Los Alamos NATIONAL LABORATORY

Using Artificial Intelligence and Physics Models to Understand Arctic Snow Patterns

Katrina E. Bennett

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AI for Earth Sciences Workshop 2026

Approvals: 194251be, 5d5f0361, LA-UR-23-33656

Dr. Katrina E. Bennett

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- **Masters** of Science at Environment Canada, University of Victoria (UVic), Victoria, BC (Dr. Terry Prowse)
  - Water balances of lakes and wetlands of Northern Alberta
- **Hydrologist**, Pacific Climate Impacts Consortium, UVic, Victoria, BC
  - Impact of climate change on BC Hydro reservoir systems
- **PhD** at International Arctic Research Center, University of Alaska Fairbanks, AK (Dr. Larry Hinzman)
  - Climate change and extreme hydro-climate events in boreal forest watersheds
- **Postdoctoral Researcher** at LANL (Dr. Cathy Wilson, Dr. Richard Middleton), Los Alamos, NM
  - Impact of climate change and vegetation disturbances on the Colorado River basin
- **Scientist**, Analytics, Intelligence, Technology, LANL Los Alamos, NM
  - Snow, streamflow, hydro-climate extremes, disturbances, climate change, national security, AI/ML tools

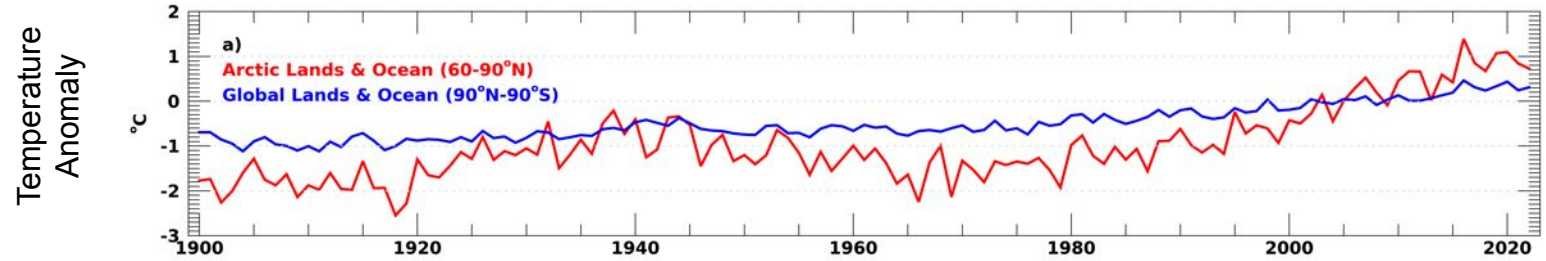
Nome, Alaska

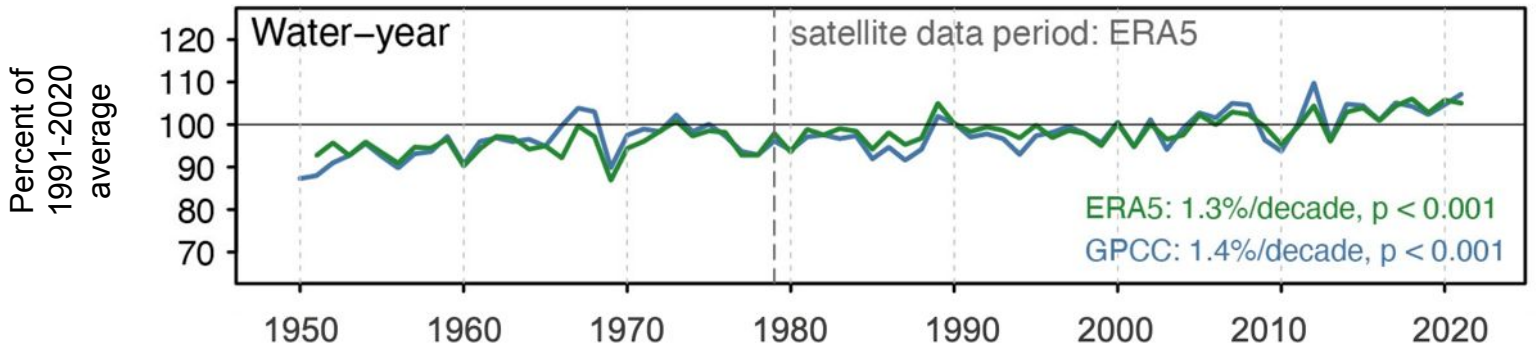
Earth System Dynamics at Shifting

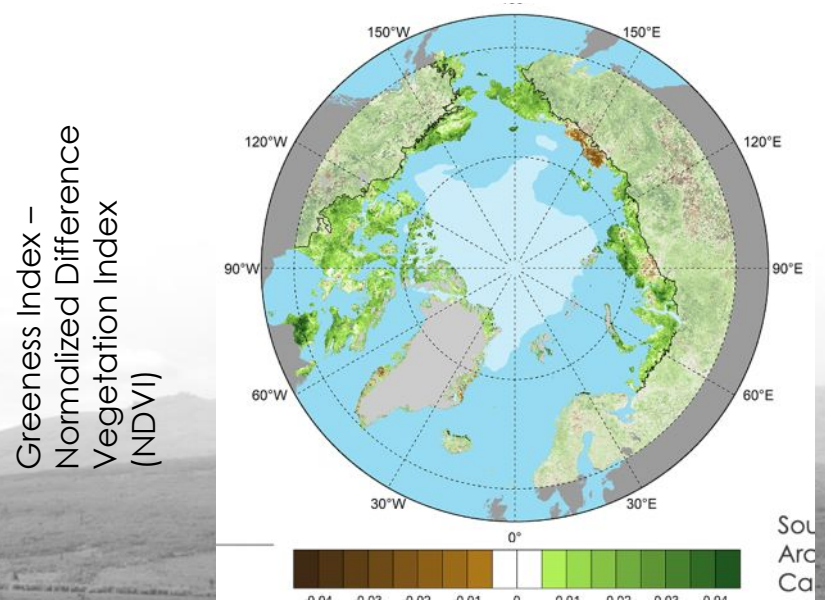
The Arctic is warming.

The Arctic is wetting.

The Arctic is getting greener and shrubbier.

