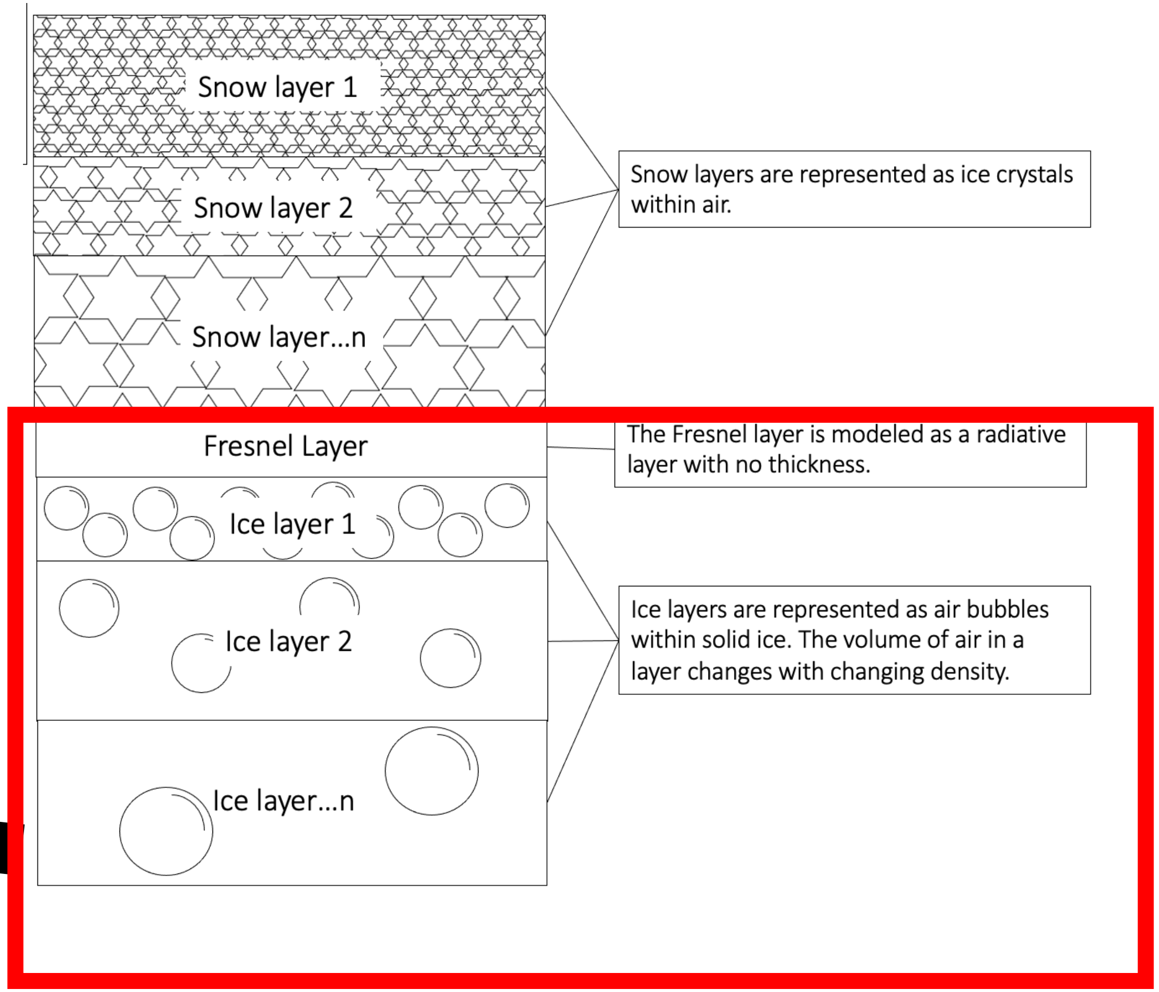
Incorporating SNICAR-ADv4’s ice radiative transfer calculations into E3SM

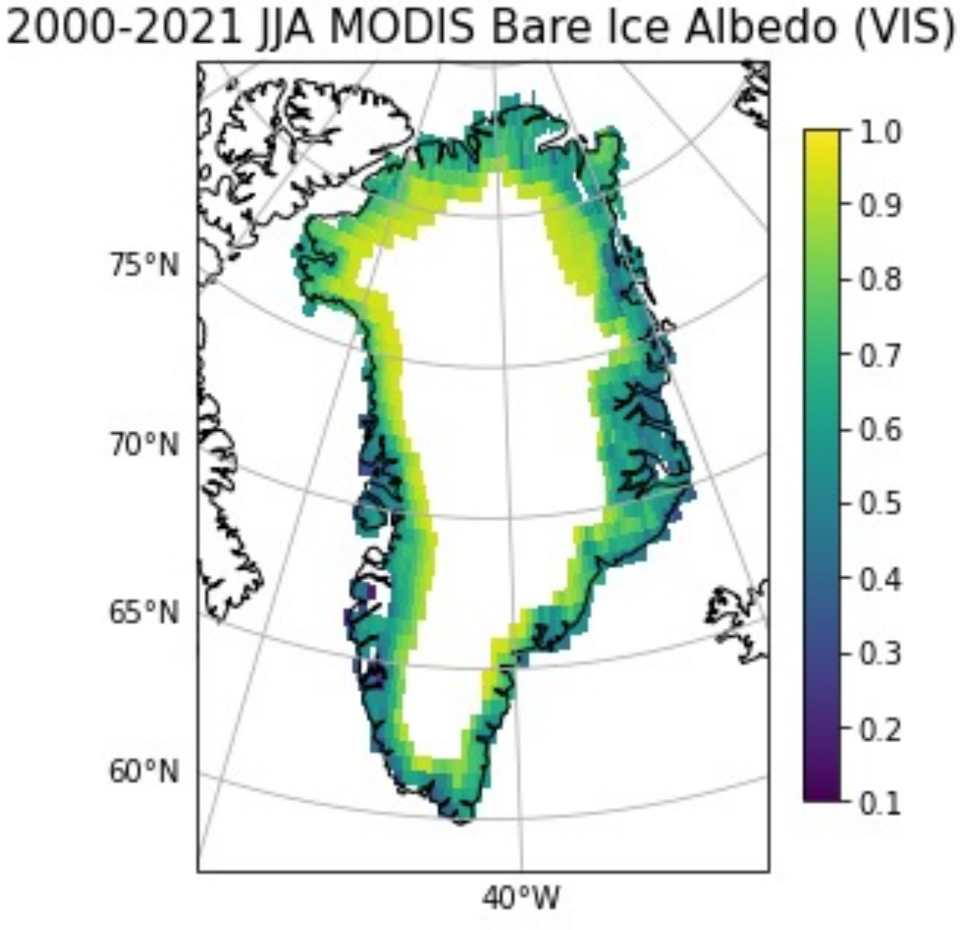
- I added the option to run E3SM with SNICAR-ADv4’s ice radiative transfer calculations





Constraining SNICAR-Adv4 ice Properties in E3SM

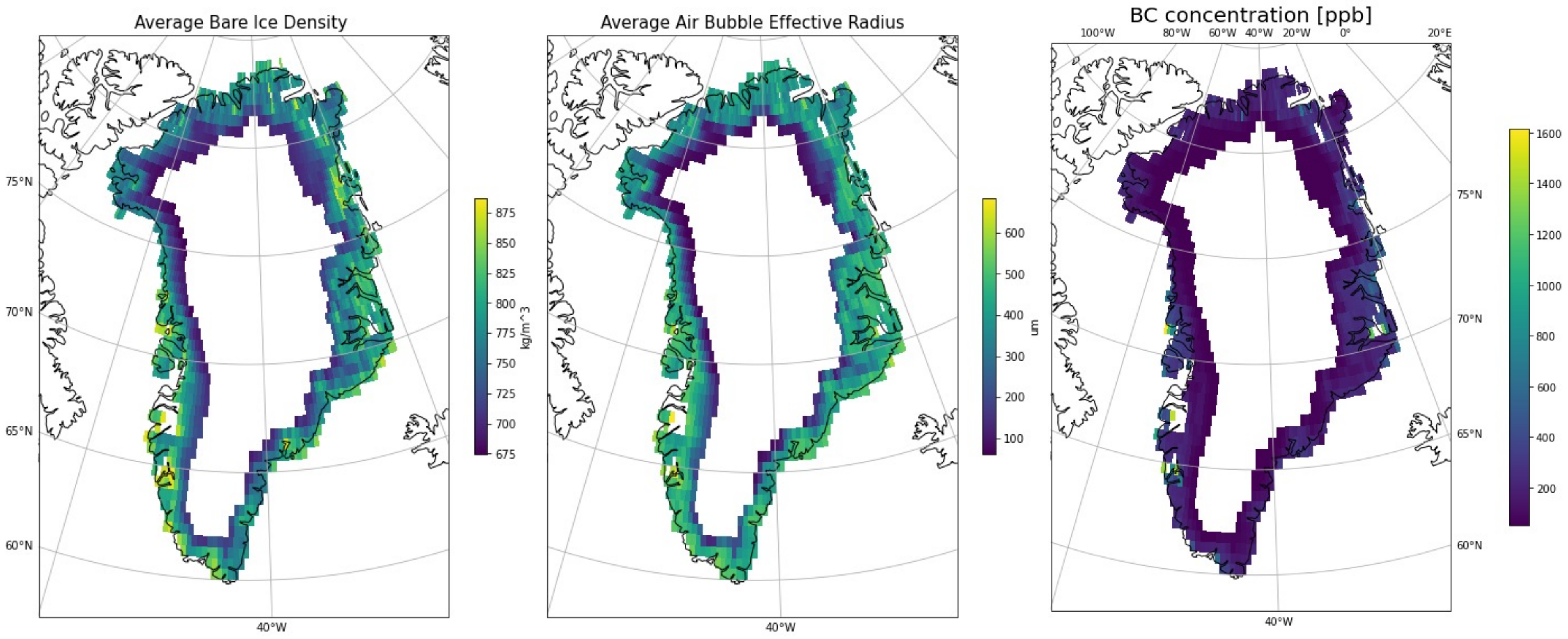
- We use MODIS albedo and reflectance products (MCD43A3, MOD09) over the ice sheet to better understand the spatial and temporal patterns in albedo and to constrain the physical properties of the bare ice for 2000 - 2021

