The NASA SnowEx Mission (2017-2023)

Presented by: Carrie Vuyovich, SnowEx 2023 Project Scientist, NASA GSFC

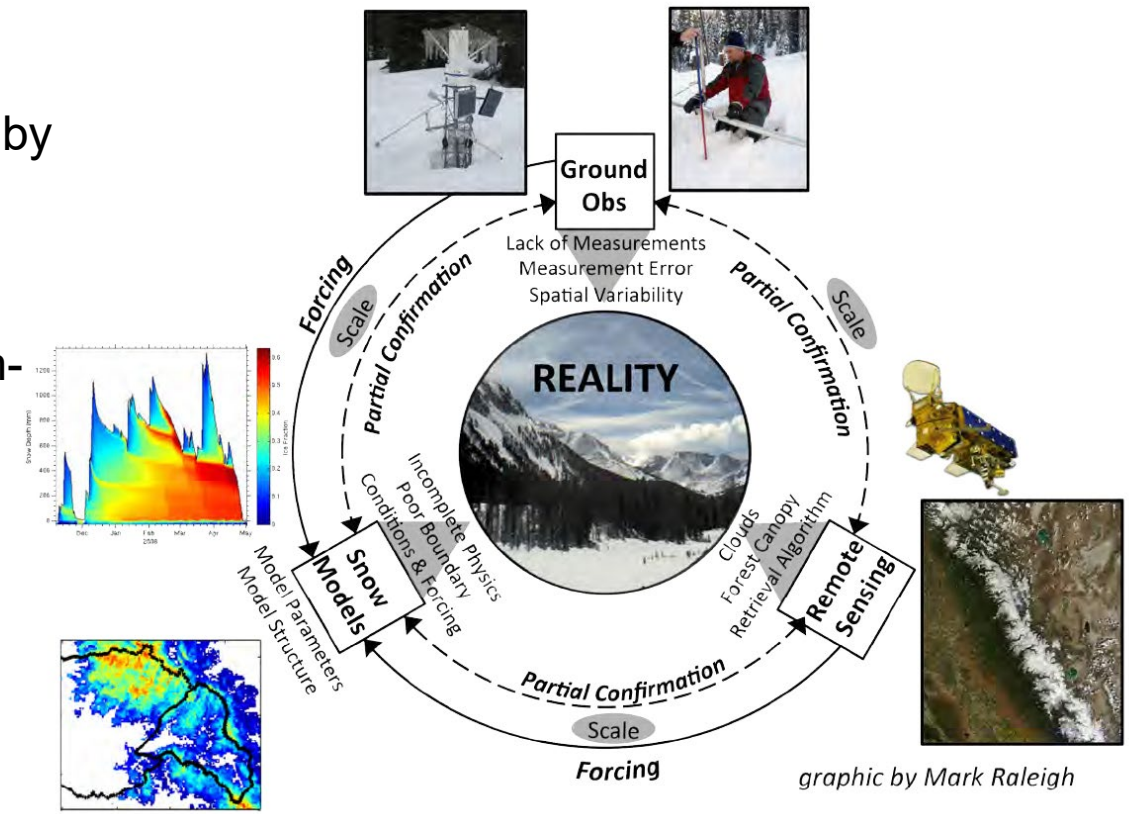
Photo credit: Kate Hale

NASA Snow Community Meeting
14-15 August 2024, Boulder, CO

Why is seasonal snow important?

- Approximately 2 billion people depend on seasonal snow for water supply. Seasonal snowmelt - over 70% of water resources in Western U.S.
- Massive impact on surface albedo and global energy balance – over 1/3 of the Earth's land surface covered by snow annually
- Contributes to disasters (floods, droughts, avalanches, wildfires)
- Patterns are changing - earlier melt, more frequent rain-on-snow, changing snowlines
- But challenging to measure and model:
  - Length scale of variability in depth 20-200m
  - Dynamic changes on time scales of hours-days
  - No current satellite remote sensing product for SWE in mountainous regions
  - Models show widespread both temporally and spatially, largely due to uncertainties in forcing data

Solution to global snow monitoring: fusion of remote sensing, models, ground obs.



What is SnowEx?

SnowEx is a multi-year coordinated airborne and ground experiment to evaluate different snow remote sensing technologies throughout the season in various landscapes. Results will help inform a future snow satellite mission.

snow.nasa.gov

NASA SnowEx Mission and community events 2013-2024

NASA Snow community meeting
3 legs of stool, airborne exp needed, gaps, SINTER formed

Boulder 2013

Community meeting
impact of forests on spaceborne SWE & albedo defined as priority gaps

Seattle 2016

Grand Mesa, CO
Senator Beck, CO
Active/passive MW, albedo, lidar
Field effort w/ pits, depths, extensive ground-based remote sensing

SnowEx 2017

Community Meeting
Summary of results, NSIDC data pubs, Working group of THP16 PIs formed

Longmont 2017

Community Meeting
SnowEx Science Plan, SnowEx 2020 Experimental Plan, Hackweek discussions

Baltimore 2019

NASA/CUAHSI SnowSchools 2016-2024

UAVSAR flies 16 sorties over 14 WUS sites, local teams deploy, 400+ snowpits, GPR, tower radar, LWC

SnowEx 2020-2021 Time Series

Grand Mesa, CO
5 aircraft, 7 airborne instruments, 3 week intensive field campaign