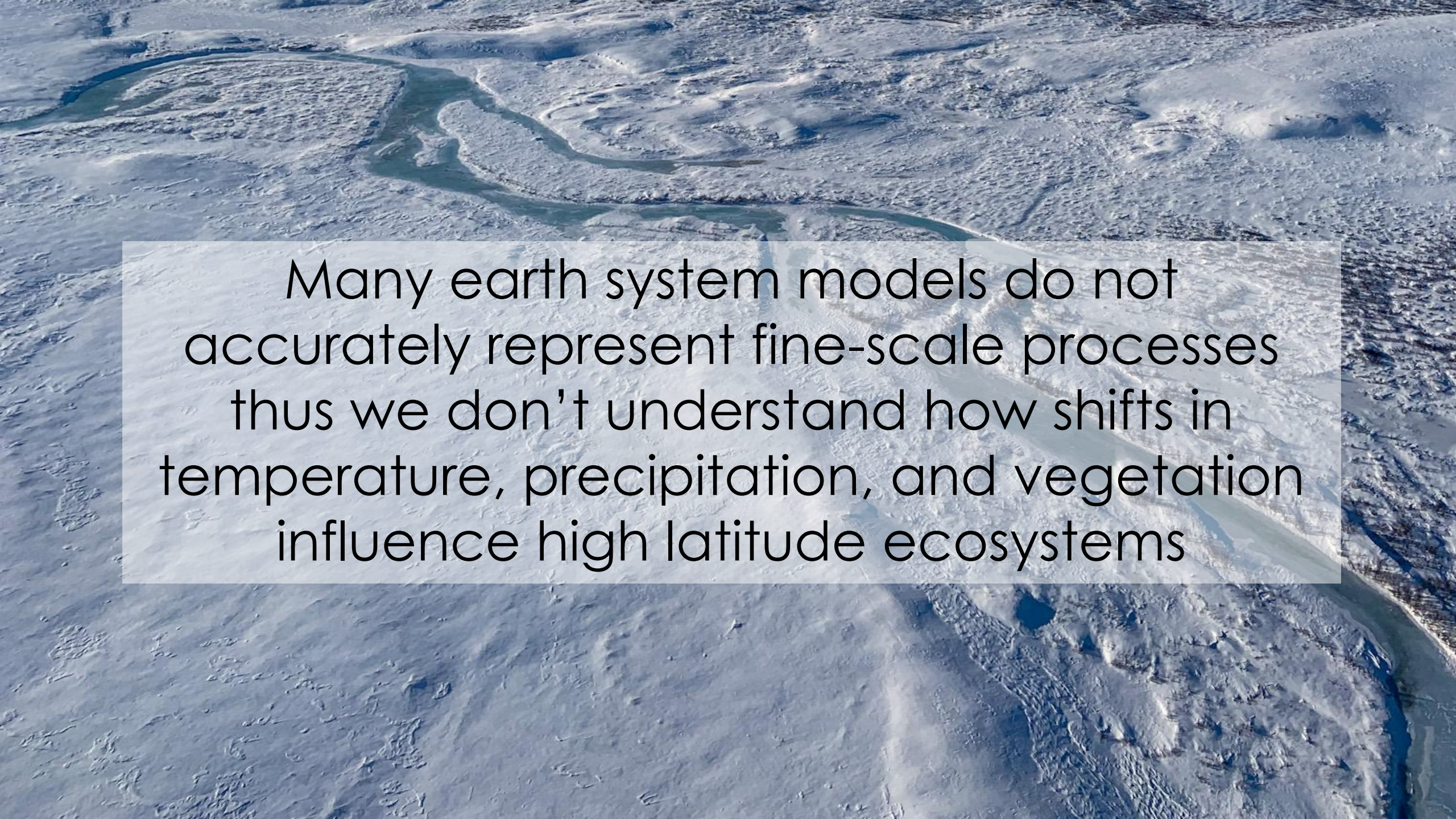






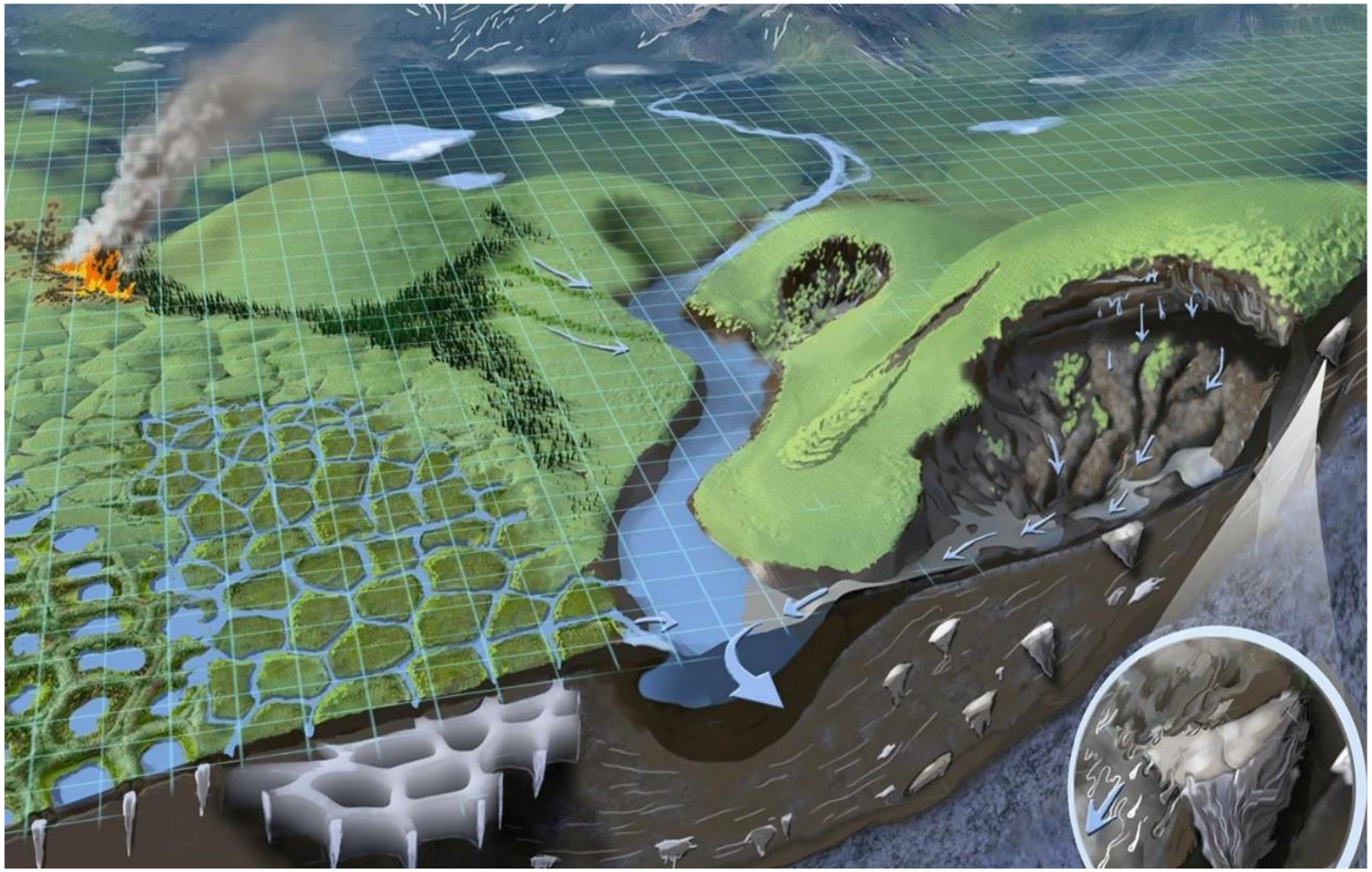
Source:
NOAA Arctic Report Card, 2022

NGEE Arctic
Next-Generation Ecosystem Experiments



Many earth system models do not accurately represent fine-scale processes thus we don't understand how shifts in temperature, precipitation, and vegetation influence high latitude ecosystems

NGEE Arctic is a **MODEL-DRIVEN, MULTI-SCALE** research project that leverages a decade-long foundation of model–data integration in Arctic Alaska to understand and predict climate-ecosystem feedbacks across the Arctic.



NGEE Arctic Project: Overview

The goal of NGEE Arctic is to improve the way that unique, interacting, tundra processes are represented in a virtual model of the entire Earth system – so we can predict the climate of the future.

12 year project

Phase IV: Final Phase (FY 25-27)

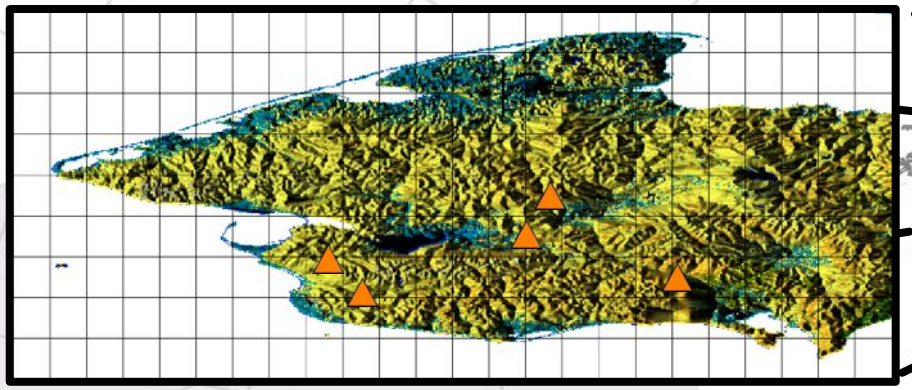
Phase

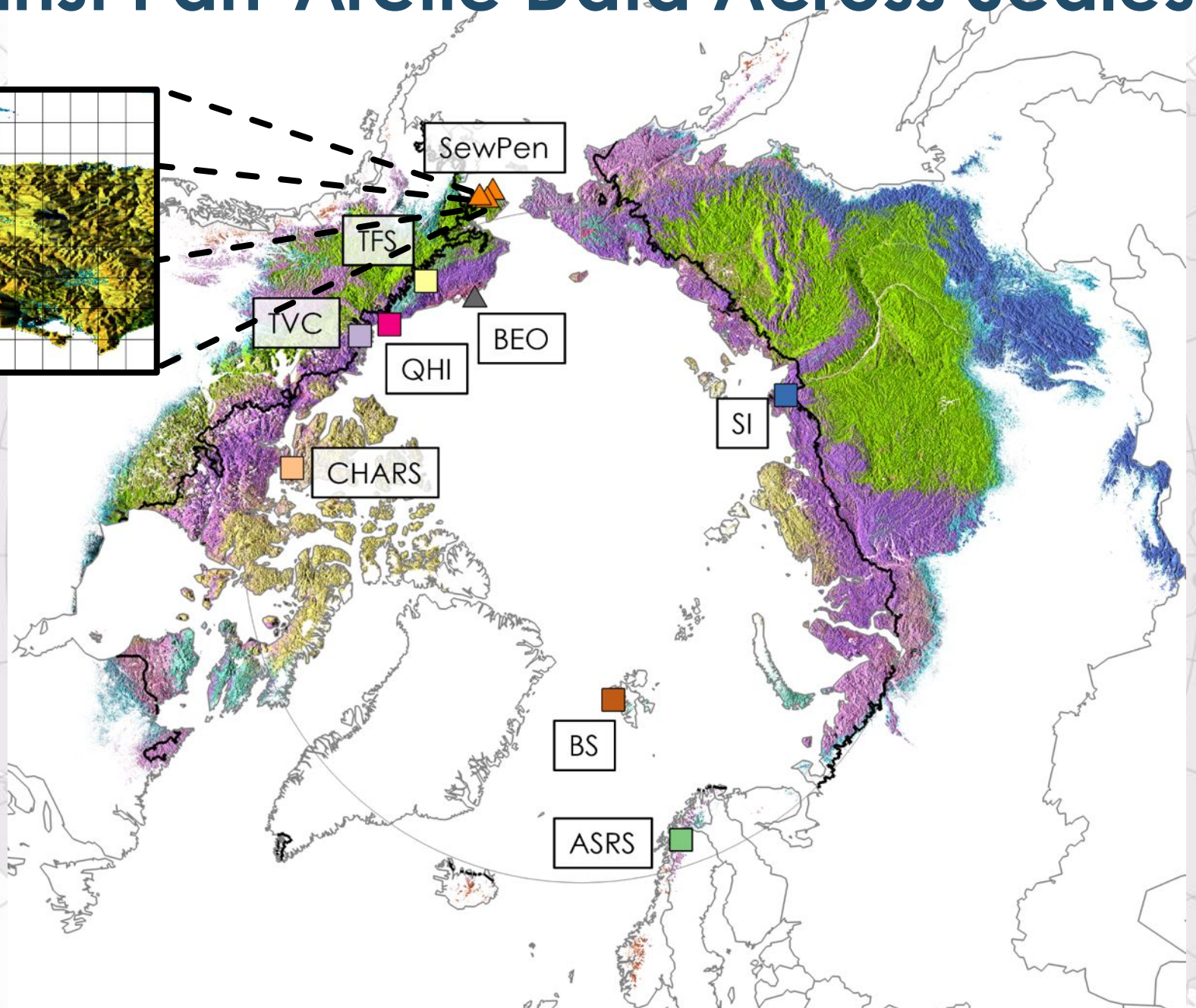
MODEL-DRIVEN AND DISCOVERY SCIENCE	MODEL-DATA INTEGRATION, PROCESS REPRESENTATION, AND EVALUATION	SOURCE CODE MODULES FOR E3SM
Q1, Q2, Q3, Q4, Q5, Q6	ELM, ATS, FATES, *ecosys*, TEM, ILAMB	IM1, IM2, IM3, IM4, IM5, IM6

DATA ARCHIVED AT ENVIRONMENTAL SYSTEM SCIENCE DATA INFRASTRUCTURE FOR A VIRTUAL ECOSYSTEM

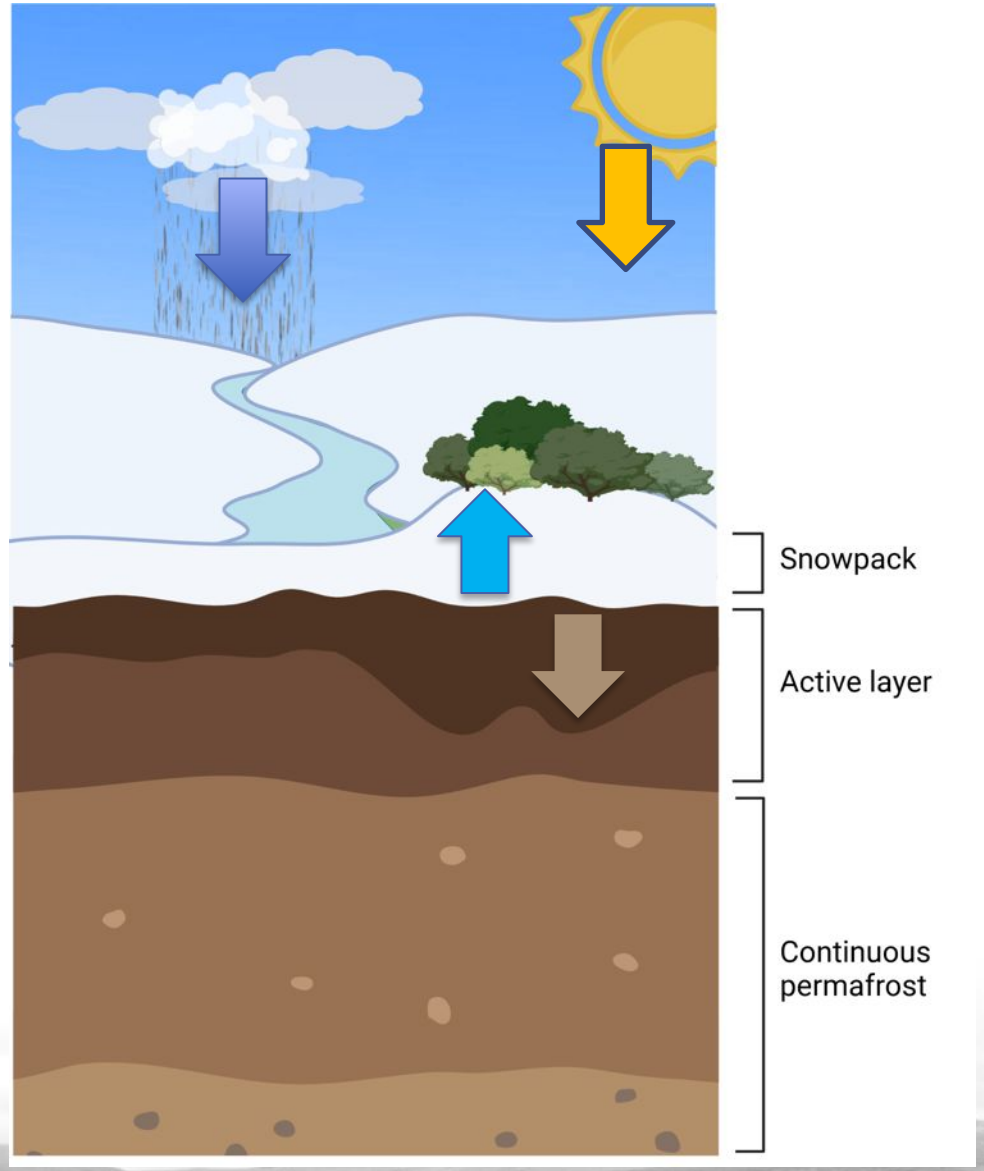
ESS-DIVE
Deep Insight for Earth Science Data