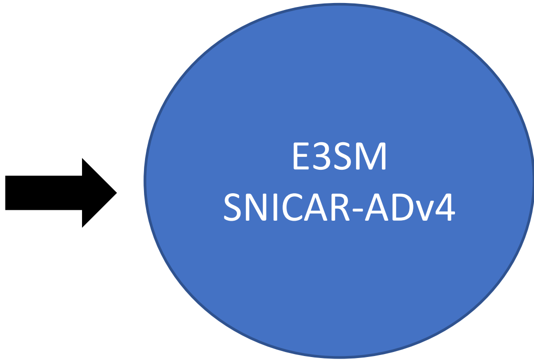


- MOD09 reflectance product is used to determine when and where bare ice is exposed (Antwerpen et al, 2022; Shimada et al, 2016)
- MCD43A3 albedo product in near-infrared part of the spectrum are used to determine the physical properties of the ice (specific surface area, density, and air bubble radius)
- MCD43A3 albedo product in the visible part of the spectrum is used to determine the impact of light absorbing impurities

Using MODIS data to inform bare ice properties

- We use the spatially and temporally varying ice density and the radius of the air bubbles within the ice as inputs for SNICAR-Adv4 within E3SM





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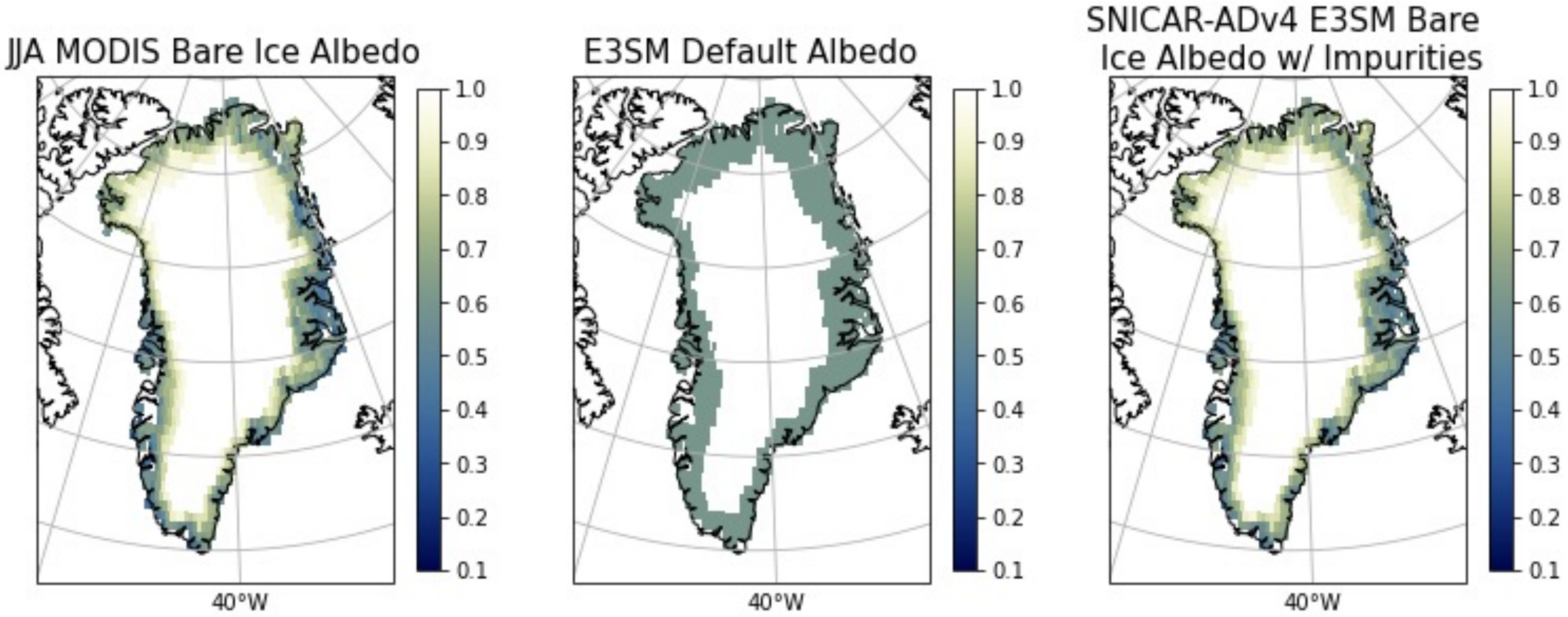
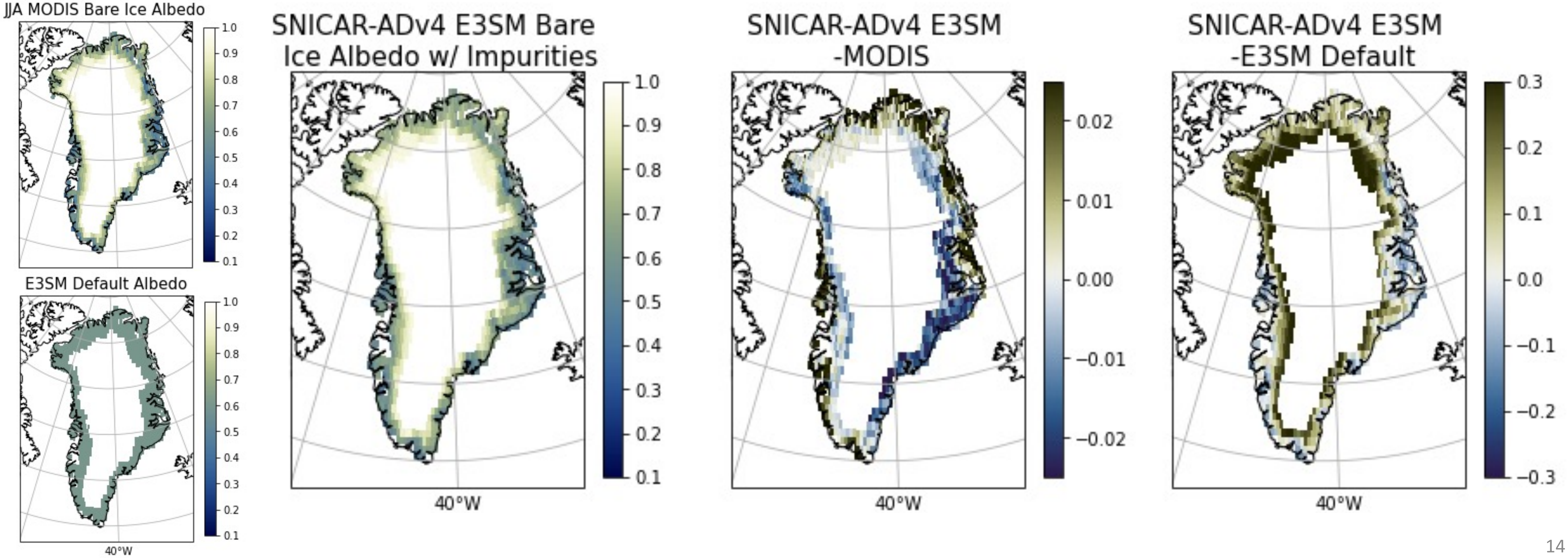
Results:
Improved Spatial and Temporal E3SM Albedo

- Our measurement informed bare ice albedo scheme is much more realistic than the default albedo scheme