SnowEx 2020

Community meeting
THP Snow Roadmap, future mission proposal opportunities, snow OSSE, SnowEx priorities

Virtual 2020

Fairbanks & North Slope, AK
Tundra & Boreal forest focus, Radar SWE, lidar, SfM, multispectral
2 fall, 2 spring campaigns

SnowEx Alaska 2022-23

NASA Snow community meeting
Define remaining gaps. Form new collaborations. Plan for next decadal survey, NISAR, future EVS/EVM

Boulder 2024

SnowEx Hackweeks 2020-2024

SnowEx Science Plan

The Science Plan lays out a recommended SnowEx plan to test sensor capabilities and sensitivities and address the most critical gaps in snow remote sensing. Identified gaps in current capabilities:

- Prairie snow
- Tundra snow
- Mountain Snow
- Maritime snow
- Forests
- Wet snow
- Snow surface energetics

Durand, M., C. Gatebe, E. Kim, N. Molotch, T. Painter, M. Raleigh, M. Sandells, and C. Vuyovich, NASA SnowEx Science Plan: Assessing approaches for measuring water in Earth's seasonal snow, Version 1.6,

NASA SnowEx Science Plan Capabilities Chart

Current capabilities from SnowEx Science Plan

Rows =
- sensing techniques
- models

Columns =
- gaps,
- snow parameters,
- space potential

SWE and Snow Depth		Snow Characteristic			Gap Capabilities						
Type	Snow Sensing Technique	Snow Depth	SWE	Melt	High-Res	Wet snow	Deep Snow	Forests	Complex Terrain	Shallow Snow	Clouds
SWE via Snow Depth	Spaceborne Lidar										
	Ka-band InSAR										
	Dual band Ku/Ka altimetry										
	SfM/Stereo										
	Wideband Radiometer										
Volume scattering	X-/Ku-band SAR										
	Passive Microwave										
	C-band SAR										
Signal interferom	L-Band/C-band InSAR										
	SoOP										
Airborne / Ground Only	UWB FMCW Radar										
	Airborne Lidar										
	Gamma										

Modeling		Snow Characteristic			Gap Capabilities						
Type	Snow Estimation Technique	Snow Depth	SWE	Melt	High-Res	Wet snow	Deep Snow	Forests	Complex Terrain	Shallow Snow	Clouds
Modeling	Physical Modeling										
	Radiative Transfer Modeling										
	Data-driven modeling										

Surface Energetics	Snow Characteristic			Gap Capabilities						
Snow Sensing Technique	Albedo	SCA	Melt	High-Res	Wet snow	Deep Snow	Forests	Complex Terrain	Shallow Snow	Clouds
Imaging Spectrometer										
BRDF										
Thermal IR										

Capability Color Key

- Demonstrated, TRL>5
- Potential, TRL 3-5?
- Potential, TRL 1-2?
- no capability