Evaluating Against Pan-Arctic Data Across Scales



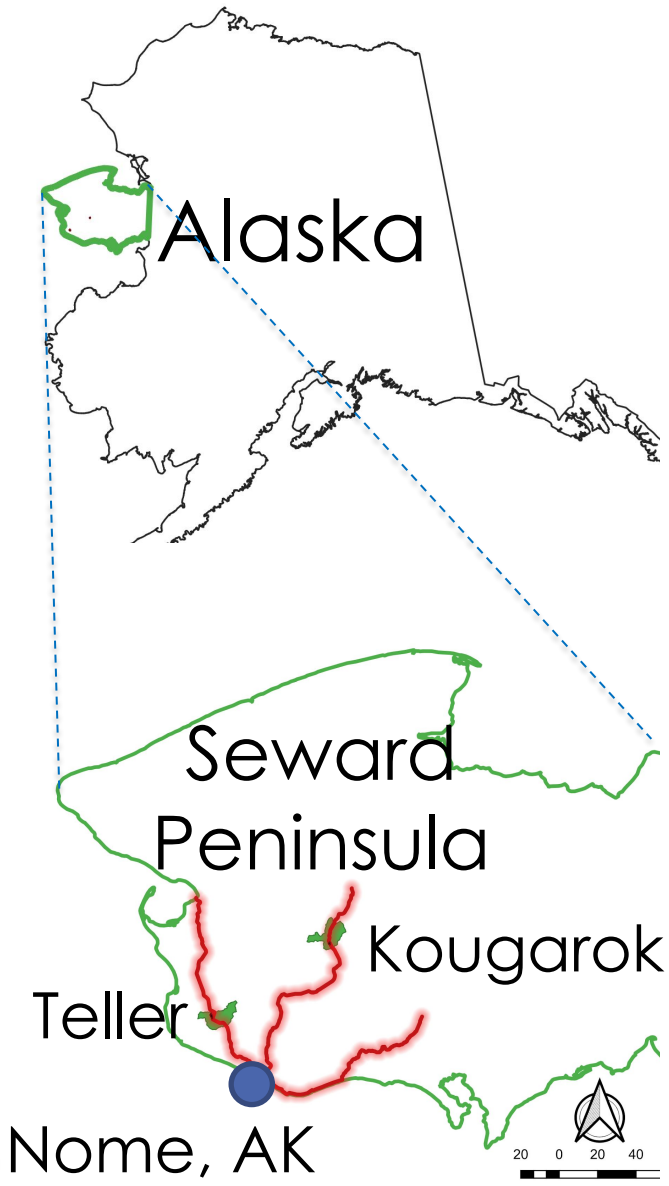


Why do we care about snow in the Arctic?

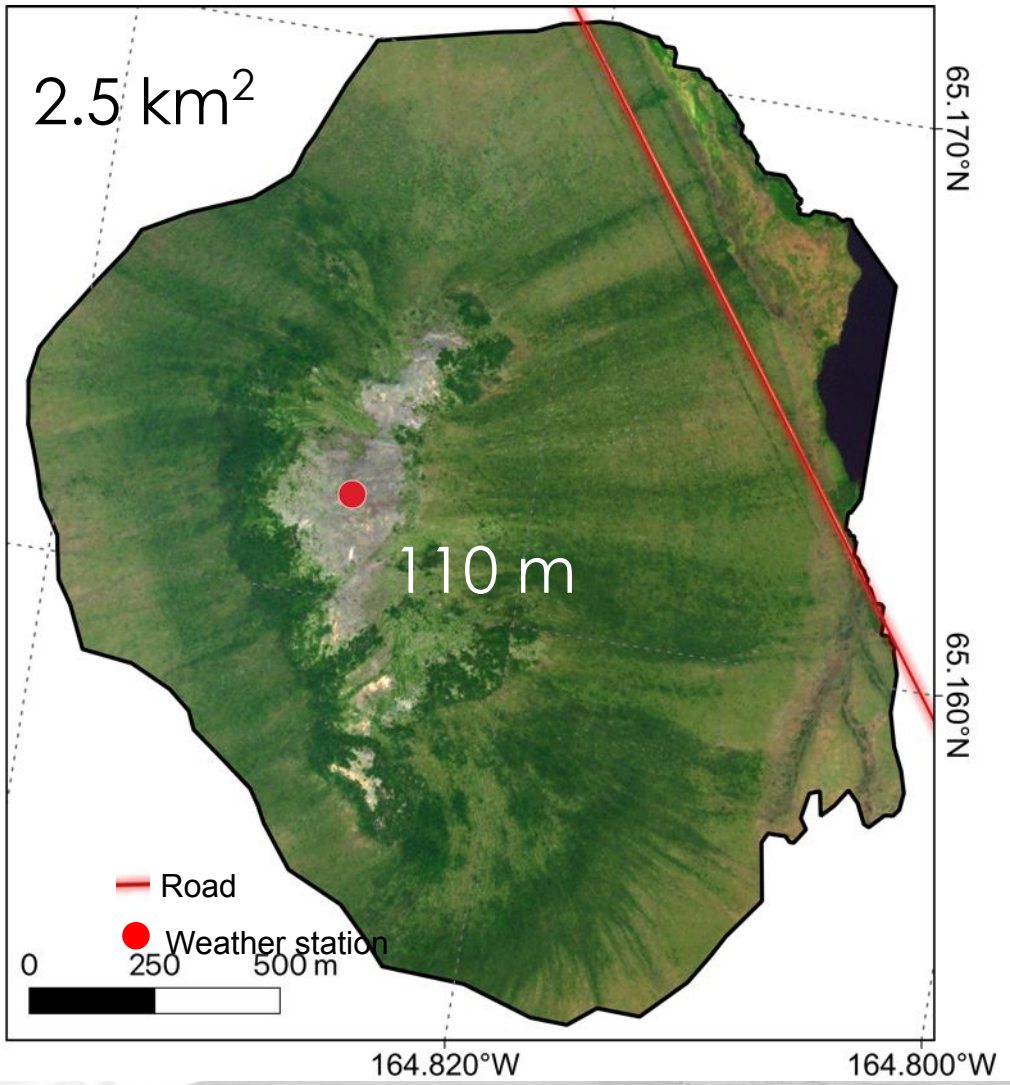


Grünberg et al. 2020

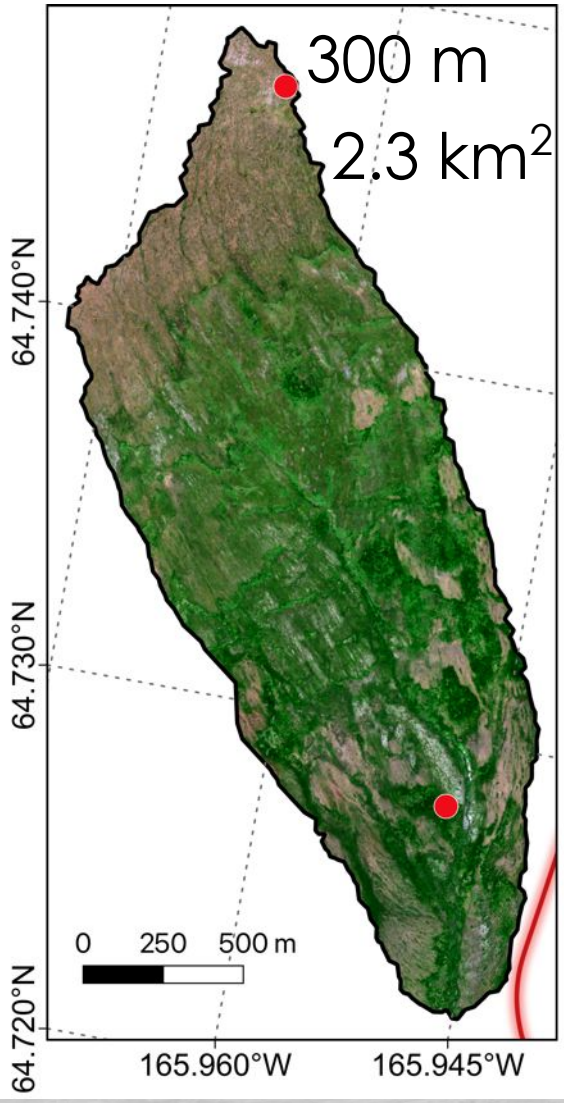
*As **temperature**, **snow+rain**, and **shrubs** increase, deeper snow acts like a blanket over the land. This leads to a decrease in the **permafrost**, with warming of the subsurface and **deepening of active layers***