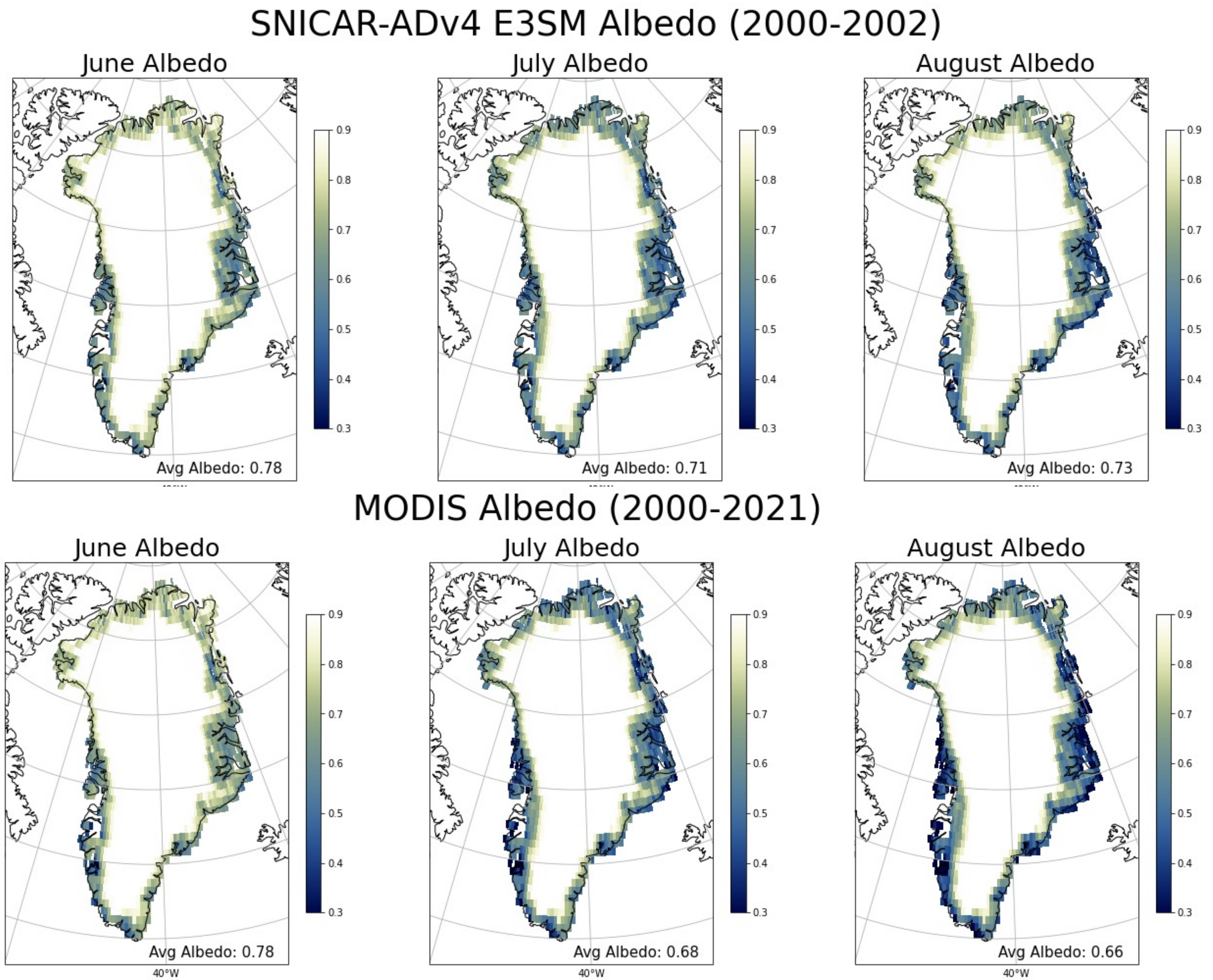
Results:
SNICAR-ADv4 E3SM Simulates Spatially Realistic Albedo

- The default albedo scheme is too high in the ablation zone and too low along the inside edge of the ice sheet
- The SNICAR-ADv4 scheme reproduces the MODIS bare ice albedo accurately (within 2%)



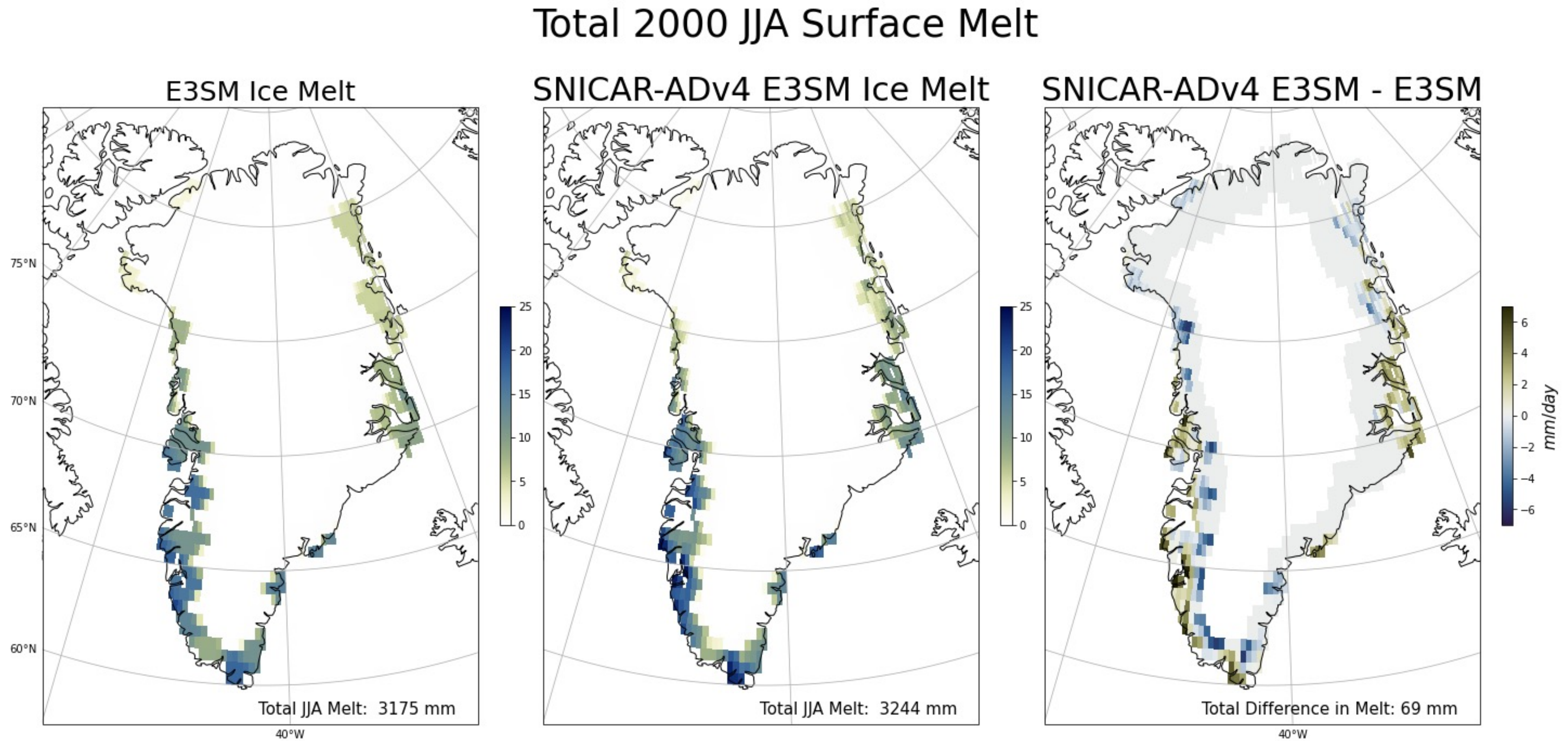
Results:
Seasonal Trends and Looking Forward

- For the years 2000—2002, we see a minimum albedo in June
- However, we expect to see a lower average albedo in longer simulations when we utilize the full timeseries of ice physical properties, following the MODIS seasonal albedo trend



Results:
Increased Surface melt in SNICAR-ADv4 E3SM

- In these SNICAR-ADv4 E3SM simulations, we see increased surface melt along the ablation zone where the albedo is lower, and decreased melt along the inner edge of the ablation zone where the albedo is higher
- In this preliminary 1 year simulation, we see a total increase in surface melt from the GrIS



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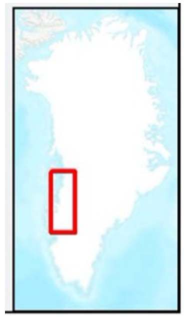
Future Work:
Greenland Ice Sheet surface melt and glacier algae

1. Use satellite data to quantify spatial and temporal patterns of glacier algae growth on the ice sheet
2. Implement the optical properties and reduction in albedo caused by glacier algae into SNICAR-ADv4 within E3SM

- Significant surface melt has been attributed to glacier algae growth
- Glacier algae has been shown to locally drop bare ice albedo by 3.5–43%