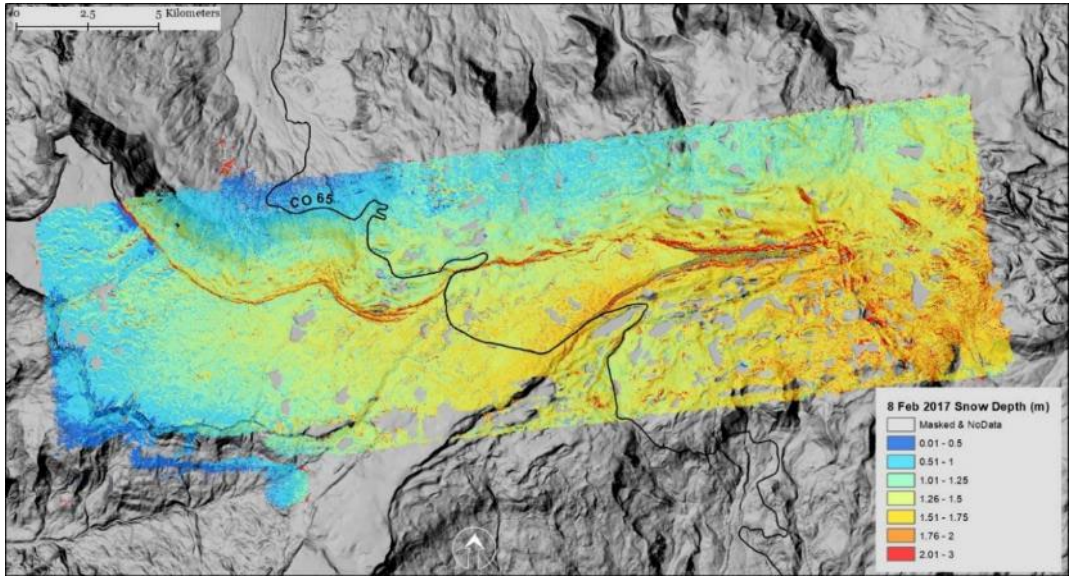
NASA SnowEx 2017

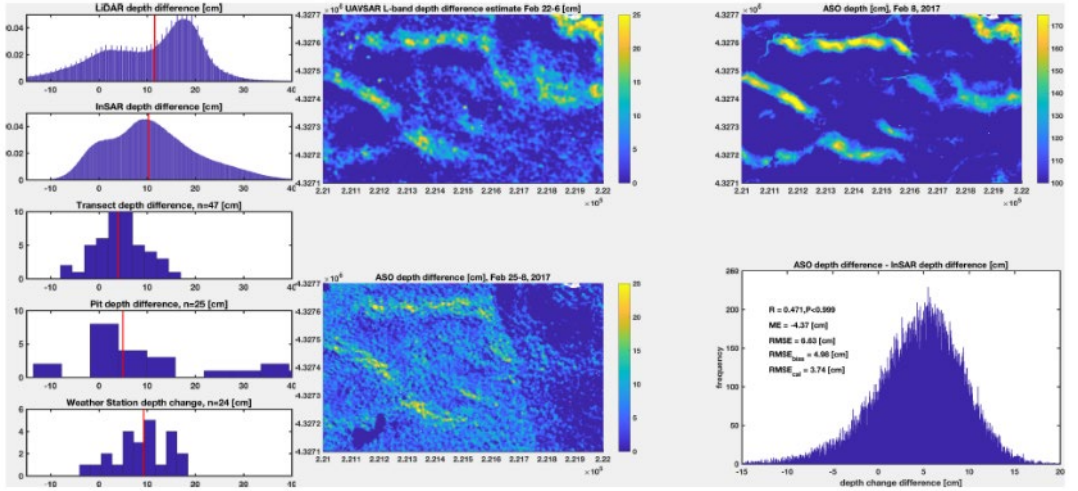
Primary Science Questions:

1. What is the distribution of SWE and the snow energy balance in different canopy types, canopy densities, and terrain?
2. What is the sensitivity and accuracy of different SWE sensing techniques in different canopy types, canopy densities, and terrain?
3. What is the optimum combination of sensing techniques to measure SWE globally?

Highlights:

- 100 participants (scientists, students, international)
- 24 institutions
- 5 of 5 aircraft & 9 of 10 sensors flown
- 154 snow pits; 165 transects
- 30 ground remote sensors
- Extensive community-building activities
- Snow.nasa.gov website stood up
- 1st SnowEx workshop Aug 2017; 92 attendees





L-band InSAR results showing agreement with lidar and depth obs

2020 Experiment Plan

NASA SnowEx 2020

Primary Objectives:

1. Test L-band InSAR phase change for Δ SWE/snow depth among different snow climates & landscapes
2. Test SWE retrieval from active & passive microwave
3. Value of satellite thermal IR observations for energy balance & modeling

Campaign design:

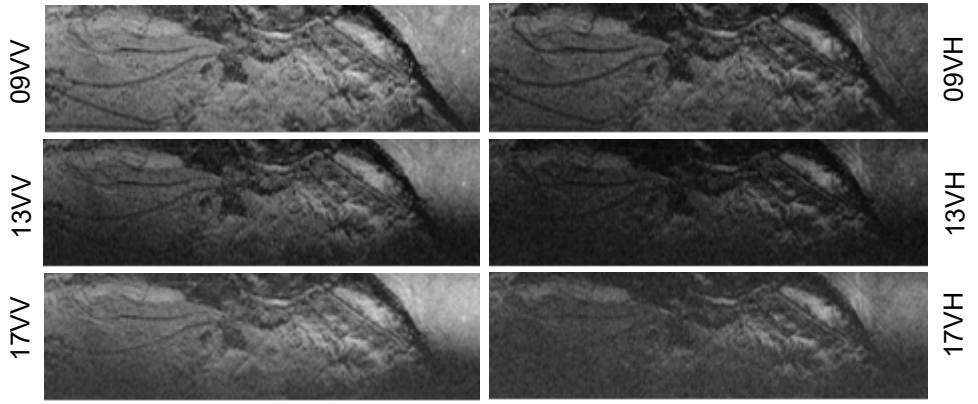
- Over 100 students, researchers from 20+ organizations
- Time Series of weekly to biweekly UAVSAR flights, Dec-March
- Intensive observing period (IOP) in Grand Mesa, CO, Nov/Jan/Feb

Data Collected

Ground observations collected:
- Snow Pits (>400)
- Snow depth transects
- Snow interval boards
- Over 10 different ground-based remote sensing instruments, including (SMP, SSA, Radiometers, various-frequency GPR, TLS, soil moisture sensors)

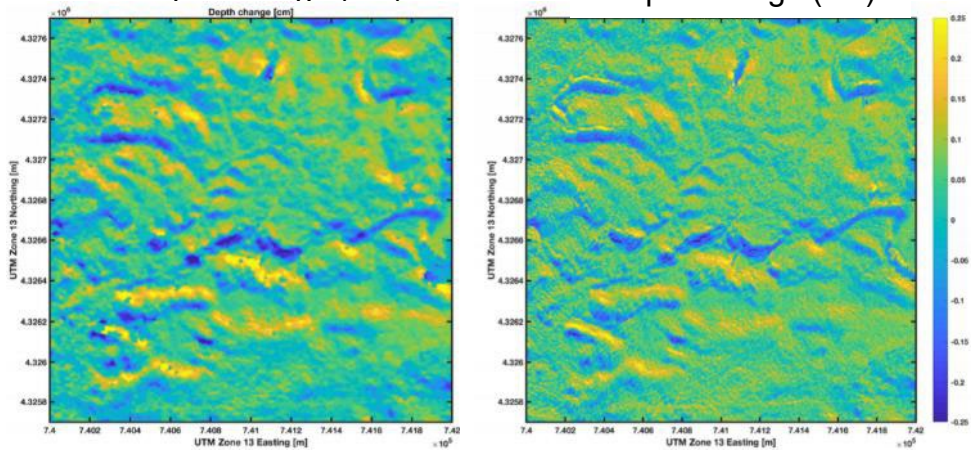
Airborne observations collected:
- L-band InSAR (UAVSAR)
- Active/Passive microwave (SWESARR)
- Thermal IR (U. of Washington)
- Reigl 1560i Lidar (Quantum Spatial)
- CASI hyperspectral (Quantum Spatial)
- FMCW Radar (University of Alabama)
- Gamma Airborne Survey (NOAA NOHRSC)