Kougarok Hillslope



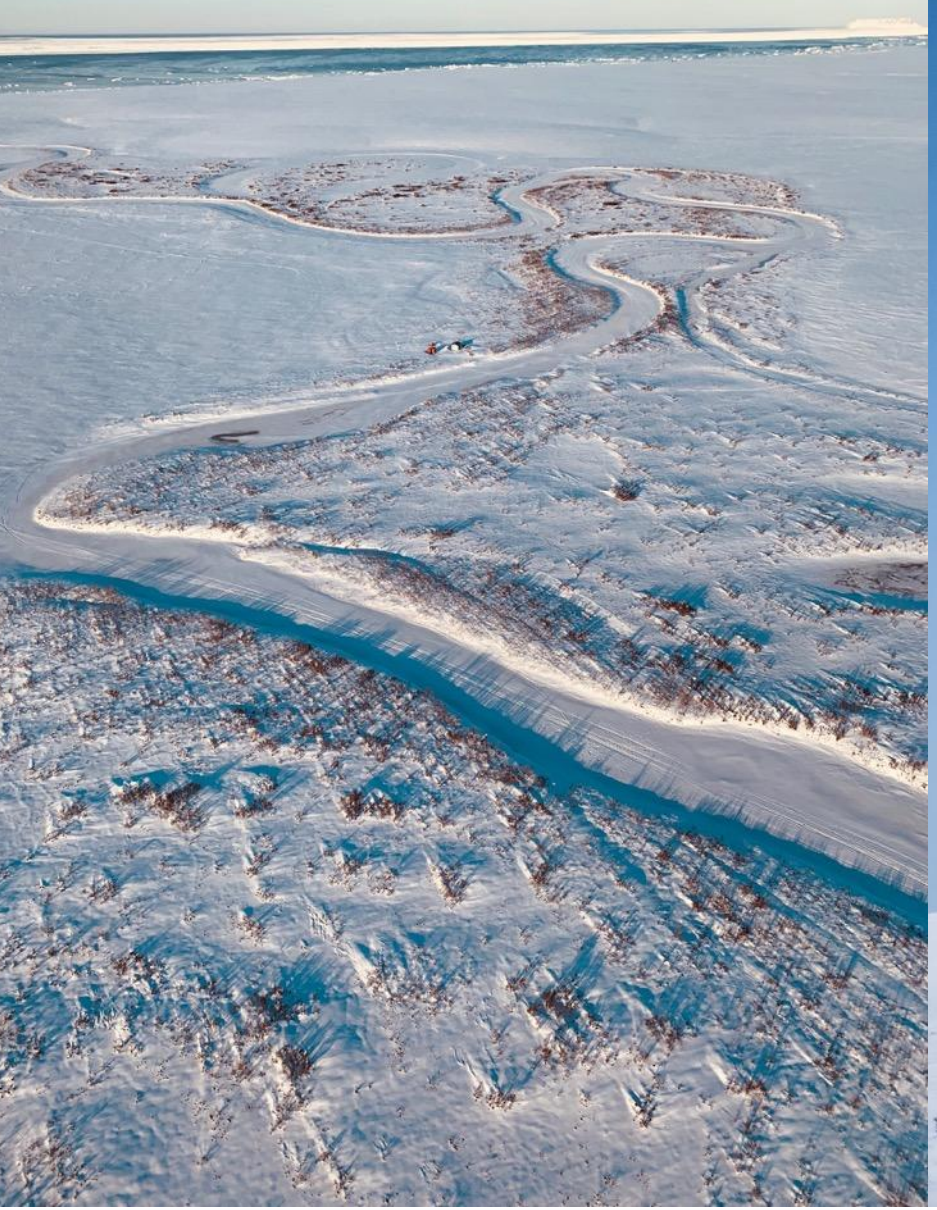
Teller Watershed



NGEE Arctic
Next-Generation Ecosystem Experiments

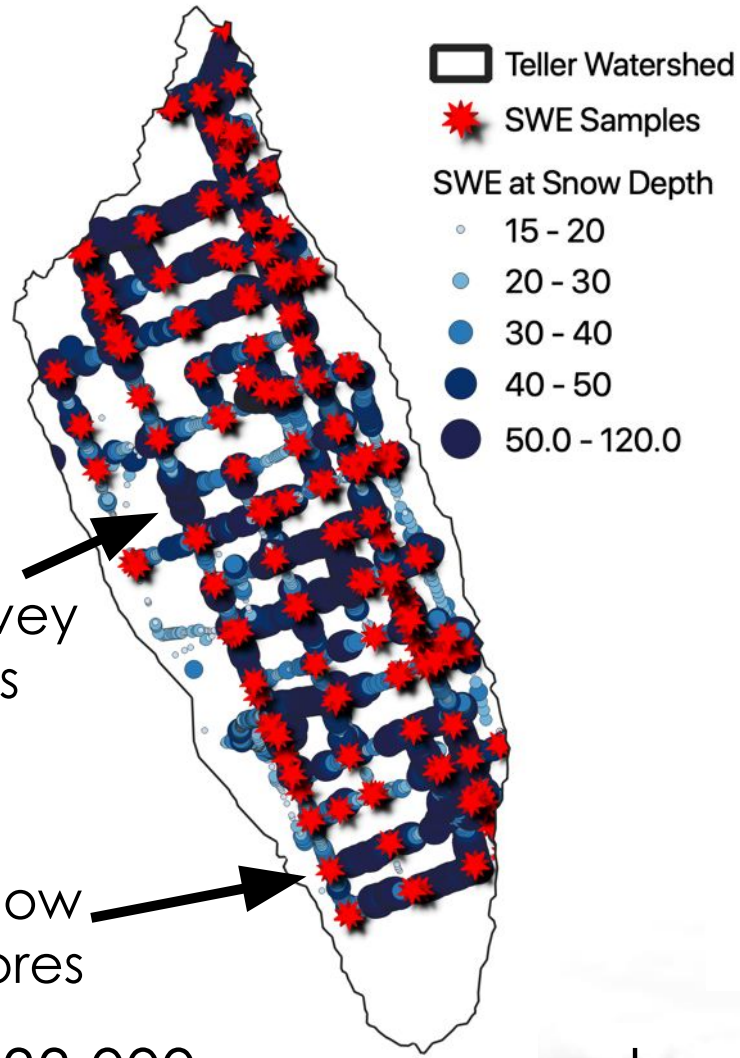
Snow Observations & Modeling

NGEE Arctic
Next-Generation Ecosystem Experiments

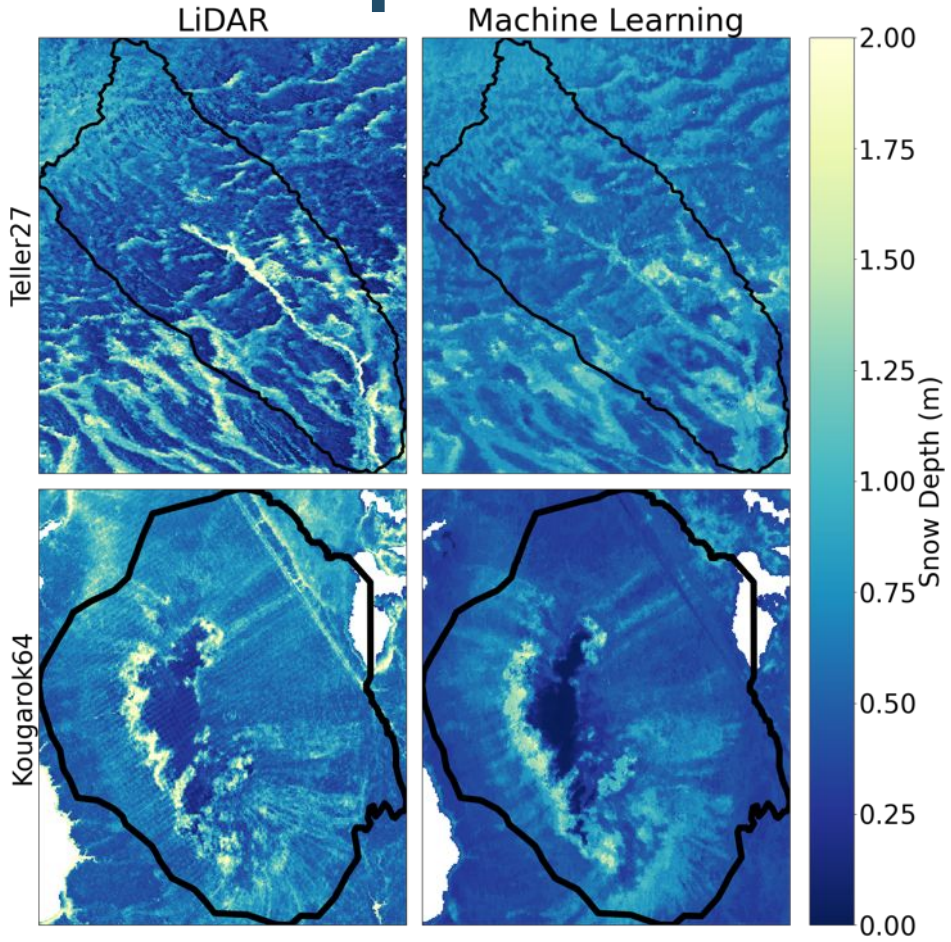


End-of-winter Peak Snow Depth Distribution

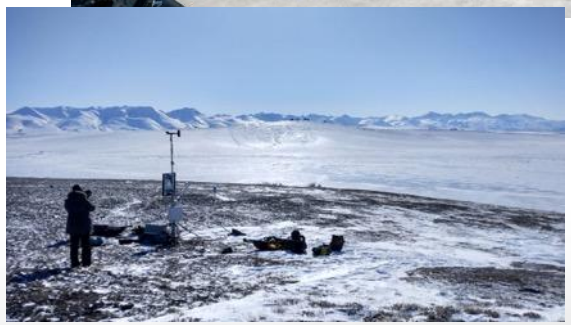
Teller Watershed



>33,000 measurements



2017, **2018***, 2019, **2022***, 2023 (**bold**, measurements at both locations)



NGEE Arctic
Next-Generation Ecosystem Experiments

Bennett et al. 2022, Crumley et al. 2024, Shirley et al. 2025

Snow Sensor Monitoring Network

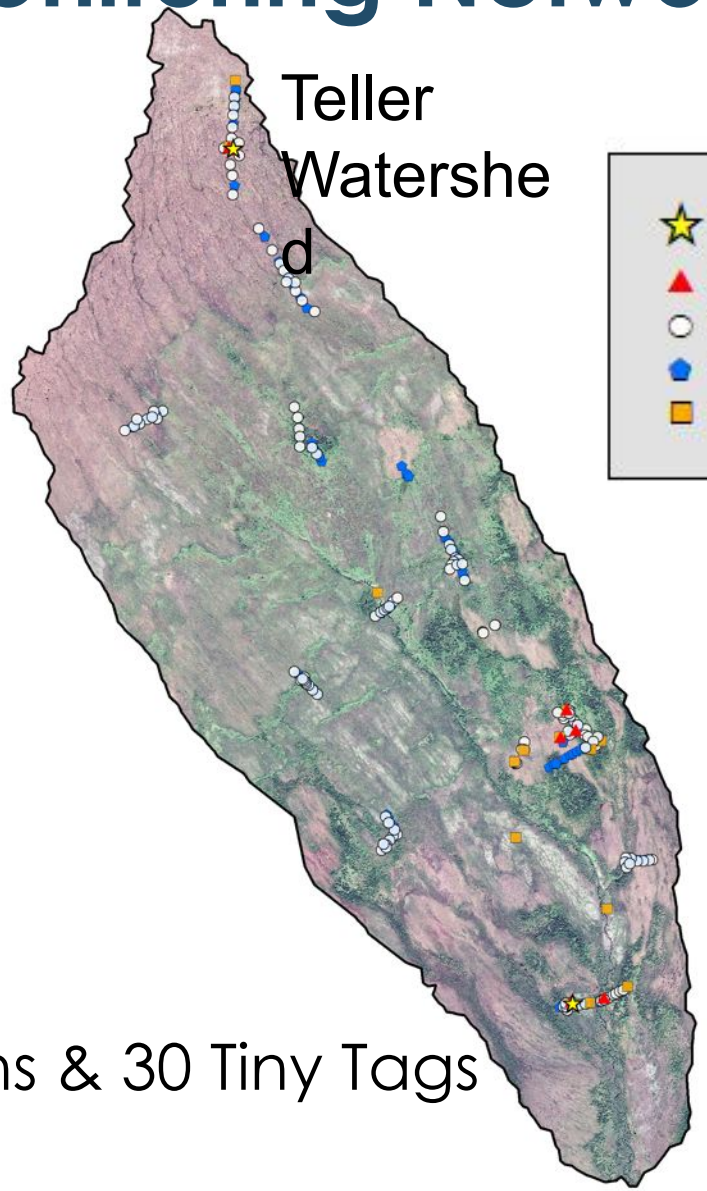
Tiny Tags temperature sensors

iButtons temperature sensors

sonic snow sensors

Surface Only

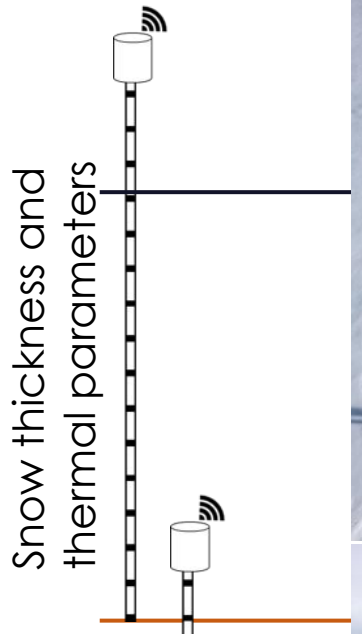
151 DTPs
234 iButtons & 30 Tiny Tags
12 sonics