Glacier algae growth



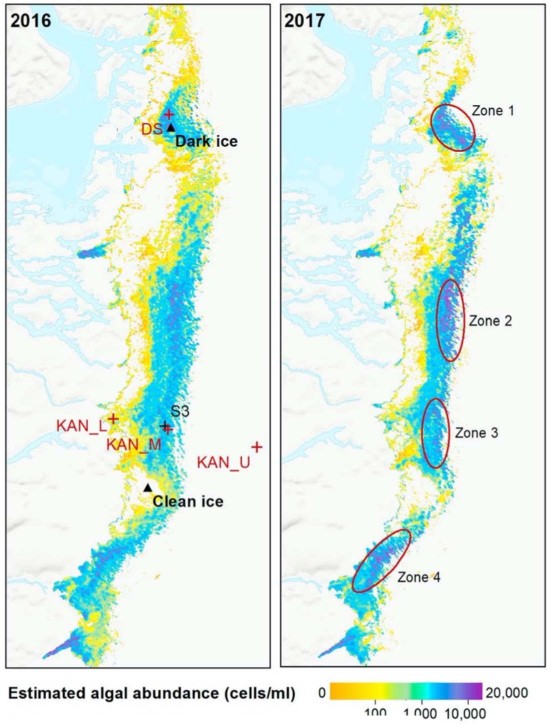


Figure: Wang et al. (2020)

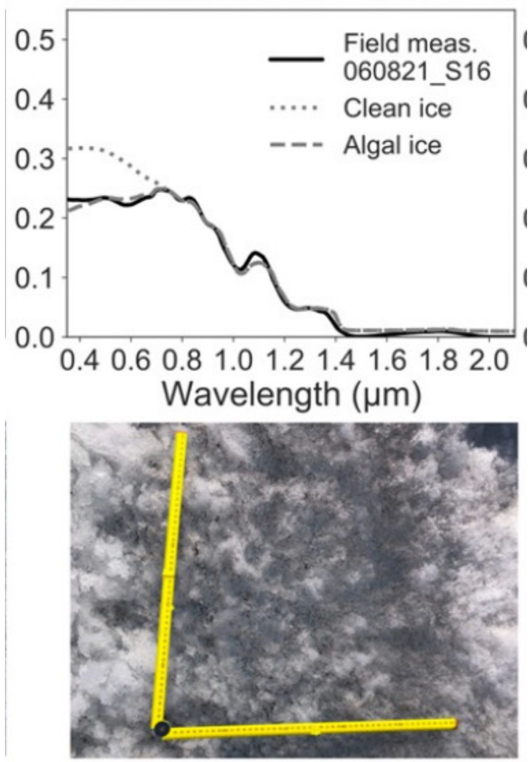


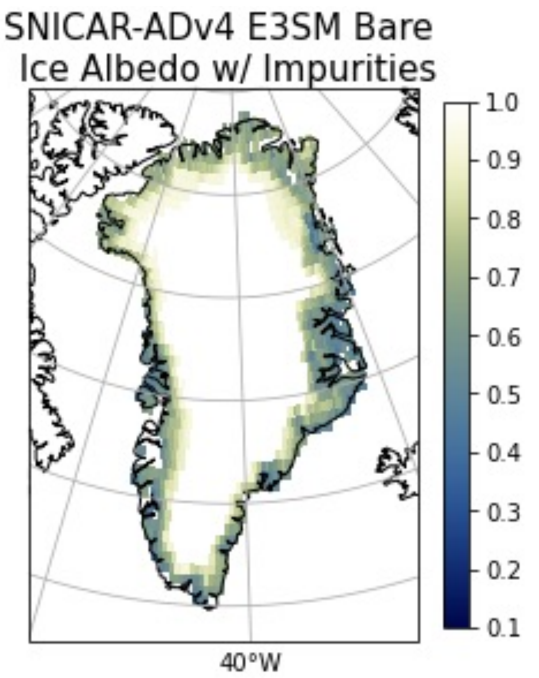
Figure: Chevrollier, et al. (2022)

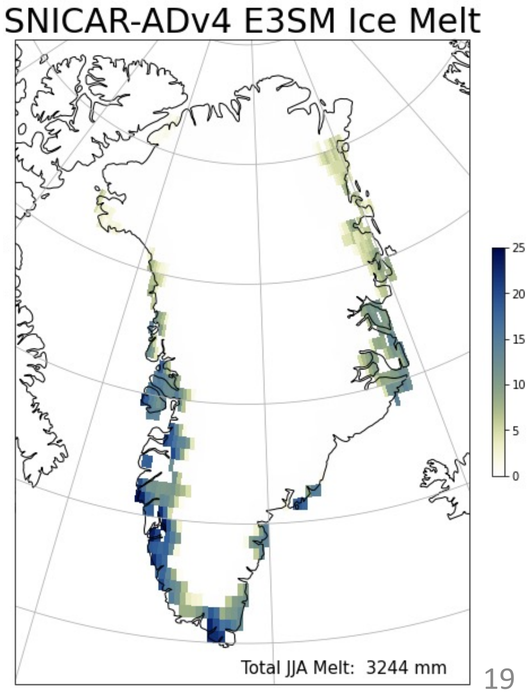
Conclusion

- This work improves our ability to model bare ice albedo over the Greenland Ice Sheet within E3SM
- We see improved spatially and temporally varying bare ice albedo
- The changes in albedo have varying impacts on the ice sheet surface mass balance
- This work currently only applies to the Greenland Ice Sheet in land simulations with a data atmosphere for the years 2000—2021, however, future work can expand these methods over different regions and use our ice property data to develop climatology values for bare ice properties
- My next steps are to perform simulations over the time period we have bare ice physical properties (2000-2021) and then to quantify the impact glacier algae have on regional melt and the radiative budget

Thank you!

Any questions?