Satellite obs:
- GOES – 16/17
- ASTER
- ECOSTRESS
- ICESat-2
- WorldView
- Sentinel-1



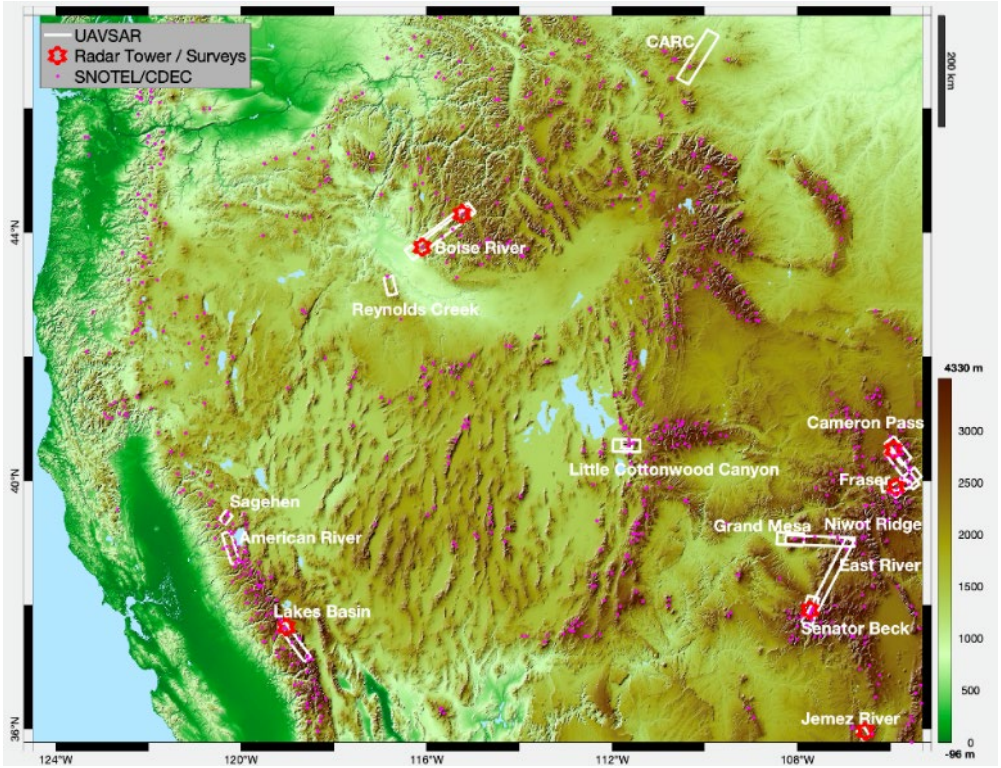
SWESARR Radar data collected over Grand Mesa, CO during the Feb 2020 IOP. The data were processed with a Time Domain Back Projection algorithm and used for snow water equivalent (SWE) retrieval.

L-band InSAR Depth change (cm) | Lidar Depth change (cm)



Preliminary results from SnowEx 2020 show good snow depth change agreement between L-band InSAR and lidar data: R-value = 0.76, RMSD=4.7cm depth, 0.9cm SWE.

SnowEx 2020 & 2021 Campaign sites
Dec, 2019 – Mar 2020; Dec 2020 – May 2021



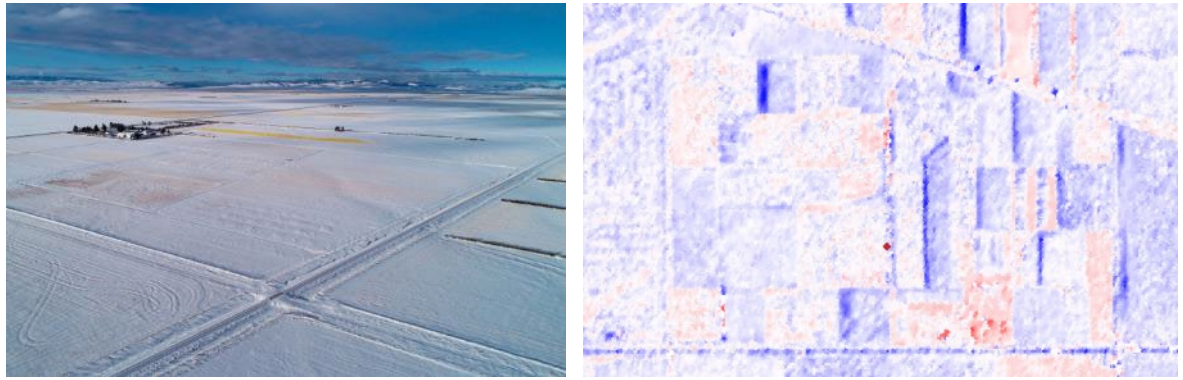
NASA Airborne observations		
Observation	Sensor	Aircraft
L-band InSAR	UAVSAR (JPL)	JSC GIII
Lidar and Hyperspectral	Reigl 1560i and CASI (QSI)	Dynamic Aviation A90
VIS-IR Imaging Spectrometer	AVIRIS-NG (JPL)	B-200 King Air