Total: 427 Sensors

2019, 2021-2024

Surface and Ground

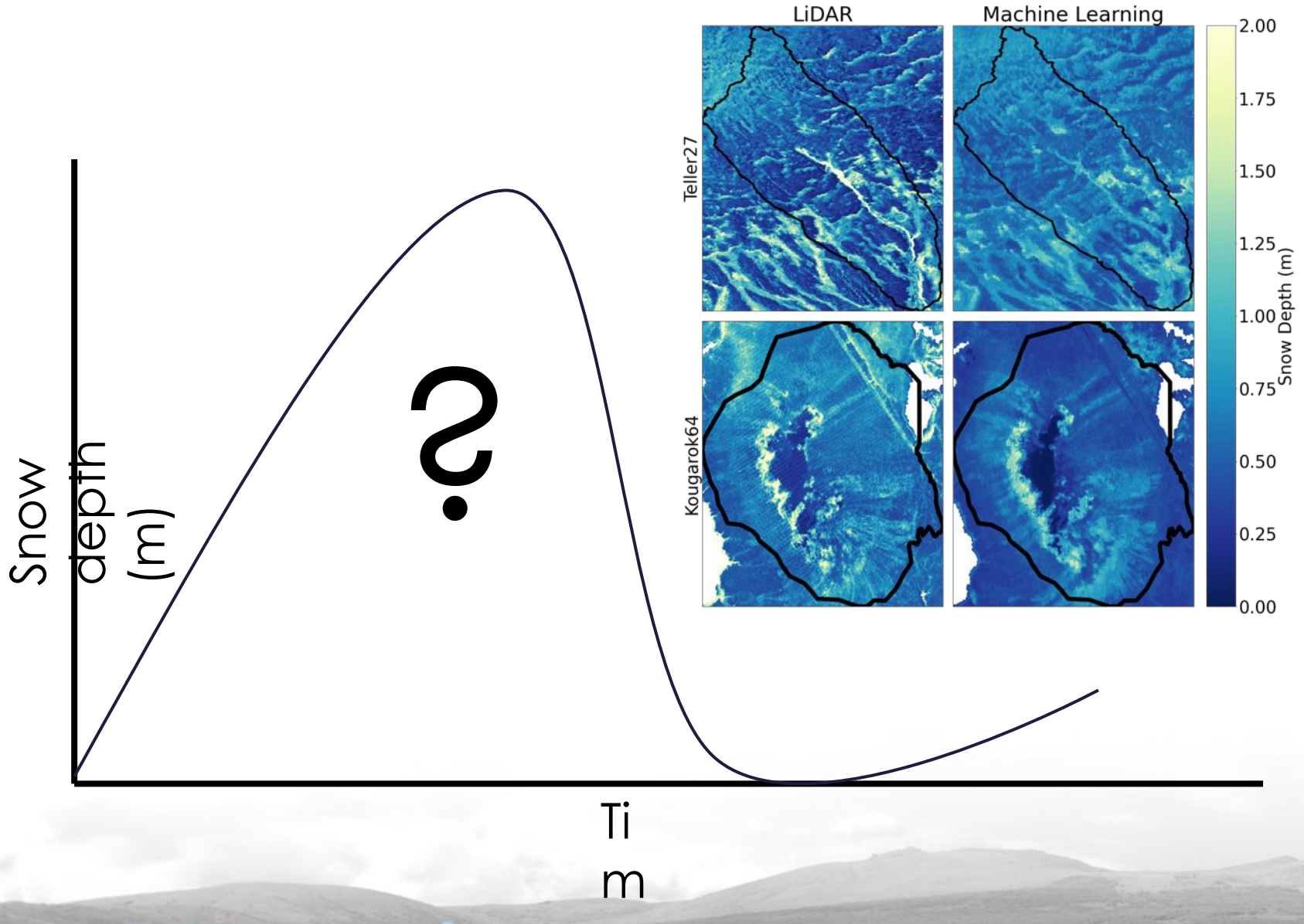


Distributed Temperature Profile (DTPs)

NGEE Arctic
Next-Generation Ecosystem Experiments

Wang et al. 2024, 2025; Dafflon et al., 2022; Wielandt et al., 2021, 2022; Gasarch et al. 2024; Lathrop et al. 2025

Peak Snow Distribution to Snow Depth Time Series



- Builds on research to estimate peak snow distribution (Bennett et al. 2022) using a random forest approach
- Limited to only ground surface temperature variability
- Trained on the DTPs
- Applied to iButtons/Tiny Tags

Bachand et al. 2025, Wang et al. 2025

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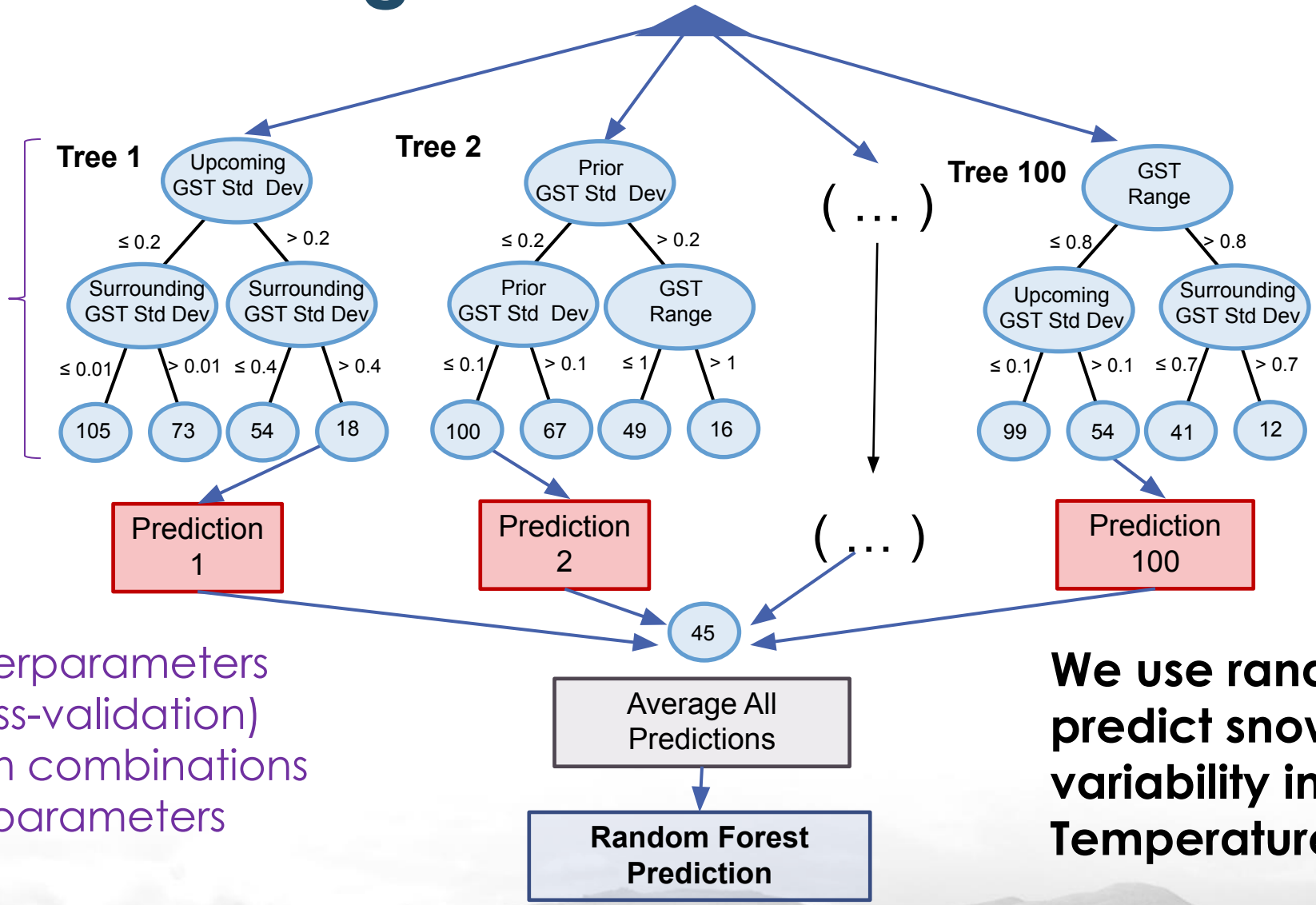
Random Forest Regression



Depth of trees

Number of trees

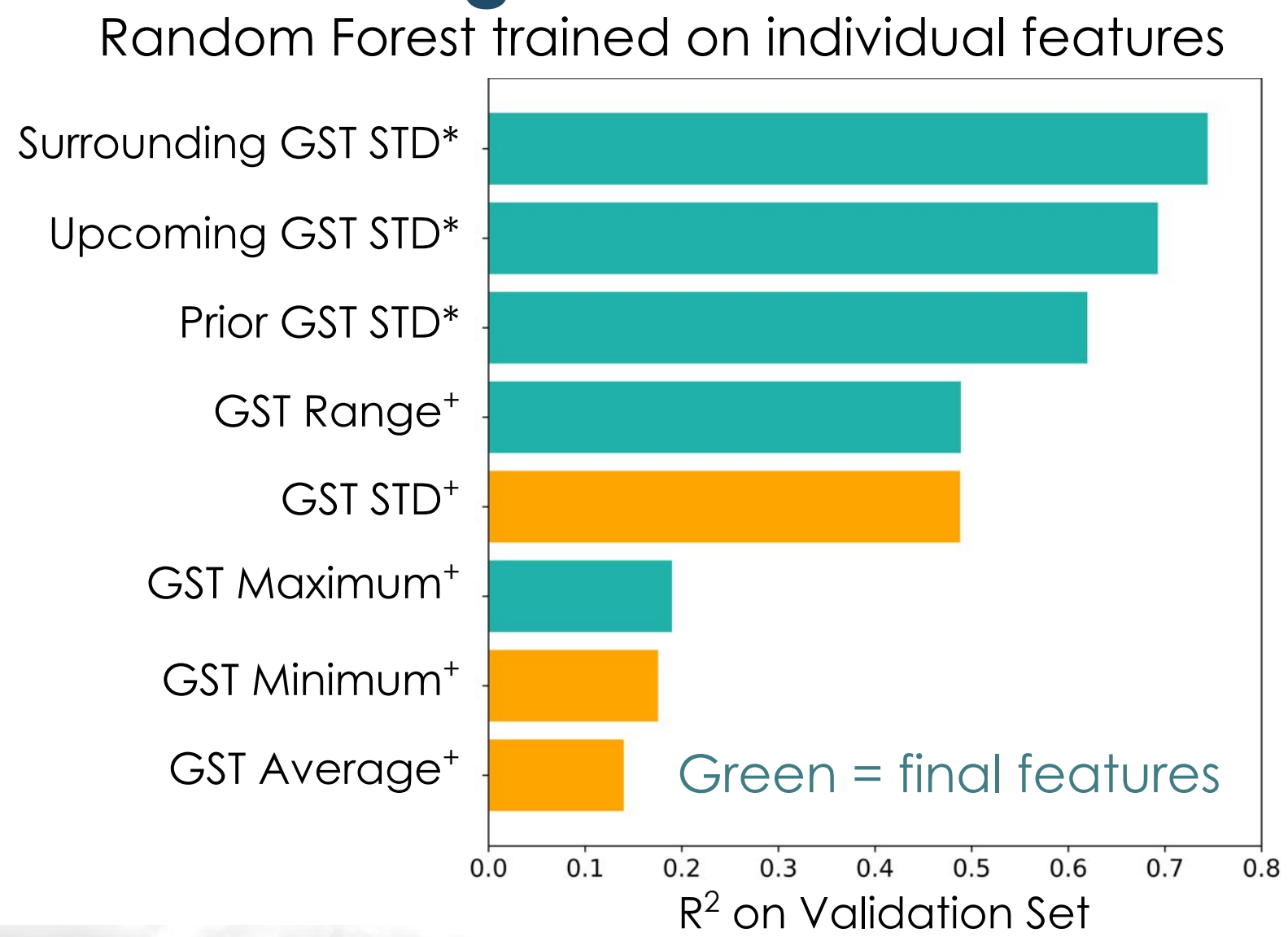
Tuned hyperparameters (K-fold cross-validation) using random combinations of hyperparameters

We use random forest to predict snow depths from variability in Ground Surface Temperature (GST)

Bachand et al. 2025

Random Forest Regression

GST=ground surface temperature
STD=standard deviation
* 30-day window +daily



All Features are derived from 4-hourly Ground Surface Temperature (GST) data.