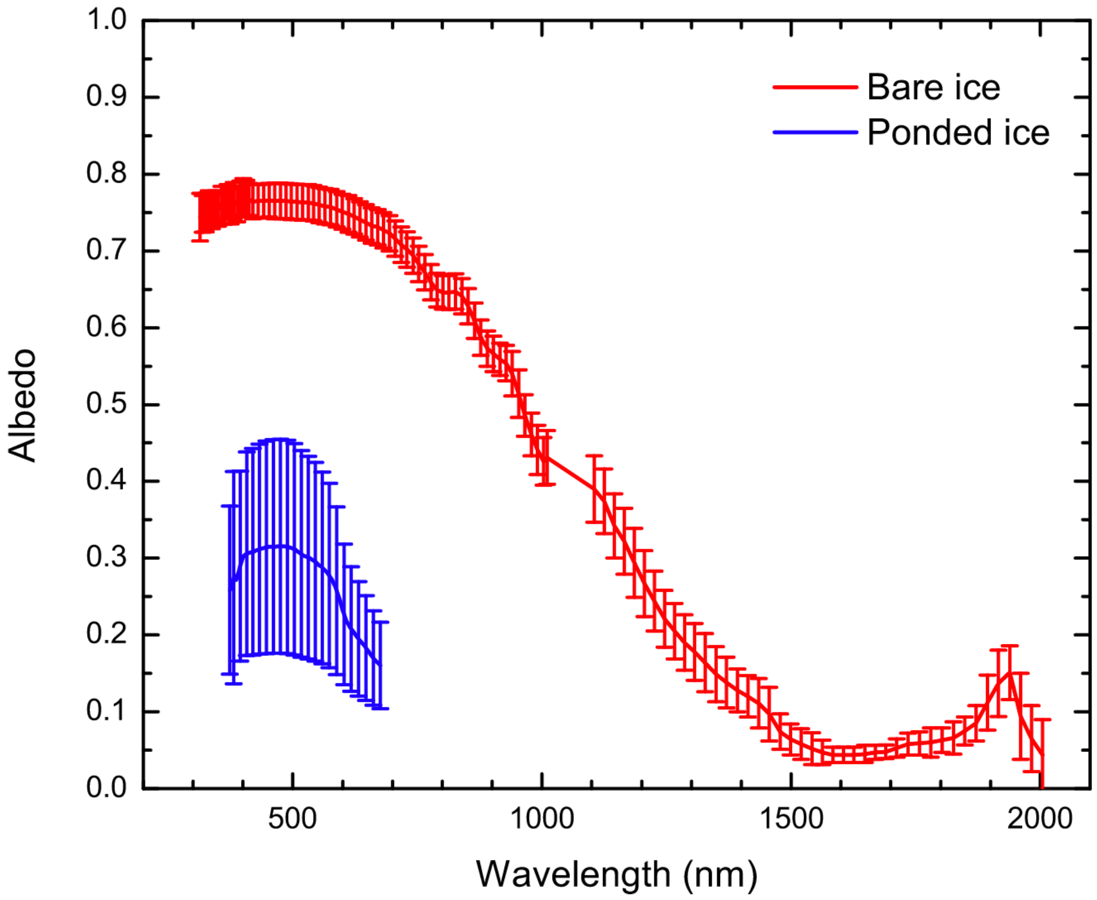




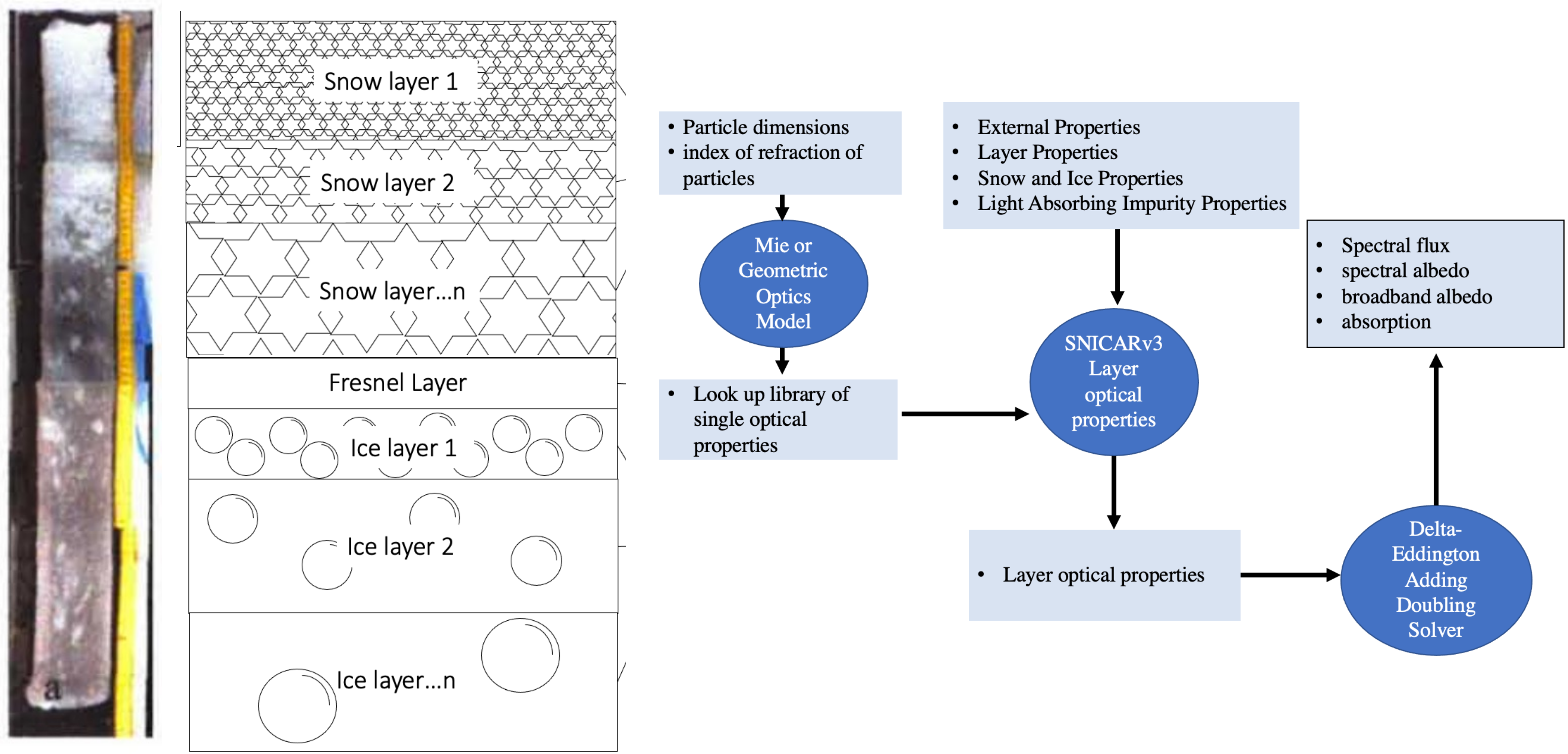
EXTRA SLIDES

Previous work modeling ice albedo with radiative transfer models (RTMs)

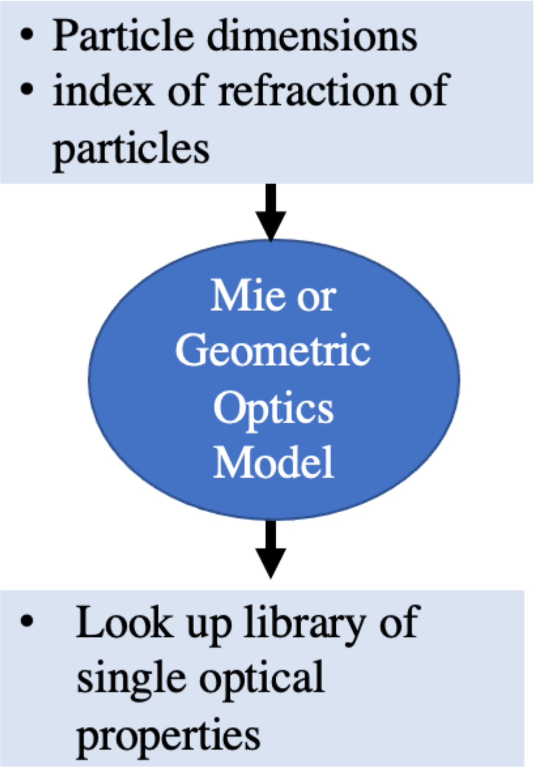
- History of ice modeling
  - Mullen and Warren (1988) developed a single column RTM that represent ice as a solid ice media, this model has only been applied to single layer lake ice
  - Current widely used sea ice model within Earth System Models is based on the Delta-Eddington Adding-Doubling 2-stream RTM method, however this model is constrained with empirical ice albedo measurements (Briegleb and Light, 2007)



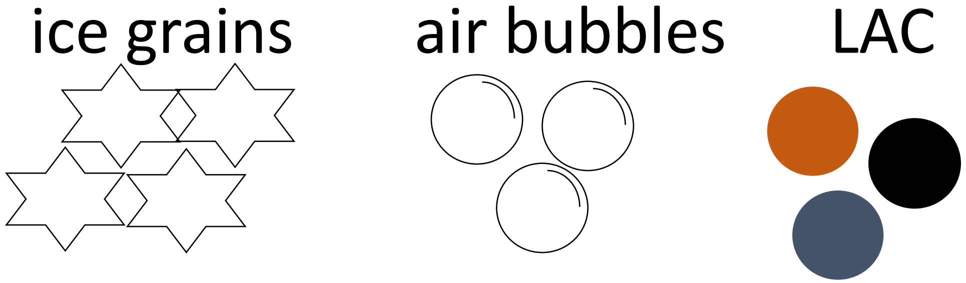
P1: SNICAR-ADv4
a single column 2-stream radiative transfer model



Model Overview: SNICAR-ADv4 components

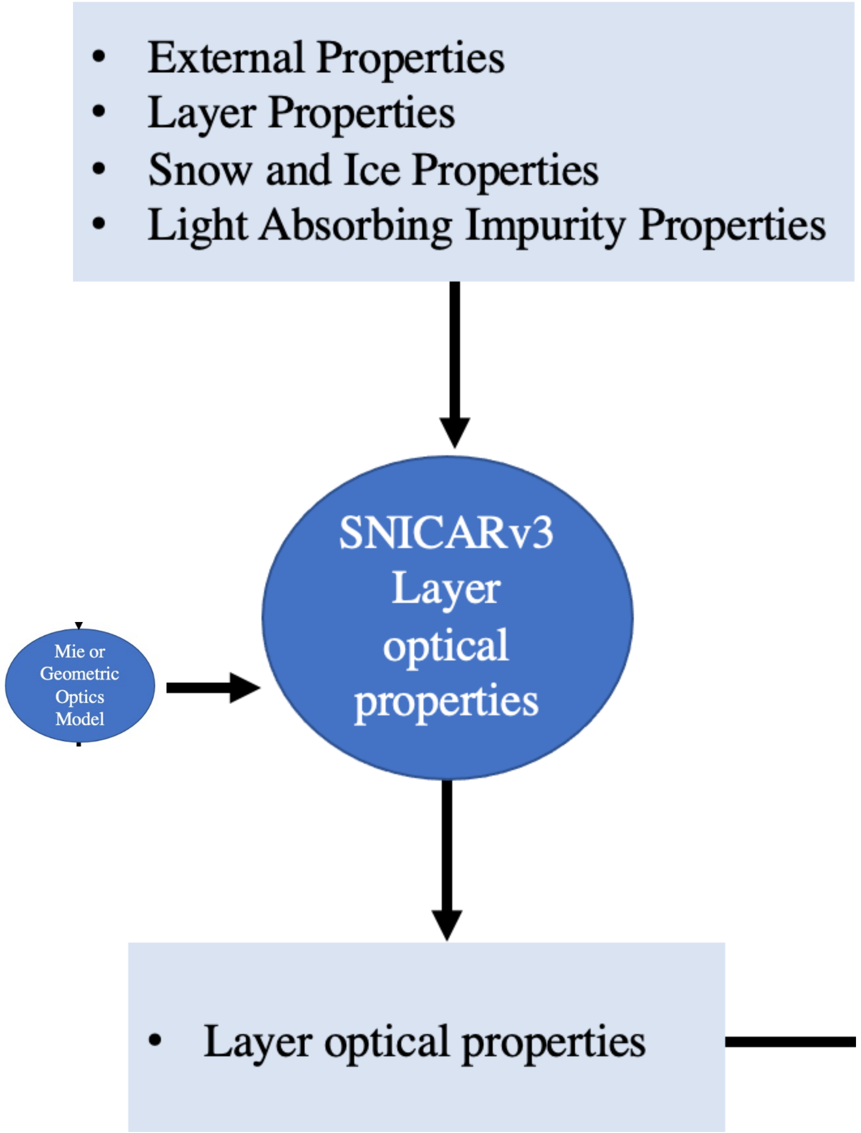


- Mie theory is used offline to determine the optical properties of each particle type used in the model