2021 Experiment Plan

NASA SnowEx 2021

Primary Objectives:

1. Quantify the accuracy of L-band InSAR SWE retrievals in preparation for NISAR
2. Define the snow conditions where L-band InSAR is likely to maintain coherence
3. Evaluate the spatiotemporal variability in snow albedo, the controls on this variability, and the uncertainty of remote sensing measurements relative to mountains, forests, and as snow albedo declines over time.
4. Characterize the spatial heterogeneity of snow characteristics at an agricultural site

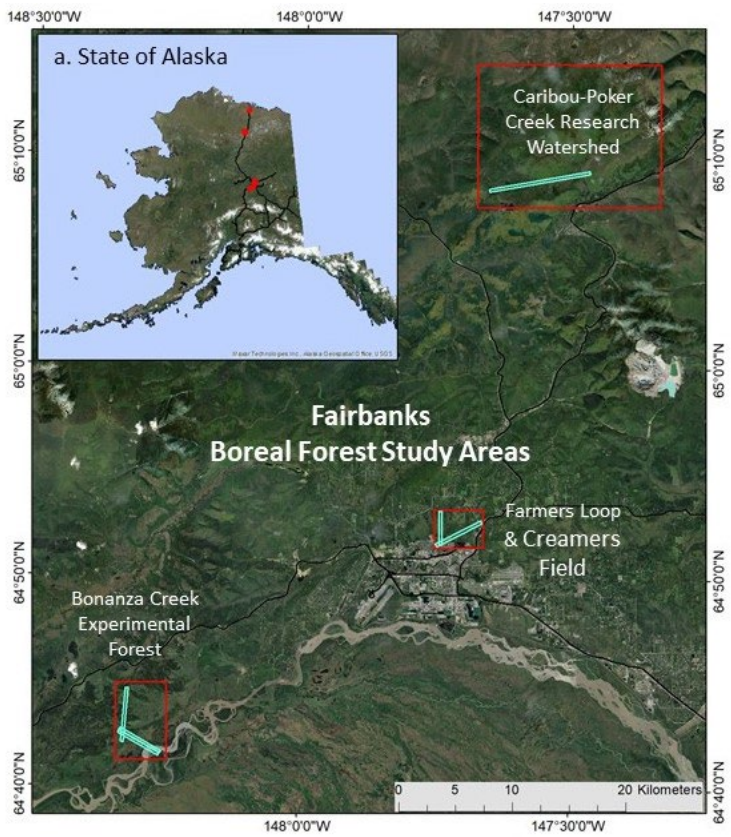


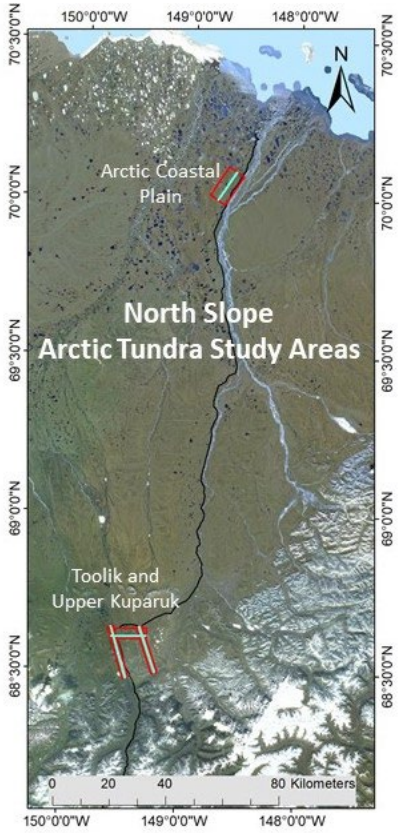
Prairie site at Central Agricultural Research Center, MT (left) showing shallow snow redistributed by wind into ditches and fields. UAVSAR image of CARC (right).

NASA SnowEx 2023

2023 Experiment Plan

Understanding unique snow remote sensing challenges in the tundra and boreal forest





Primary Objectives:

1. SWE: How do microstructure accuracy and scaling issues impact the use of models to inform Ku-band volume scattering retrievals in tundra snow? How much does Ku-band penetrate forest canopies in boreal forests?
2. Snow depth: How well do snow depth retrieval methods (e.g., lidar and SfM) work where "bare earth" surfaces fluctuate, due to the variable permafrost, water, and vegetation characteristics ubiquitous at high latitudes?
3. Snow albedo: What is the nature of spatial variability of snow reflectance/albedo and physical properties in the boreal forest, and how does it change with scale?