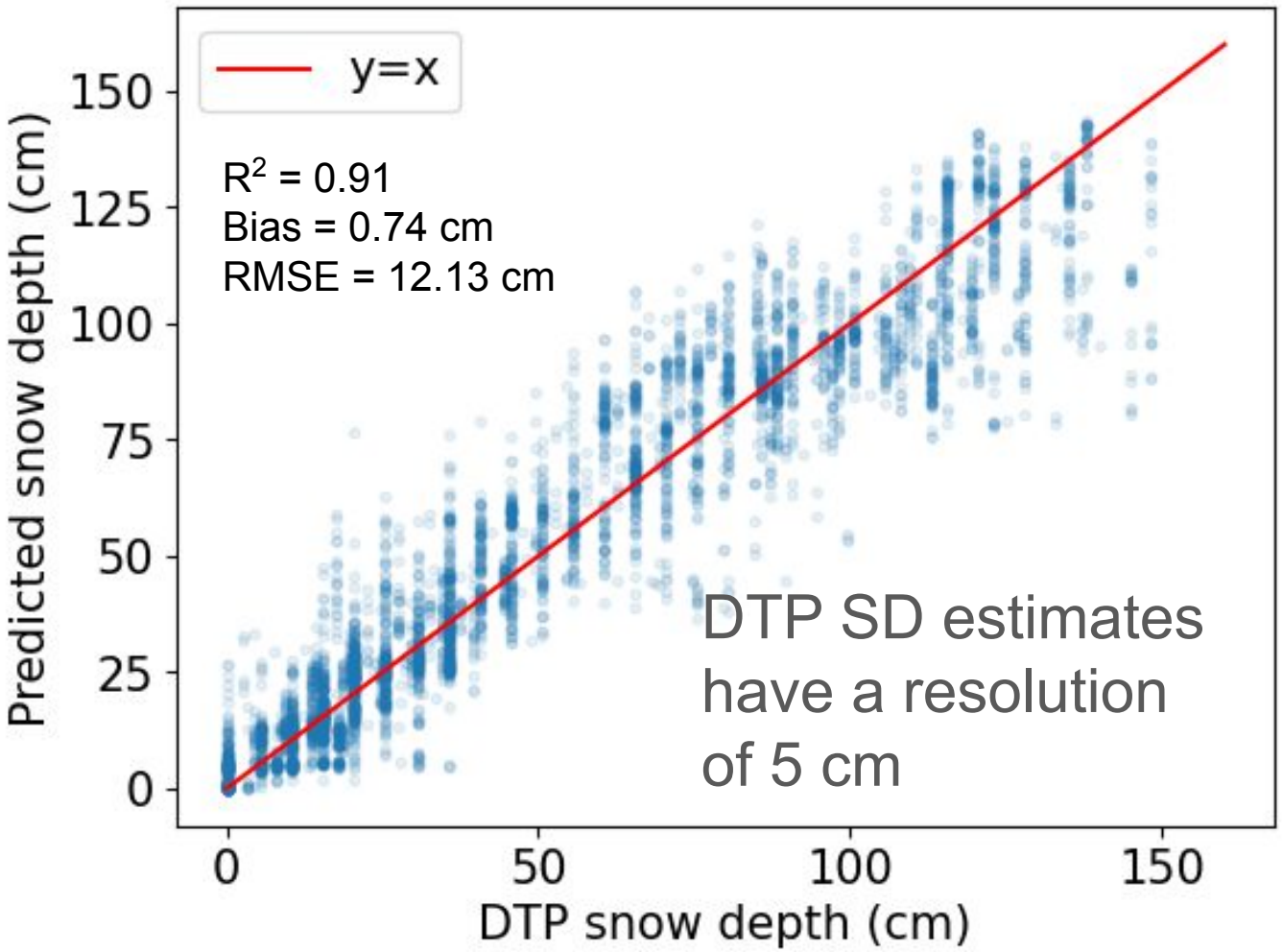
GST is recorded at the snow-ground interface. The sensors are not buried under the ground.

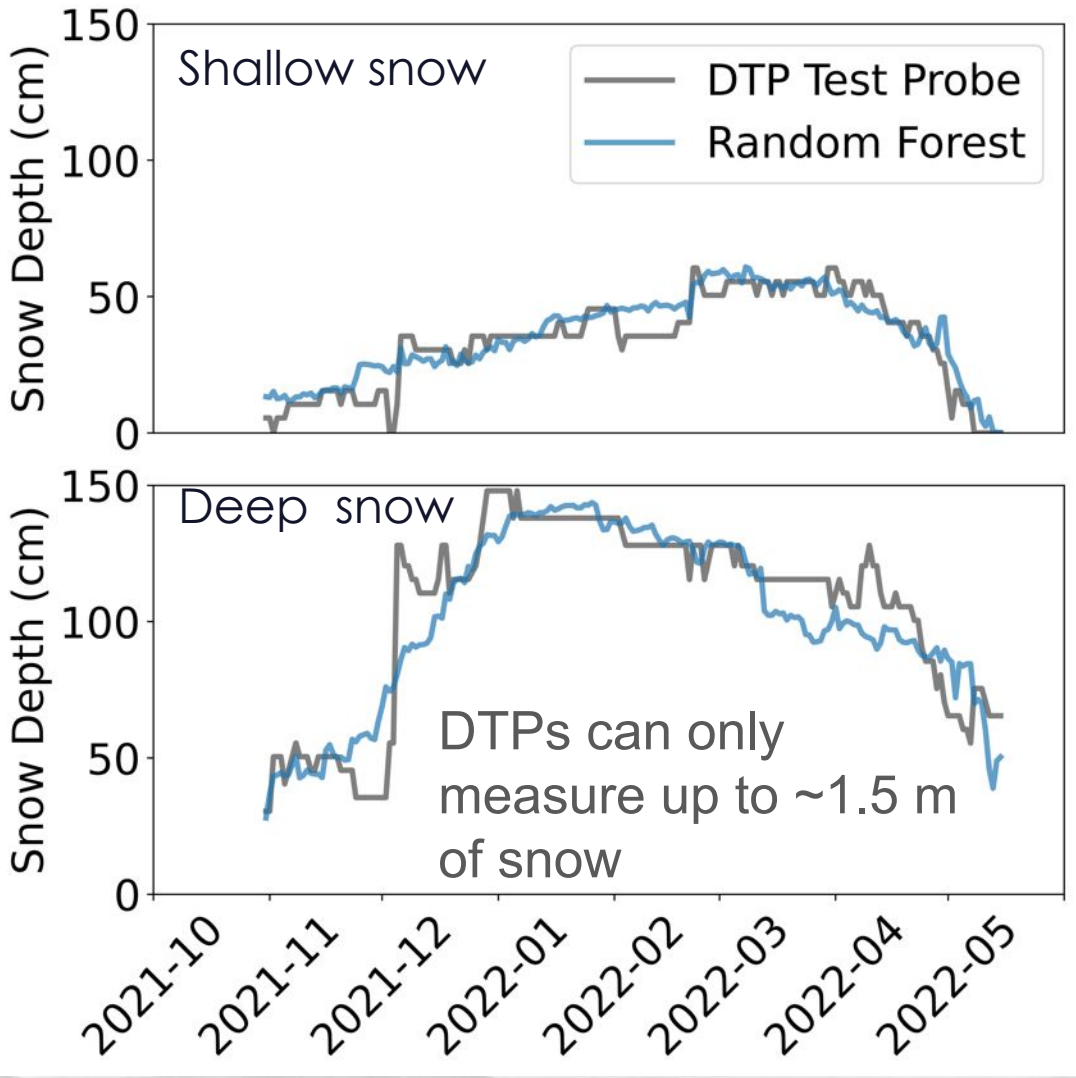
Also tested air temperature-derived features, but these only marginally affected model performance.

Bachand et al. 2025

Results – Seward Peninsula

Test Set Performance

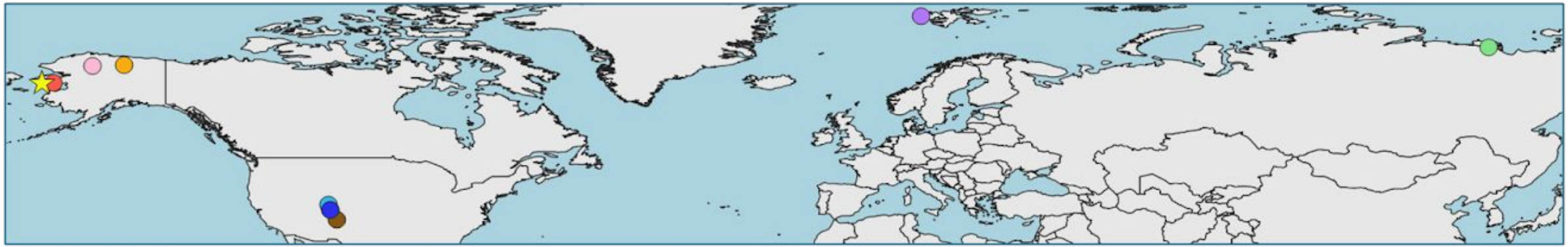


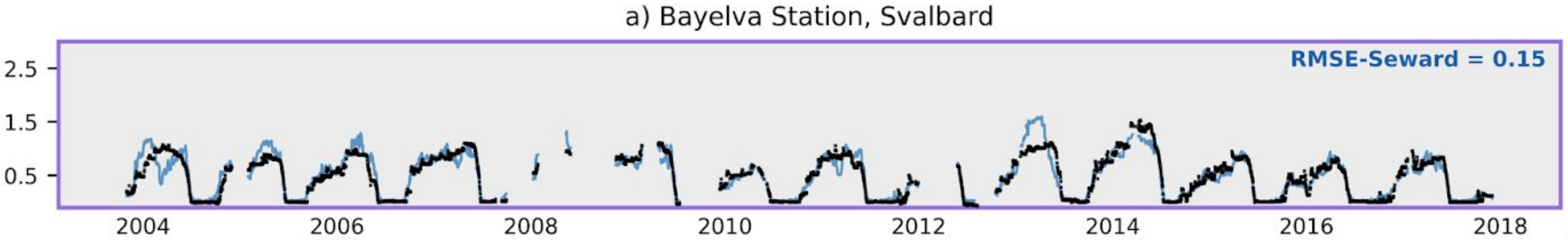


Bachand et al. 2025

Results – Svalbard, Norway

Bayelva Station, Svalbard, Norway
Snow Depth Estimates (m)





Random forest model trained on data collected on the Seward Peninsula applied to Svalbard site

Data: Boike et al. 2018
https://doi.org/10.1594/PANGAEA.880120

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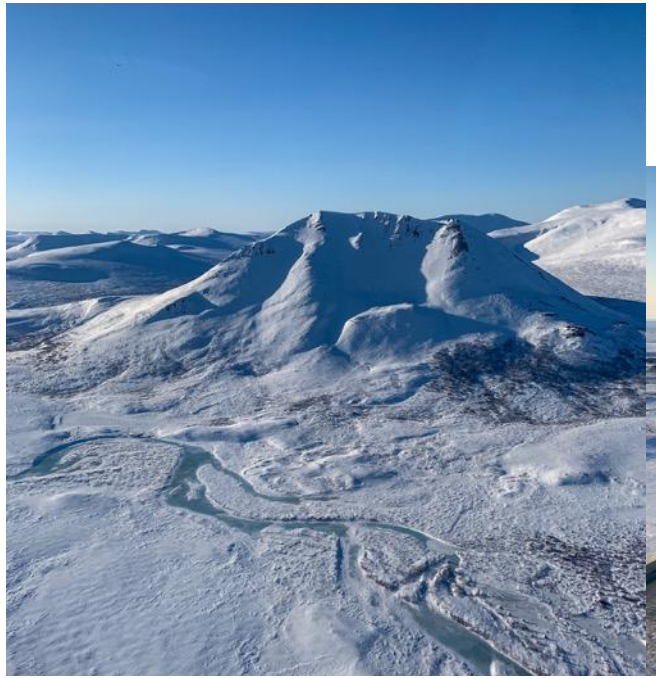
Bachand et al. 2025