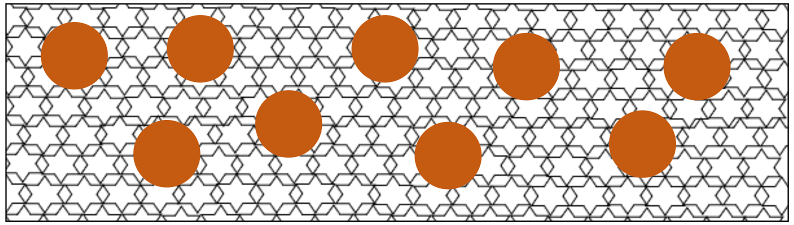


- Geometric optics were used for aspherical glacier algae optical properties (Cook et al., 2020)

Model Overview: SNICAR-ADv4 components



- The SNICAR layer optical properties solver utilizes the total layer burden of each constituent and the additive nature of optical depth to determine the total layer optical depth, single scatter albedo, and scattering asymmetry parameter



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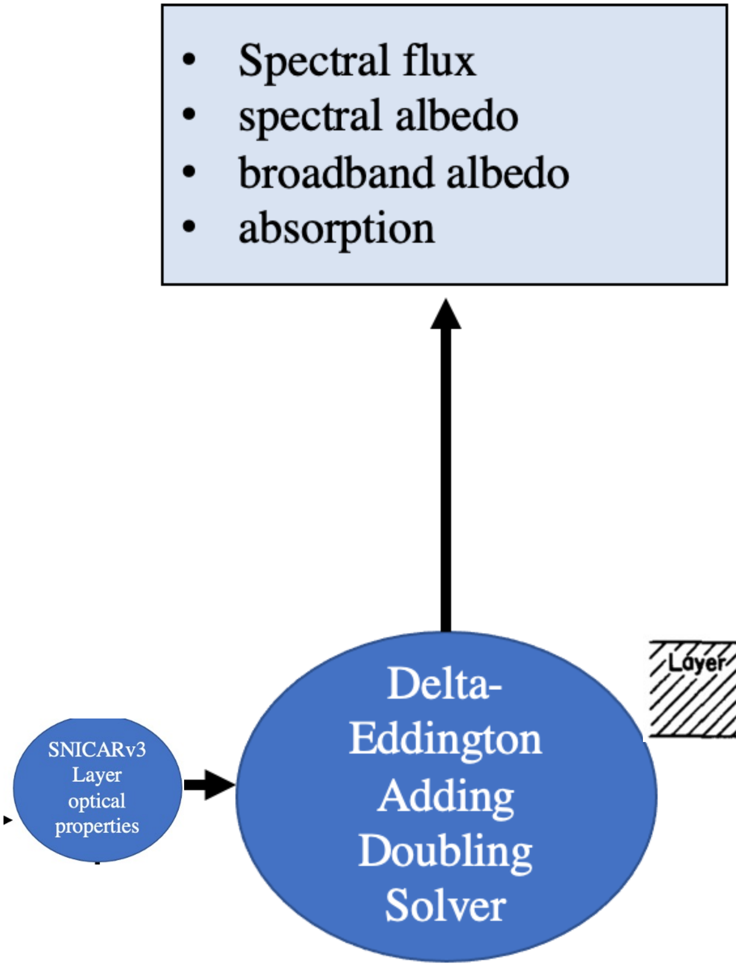
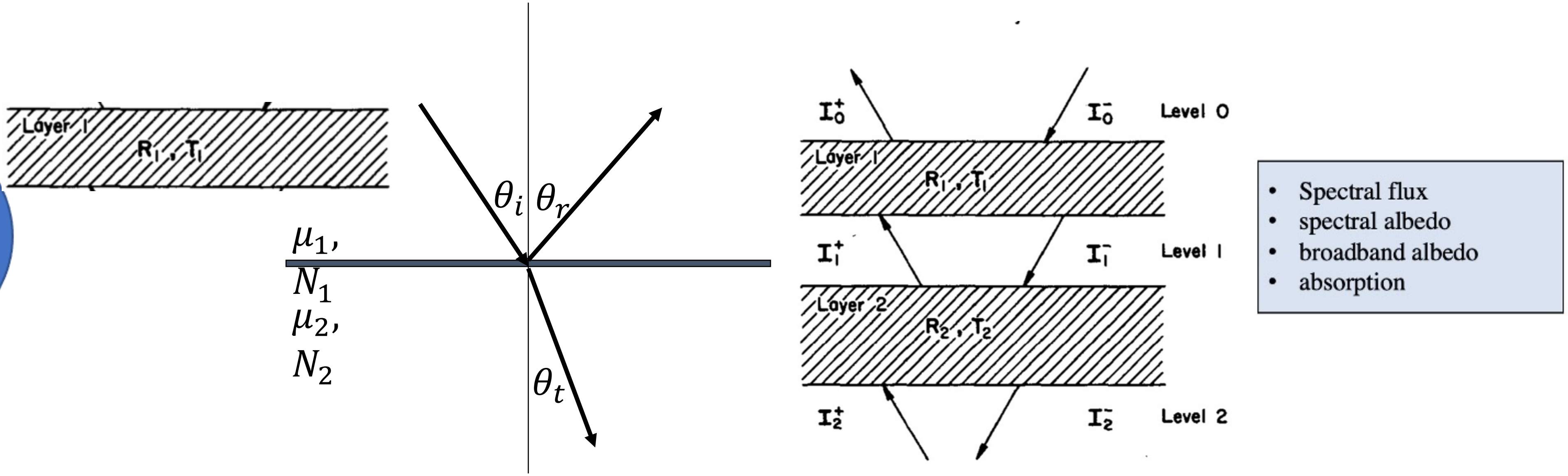


- Apply the Eddington 2-stream approximation and solve find the layer reflection and transmission
- Account for Fresnel reflection and refraction when there is a snow-ice transition
- Adding doubling technique combines reflection and transmission of the layers sequentially



The application of SNICAR-ADv4: SNICAR-ADv4 reproduces measurements of glacier algae on GrIS

- Recent work by Chevrollier, et al (2022) constrained SNICAR-ADv4 using *in-situ* measurements and found good agreement between model and measurement
- These reductions in albedo can be used to estimate surface melt, this study found glacier algae melt 0.17–1.7 cm w.e. / day due to glacier algae