Data Collected

Ground observations:
- Snow Pits (>169)
- Snow depth (>30,000)
- Snow depth profiles (>3500)
- Snow interval boards
- Over 10 different ground-based remote sensing instruments, including (SMP, SSA, various-frequency GPR, C-band radar, TLS, LWC)

Airborne observations:
- Active/Passive microwave (SWESARR)
- Riegl VQ-580ii Lidar (UAF)
- Nikon D850 optical imager (UAF)
- VIS-IR Imaging Spectrometer (AVIRIS-NG, JPL)

Satellite obs:
- ICESat-2
- Worldview
- Pleaides-HR
- BlackSky
- Planet SkySat-C
- Capella
- ICEYE
- Sentinel 1A

Community Training

Hackweeks

Hackweeks are participant-driven workshops designed to foster collaboration, provide education in the tools and methods of open science, and align community members around shared software and NASA datasets.
https://snowex.hackweek.io/

CUAHSI Field Measurement Schools

4-day hands-on field school; prepare researchers at all career levels to make quality field observations using standard techniques (depth, density, temperature, grain size/type, SWE, etc), in addition to some exposure to new technologies

Winter Wildlands Alliance Snow School

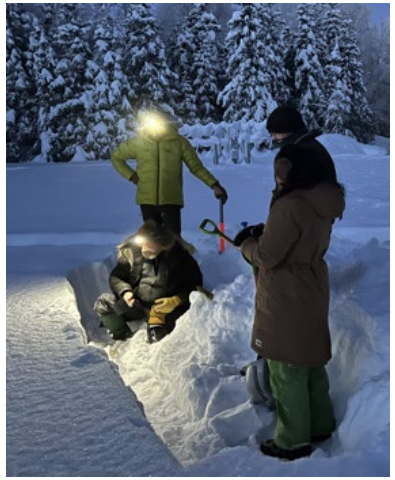
- K-12 program that takes over 35,000 students into the snow environment to teach science. 80+ local programs across the U.S.
- Students learn the importance of snow, how to measure SWE, depth, stratigraphy, in addition to winter ecology, shelter building, etc
- Pre/Post classroom visits, demonstrated increases in learning
- Students made measurements for SnowEx, improved SnowSchool curriculum

Outreach

SnowEX-ED: NASA STEAM Education With Snow

To bring the excitement and science of SnowEx to the public:

1) **Designed and built snow science kits (~800)**
2) **Distributed these across the US through outdoor schools & nature centers**
3) **Facilitated press releases highlighting snow science and society's reliance on snow for water**
4) **Delivered fun in-person outdoor snow experiences to thousands of adults and youths across Alaska.**



University of Alaska student measuring SWE at Fairbanks campus during SnowEx 2023

SnowEx-MAIANSE Internships, 2000-present

- 7 Interns to date from American Indian and Alaska Native serving institutions
- Projects developed based on SnowEx data needs & student interest and ongoing local activities
- Student paired with mentor to work on the project

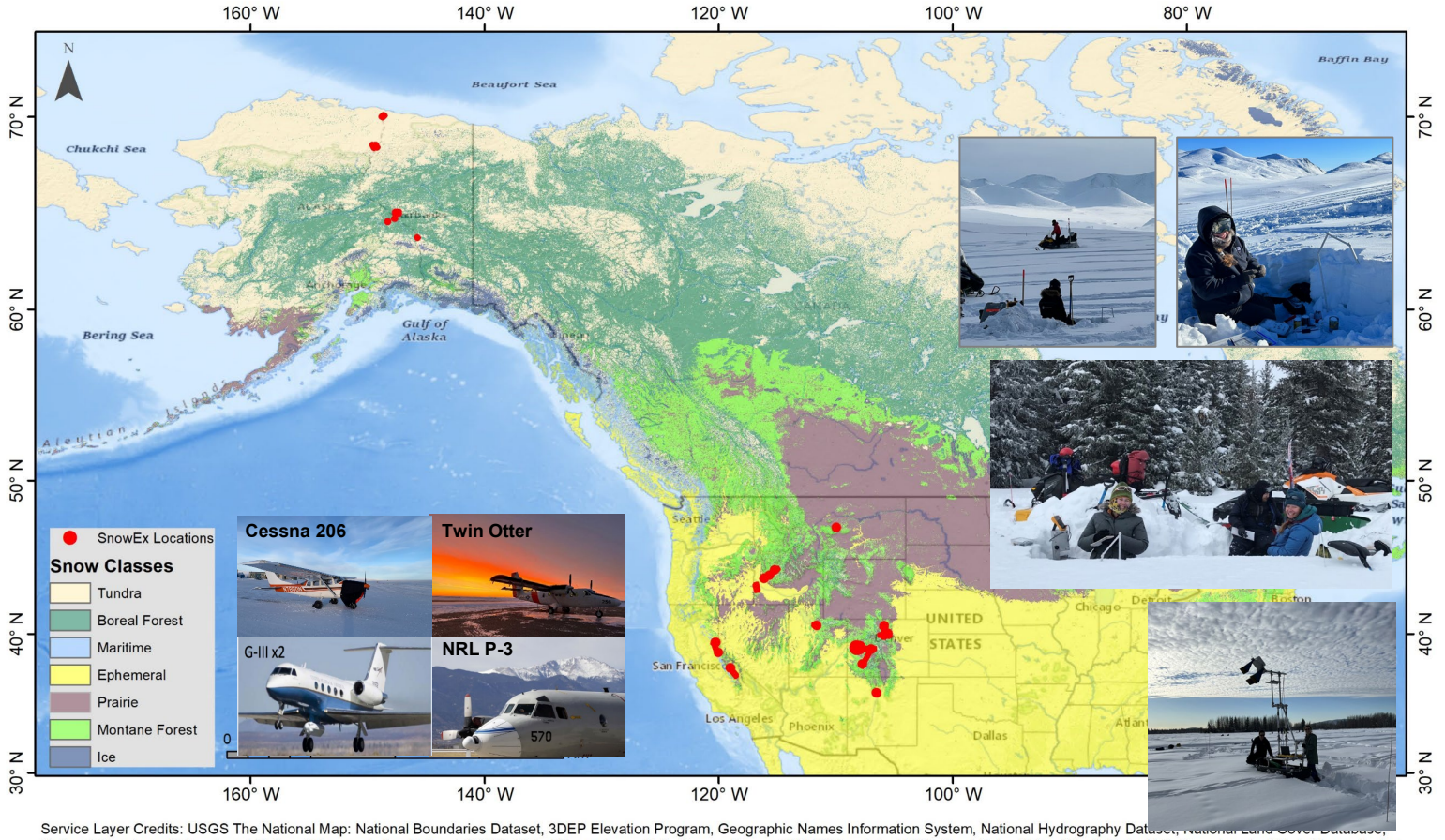
Fond Du Lac Tribal and Community College students measuring SWE at Minnesota campus location