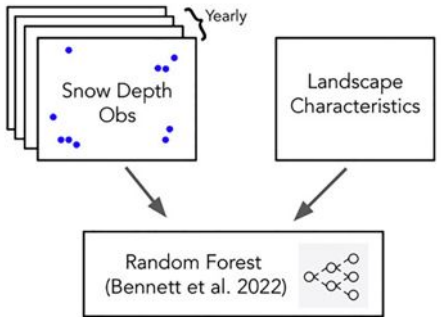






Models - Hybrid snowpack model (Physics + ML)

Random Forest ML



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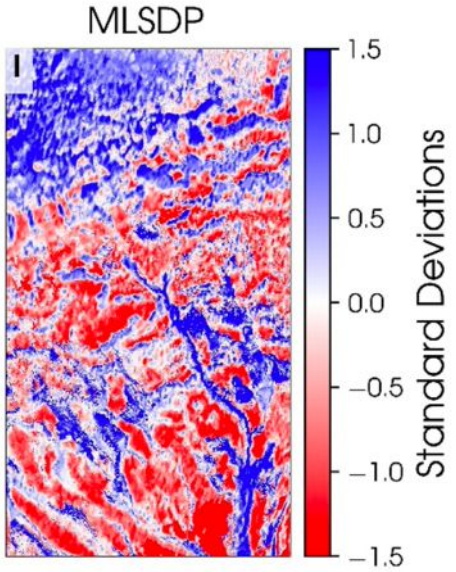
Snow Distribution Pattern



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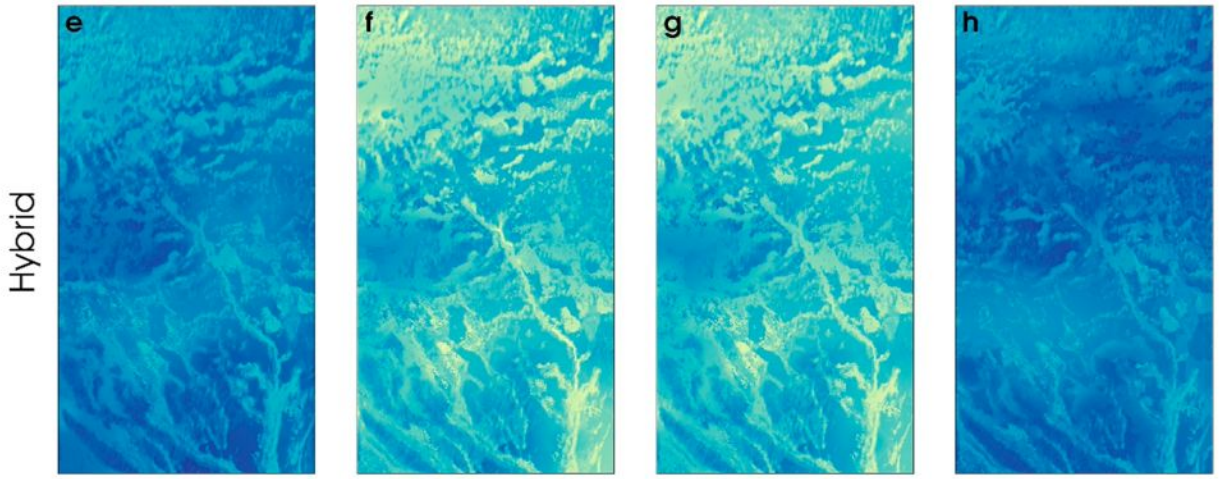
Snow Depth Pattern

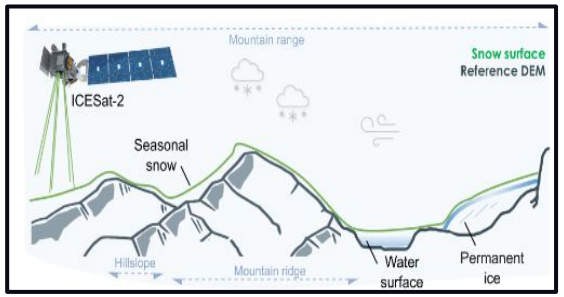


April 2017 **April 2018** **April 2019** **April 2022**

Crumley, R.L., Bachand, C.L. and Bennett, K.E., 2024. Snow distribution patterns revisited: A physics-based and machine learning hybrid approach to snow distribution mapping in the sub-Arctic. Water Resources Research, 60(9), p.e2023WR036180.

Synthesis – Snow

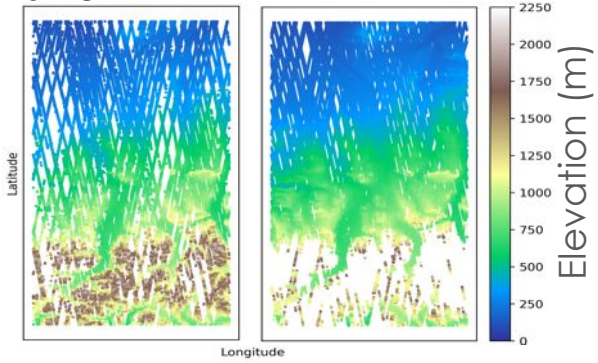
ICESat II Overview



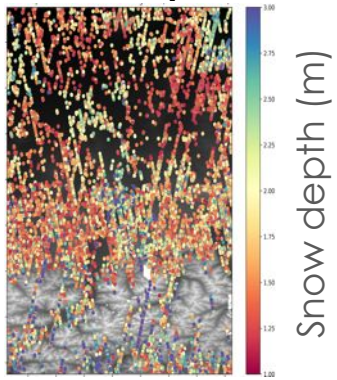
Modified from Liu et al. (2025)

ICESat II SNOW-FREE

ICESat II SNOW-ON



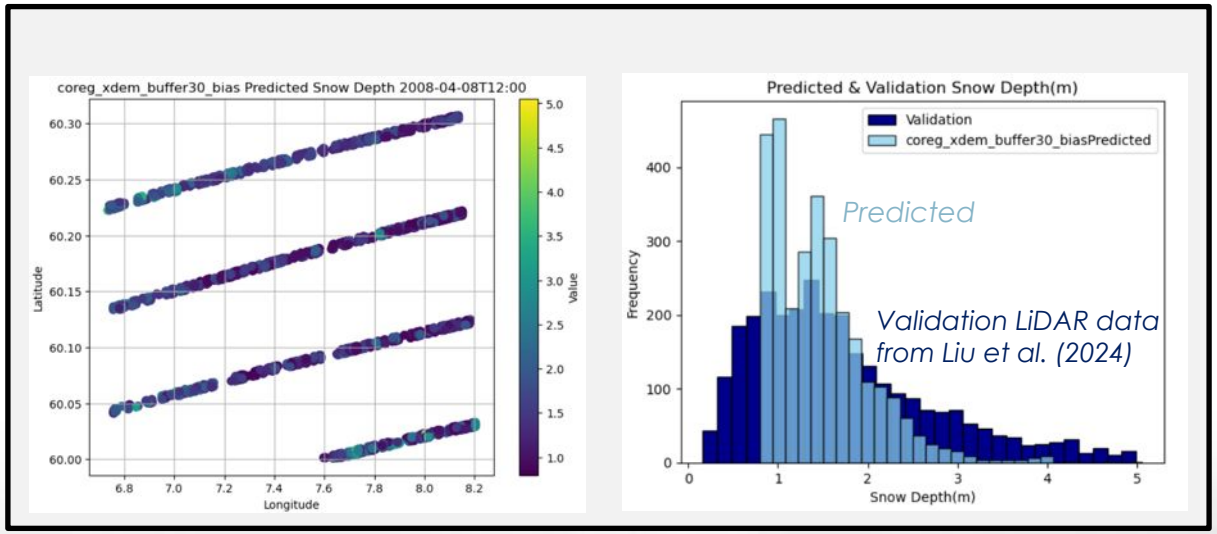
Calculated snow-depth



ML Model: Topography, ERA5 Forcing ERA5 SWE, Wind

Predicted snow depth

- ICESat II: Photon counting laser altimeter
- Snow free and snow off ICESat data gives snow depth
- Trained Random Forest ML model on topography and forcing data to predict snow
- Can potentially provide snow depth down to 2 m (ArcticDEM)