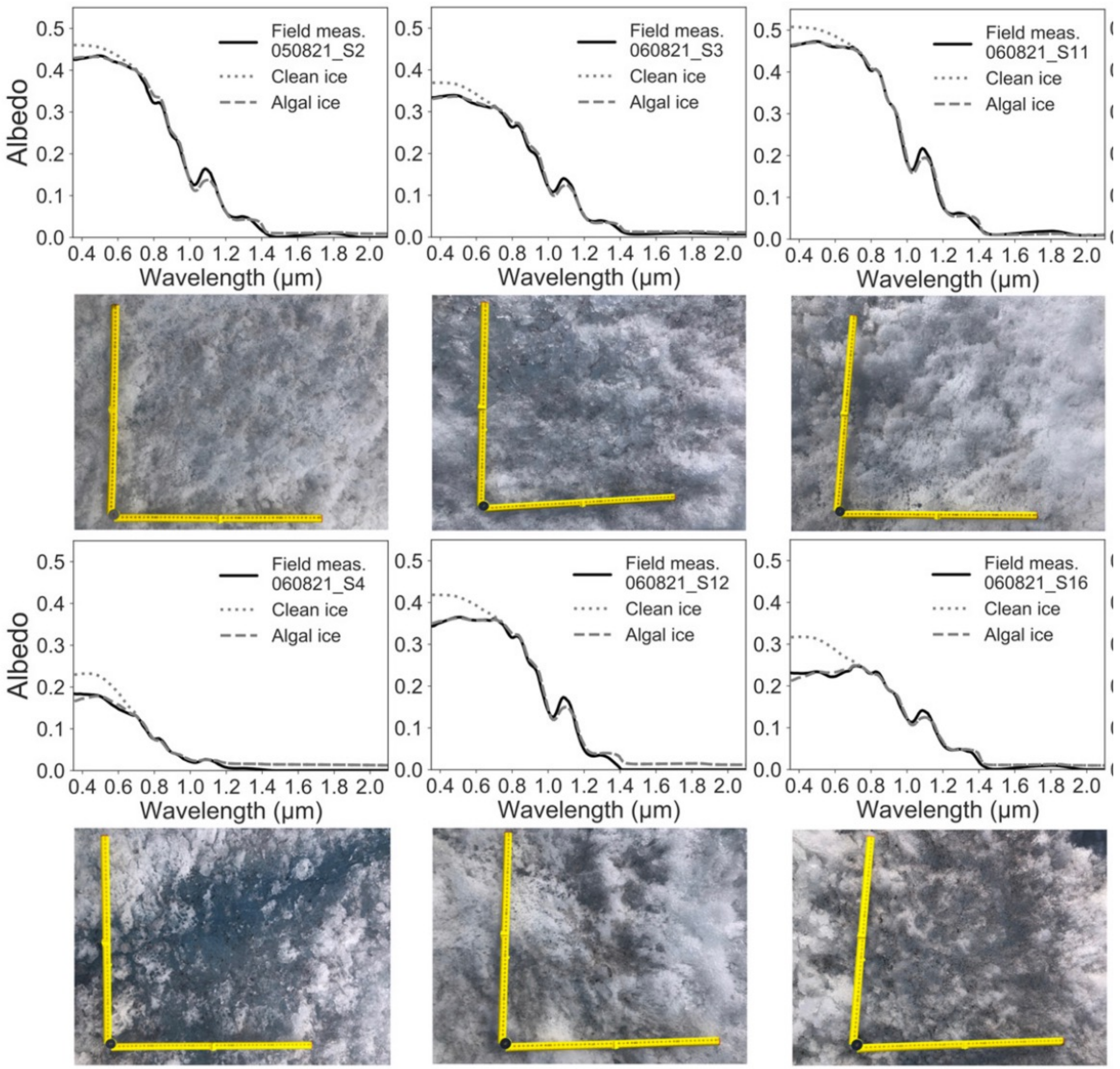
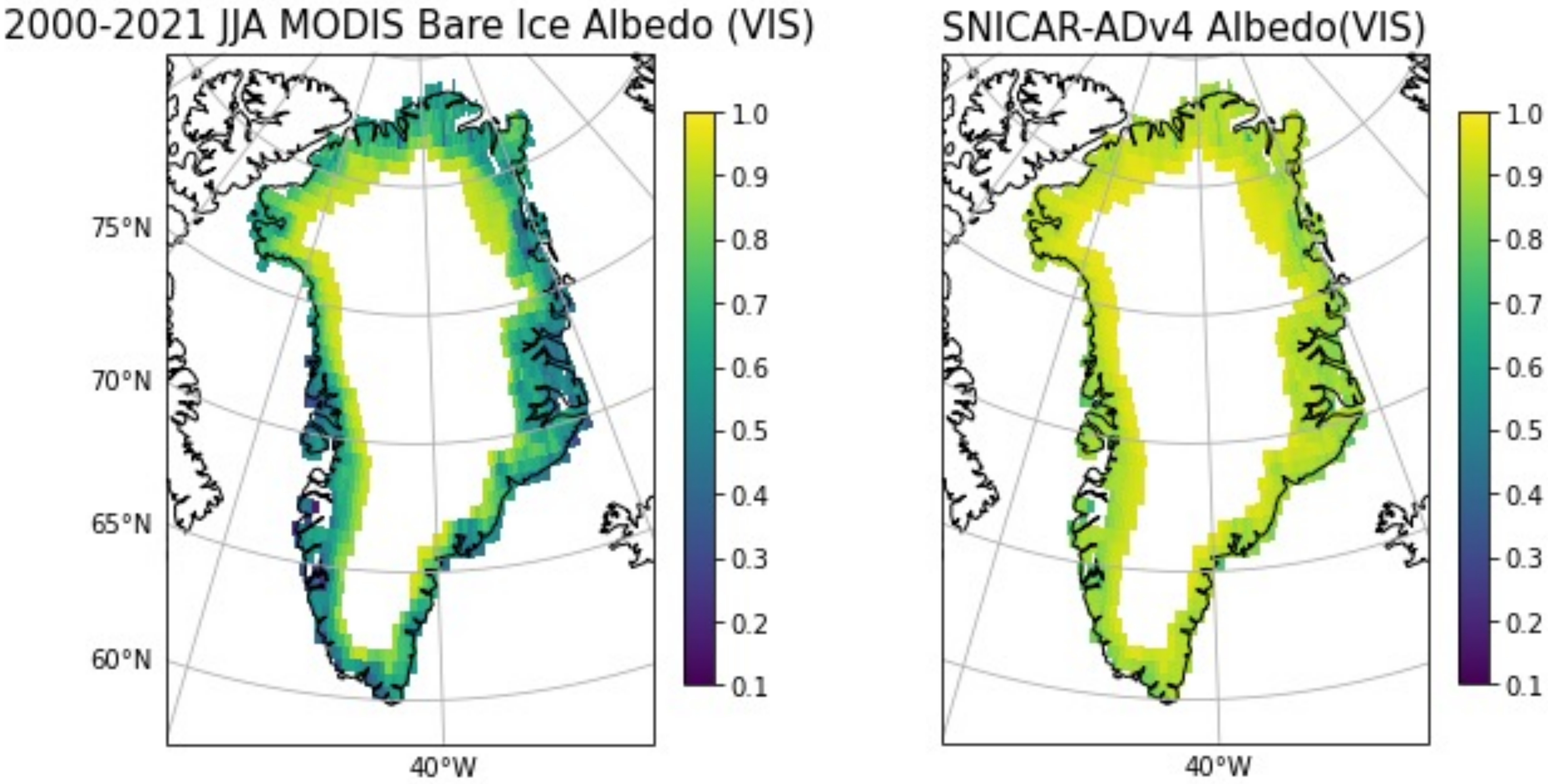


Figure: Chevrollier, et al. (2022)

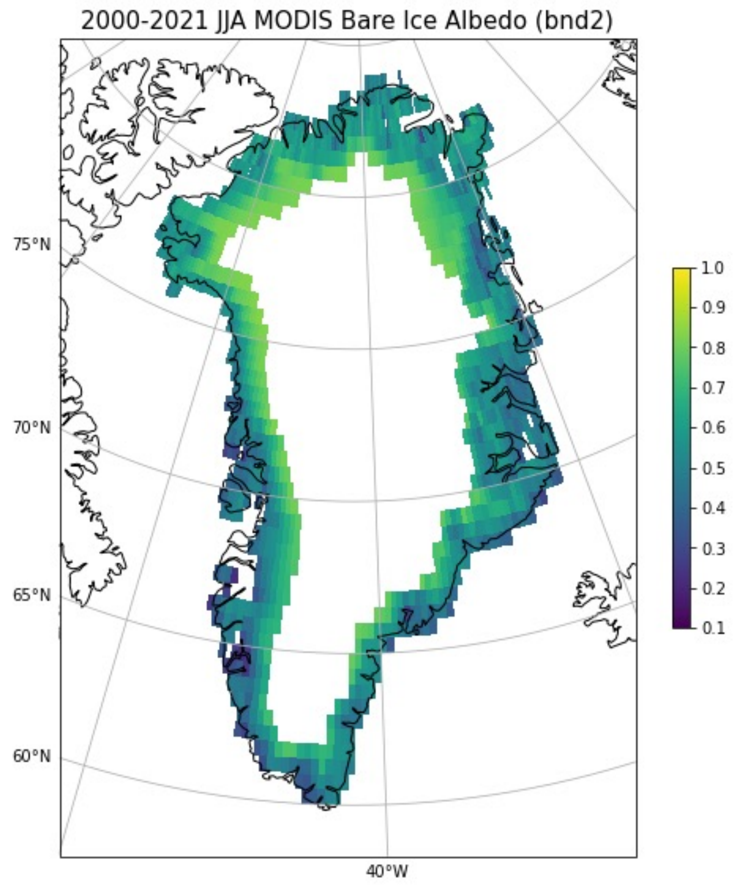
E3SM bare ice albedo with and without LACs

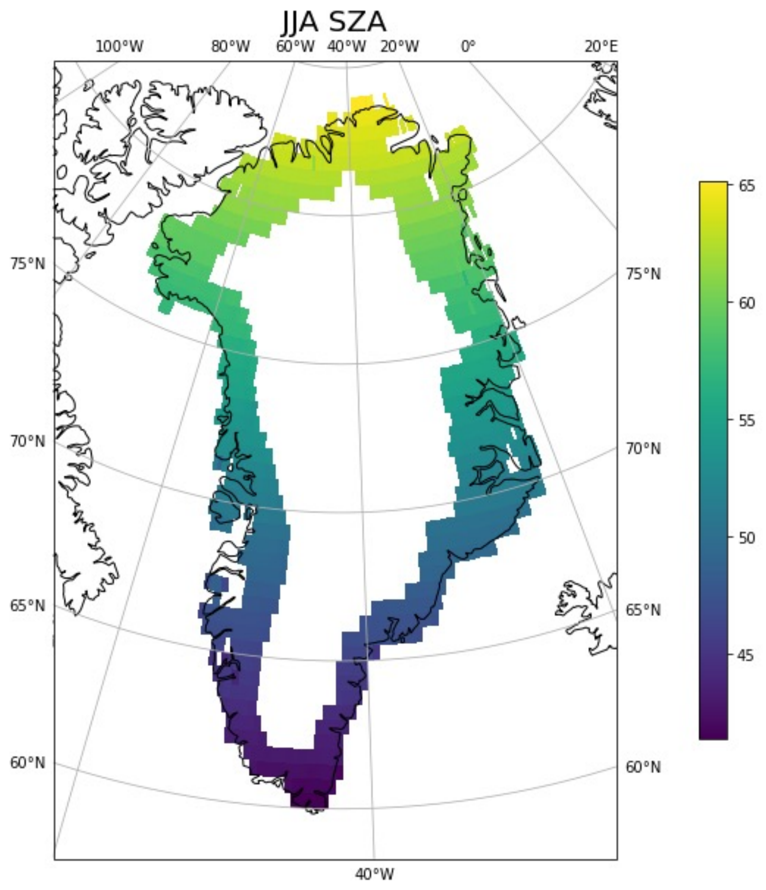
- Because we are using the NIR (MODIS band 2) albedo to determine the physical properties of the ice, we are not seeing the influence of LAC or surface impurities