NASA SnowEx, Accomplishments to Date

NASA Terrestrial Hydrology Program
SnowEx Summary:

- Over 250 Participants
- From 49 Institutions
- 8 Aircraft
- 14 Airborne Instruments
- 184 Individual Datasets
- >40 Publications using SnowEx data
- 26 PhD Dissertations and 6 Masters Theses complete or in progress
- 2 satellite mission proposals to the Earth System Explorer solicitation

SnowEx References
What's missing?



Service Layer Credits: USGS The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; USGS Global Ecosystems; U.S. Census Bureau TIGER/Line data; USFS Road Data; Natural Earth Data; U.S. Department of State Humanitarian Information Unit; and NOAA National Centers for Environmental Information, U.S. Coastal Relief Model. Data refreshed April, 2023.

Four SnowEx campaigns were conducted at 20 different locations in the Western US and Alaska (red dots). Base map shows snow classes defined in Sturm & Liston (2021). Map credit: Svetlana Stuefer, UAF

Data Inventory Update

SnowEx Data
Data collected through instrumentation and processing funded by the Terrestrial Hydrology Program (THP).

Partnered Data
Data collected through partnerships outside of the THP resources, with the agreement of being shareable and publicly accessible.

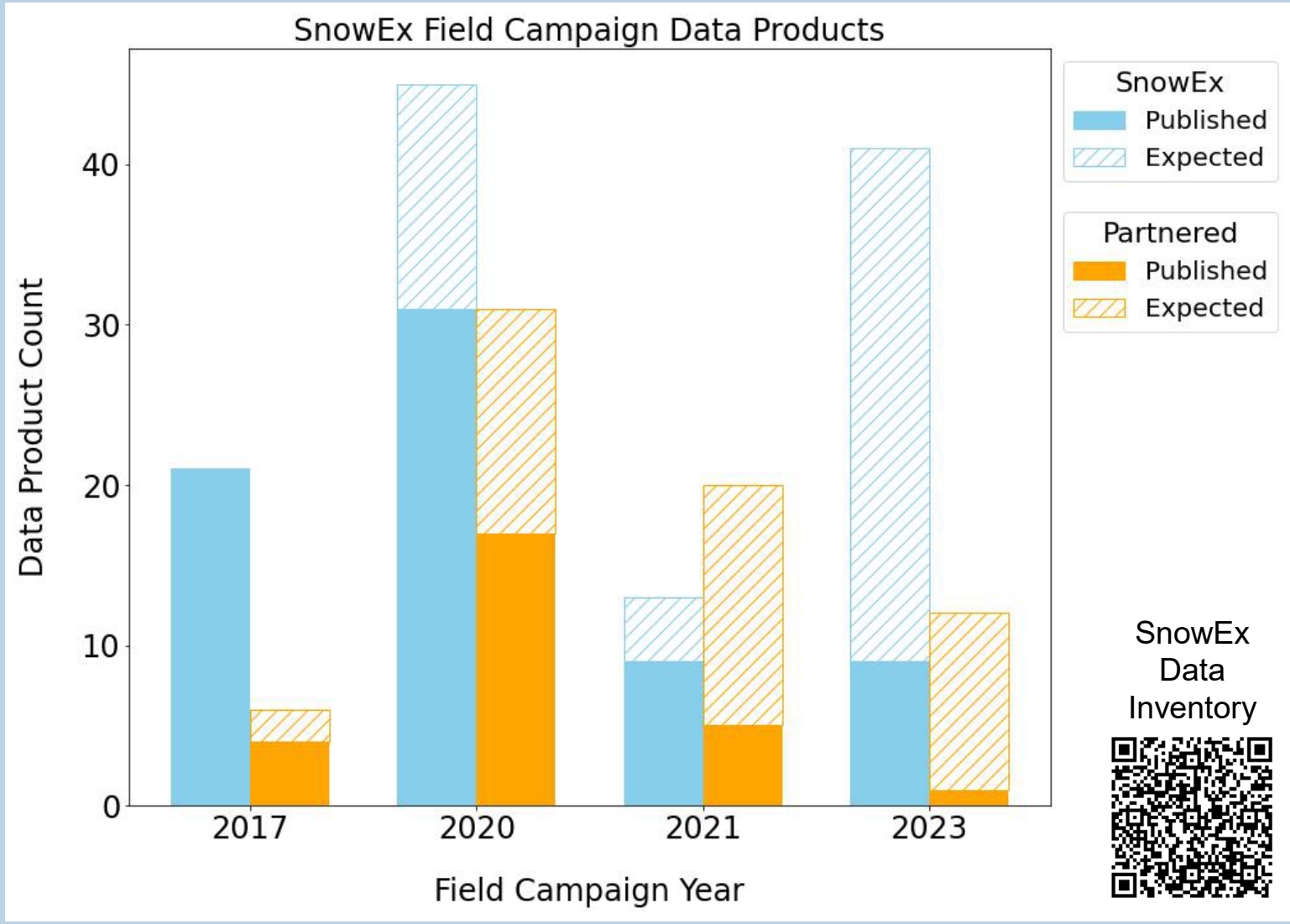
2017: All non-partnered data are published

2020 & 2021: >50% of non-partnered data are published

2023: <20% of non-partnered data are published. Recent increase in submissions following Jan 2024.