Preliminary prediction of LiDAR validation in Norway

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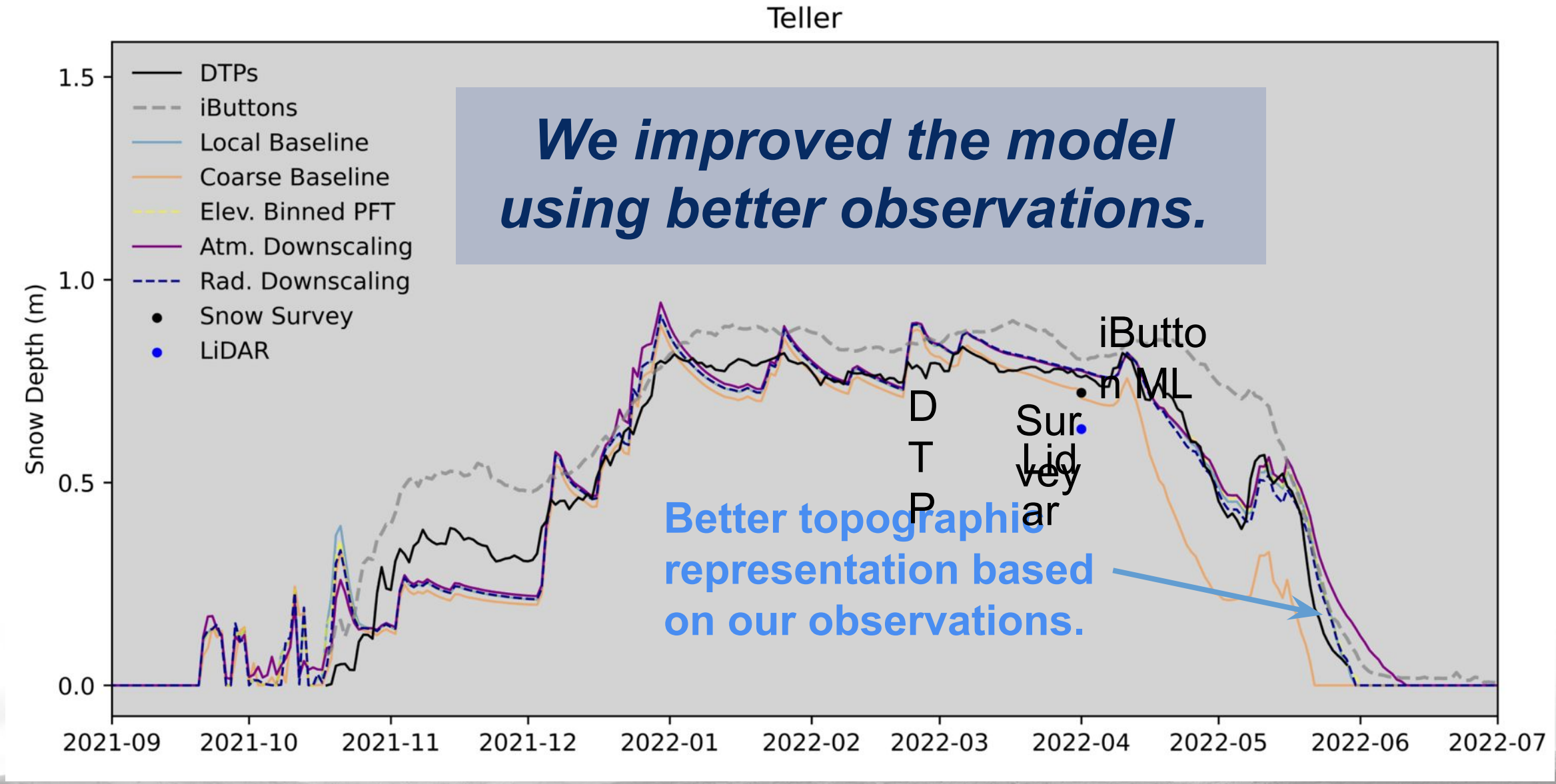
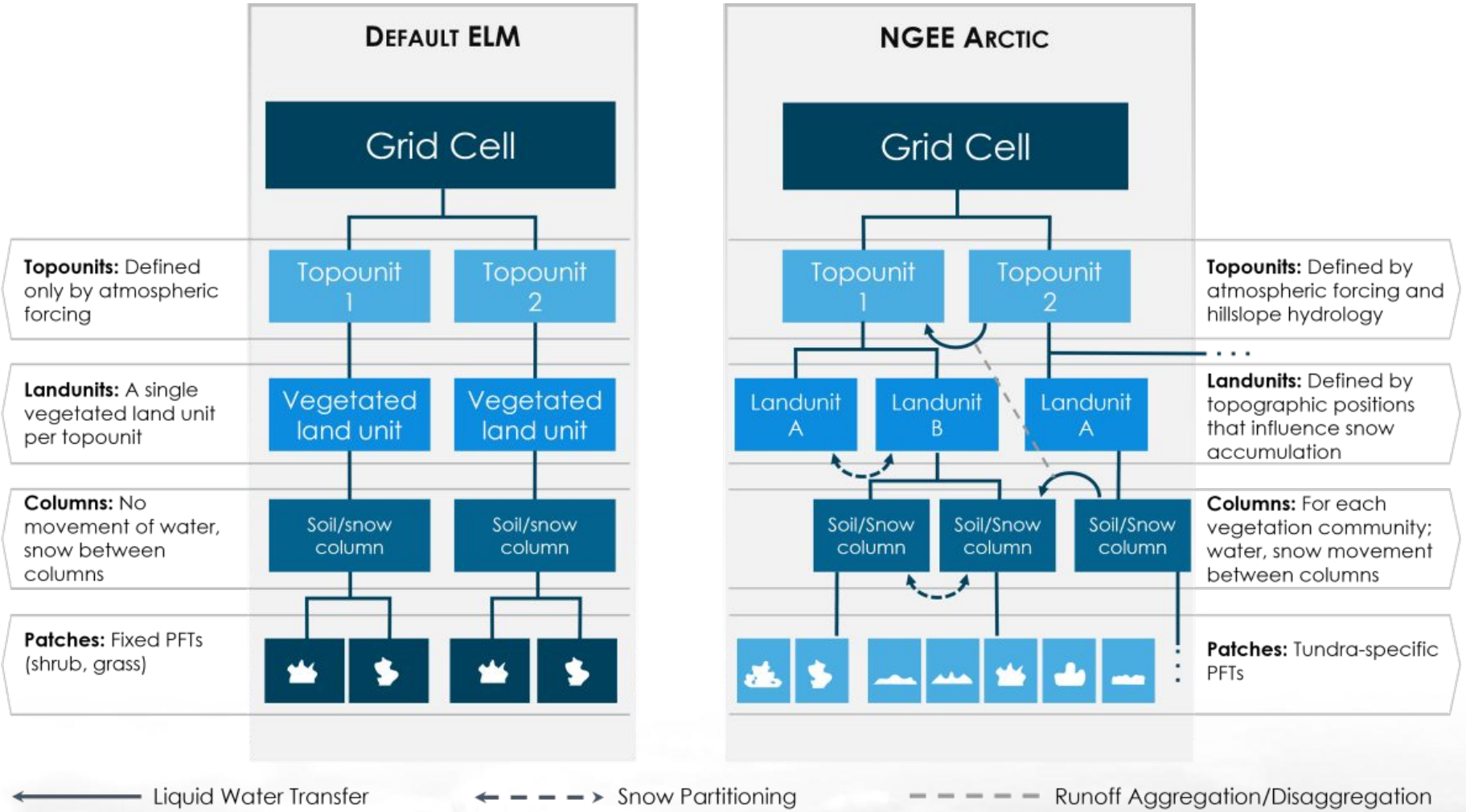
Physics Model – Snow Improvements



Snow Improvements 4 – Snow and Vegetation Feedbacks



We will represent movement of snow across topounits and shrub interactions.

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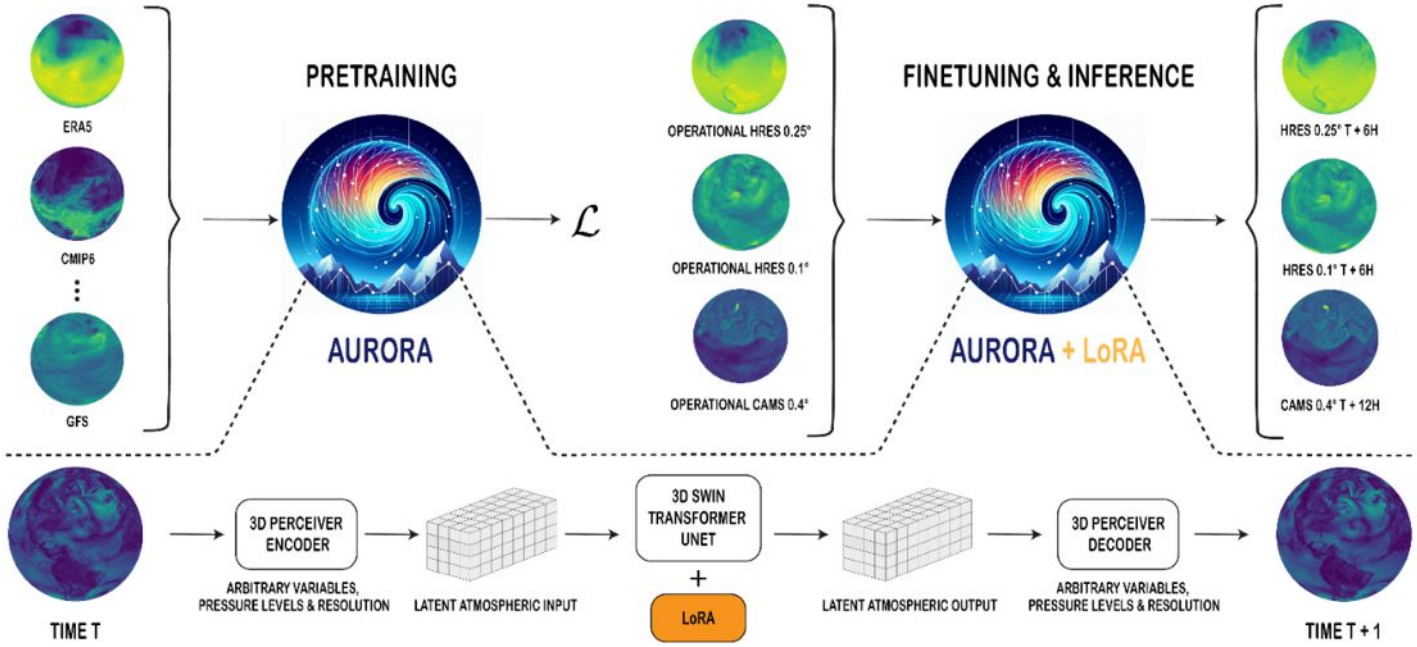
Next-Generation Ecosystem Experiments

AI foundation and time-series models for earth system and weather predictions: snow case studies

Can an AI earth system model be used in place of emulators/ML models?

Does fine-tuning improve its representations?

GENESIS Team 2026



Bodnar et al, 2024

Aurora

Chronos

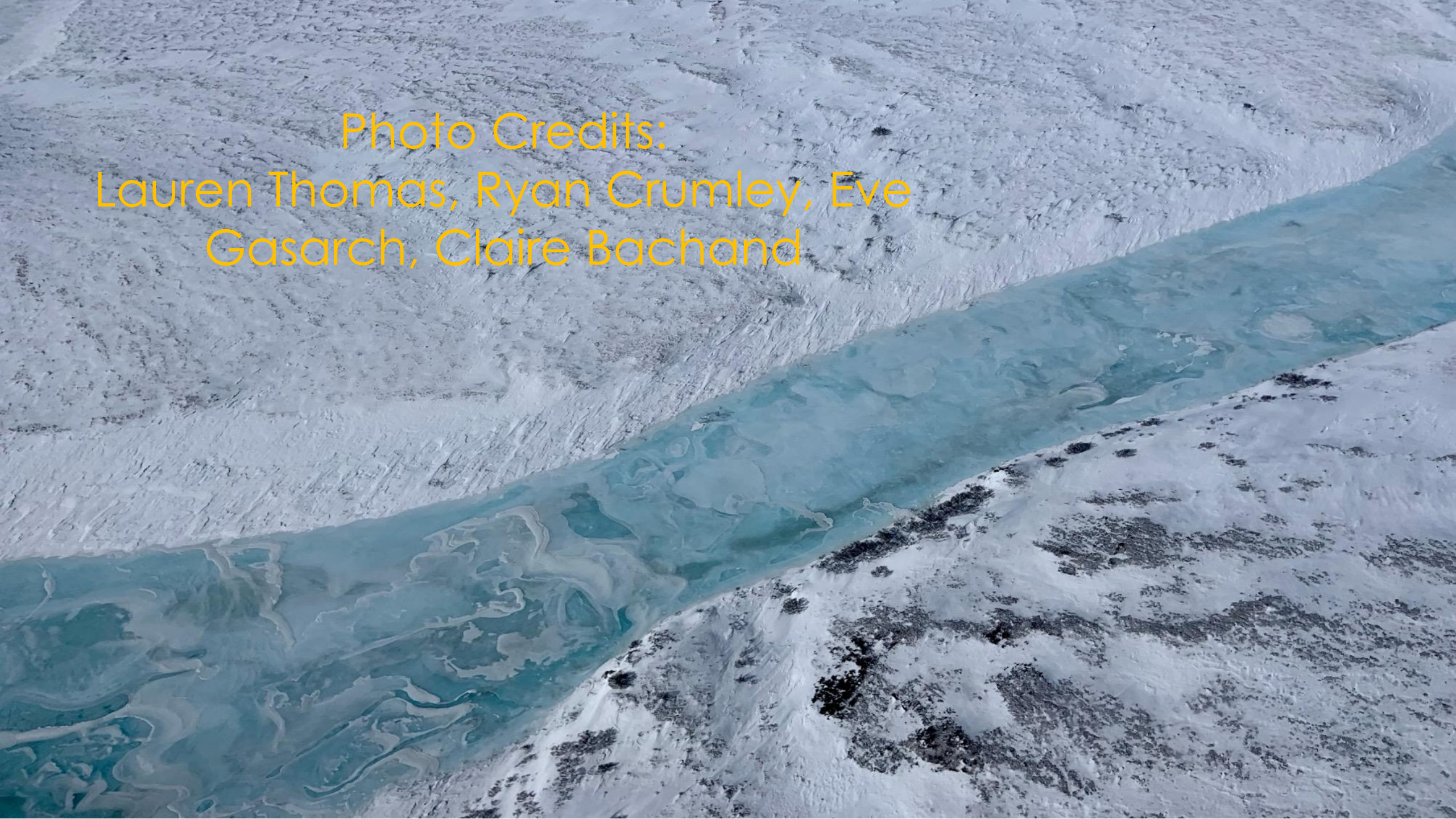


Photo Credits:
Lauren Thomas, Ryan Crumley, Eve Gasarch, Claire Bachand

Acknowledgements

NGEE Arctic is supported by the Biological and Environmental Research Program in the Department of Energy's Office of Science.

We thank our partners from the Native Communities in Alaska for allowing us to conduct our research on the traditional homelands of the Iñupiat, including the UIC Science, Mary's Igloo, Council, Sitnasuak, and Bering Straits Native Corporations.

We also thank our Science Advisory Board as well as colleagues in Utqiaġvik and Nome, Alaska, for their insights and support.

NGEE Arctic is underscored by a foundation of open science and data sharing and a safe, inclusive project culture.

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ESS Environmental System Science

Questions?

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