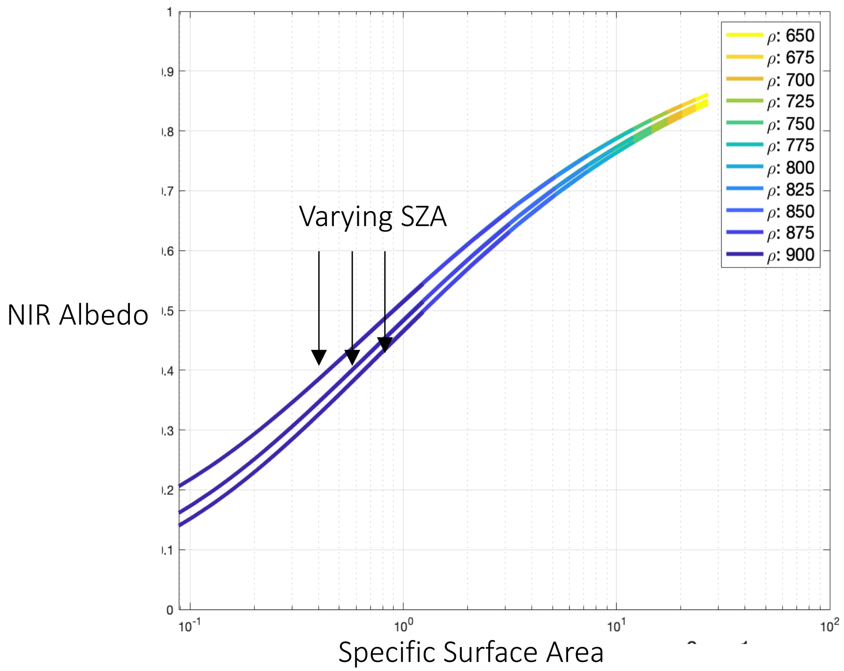


Using MODIS data to inform bare ice properties

- We utilize the relationship between the NIR albedo and the specific surface area of the ice to determine the ice density and the radius of the air bubbles within the ice

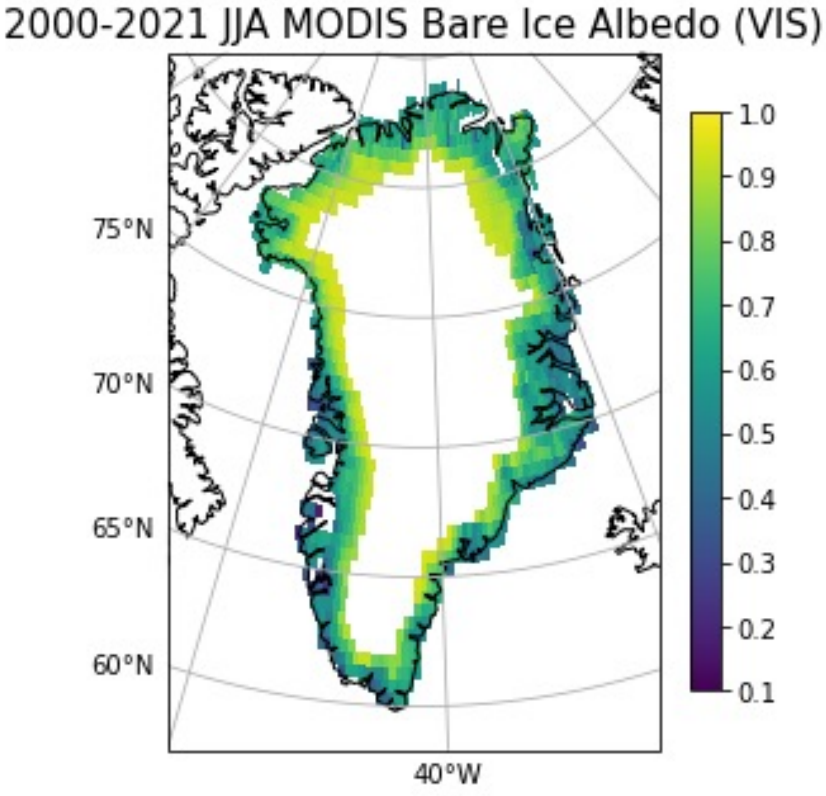


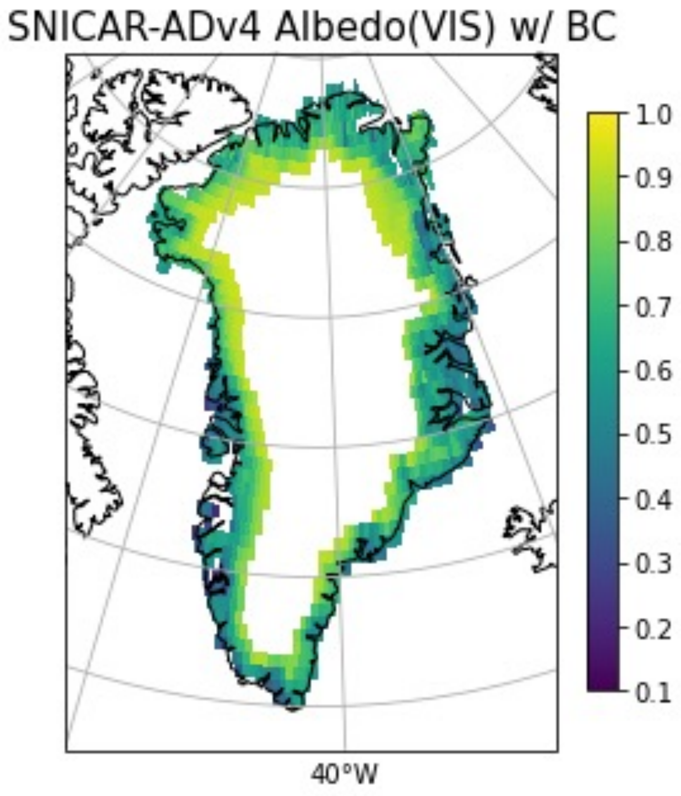


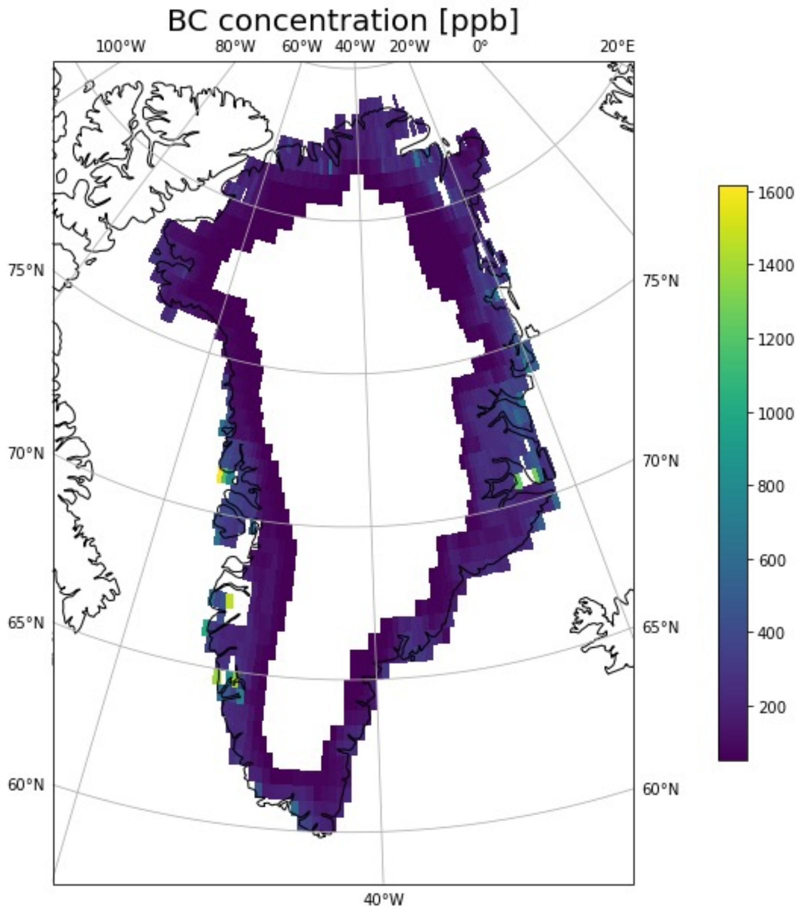


E3SM bare ice albedo with and without LACs

- We prescribe an “equivalent black carbon concentration” to account for darkening of the ice surface by LAC, surface roughness, ponding, or other sources of darkening







E3SM - MODIS plots