Partnered data products are lagging, likely due to dropped communication, funding, time, resources, and community requests, etc.

Provided by Megan Mason, NASA GSFC



SnowEx Data Inventory

Data Inventory Update

Airborne
S: SWESARR, L-Band InSAR, AVIRIS-NG, QSI/ASO
P: Gamma, FMCW radar, helipod lidar

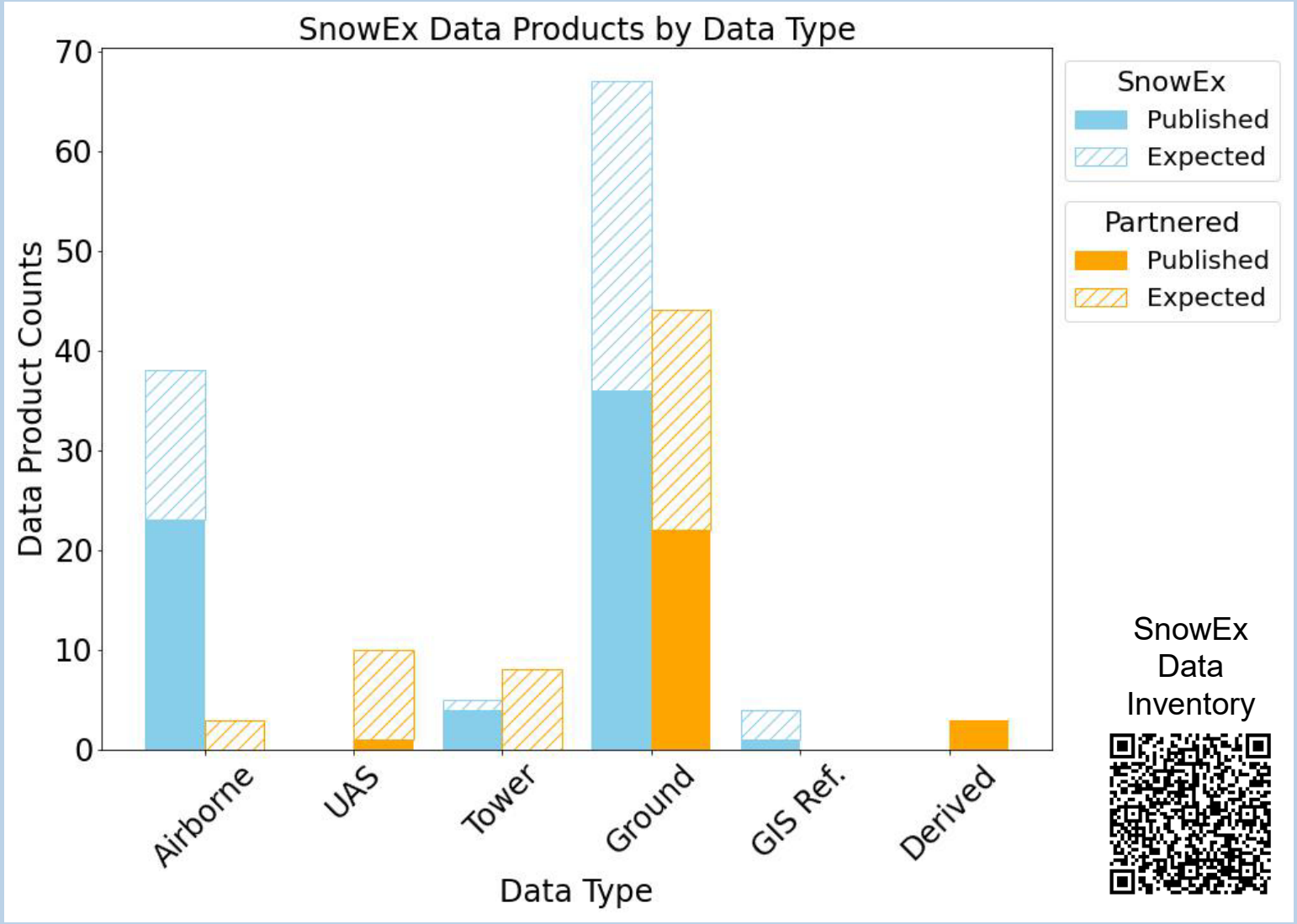
Unmanned Aerial Systems (UAS)
S: n/a
P: UAV-based lidar, UAV-based Hyperspectral, Orthoimagery

Tower
S: Grand Mesa Met stations, AK tree-mounted met stations, GM sonic depth sensors, COSMOS soil moisture stations
P: C, P-band radar, snow temp. array, prairie met station

Ground
S: Snow pits, probed depths, SSA, TLS, Gravimetric SM
P: GPR, FMCW radar, surface temps, Lyte Probe, SnowScope

GIS Reference
S: GIS reference data sets
P: n/a

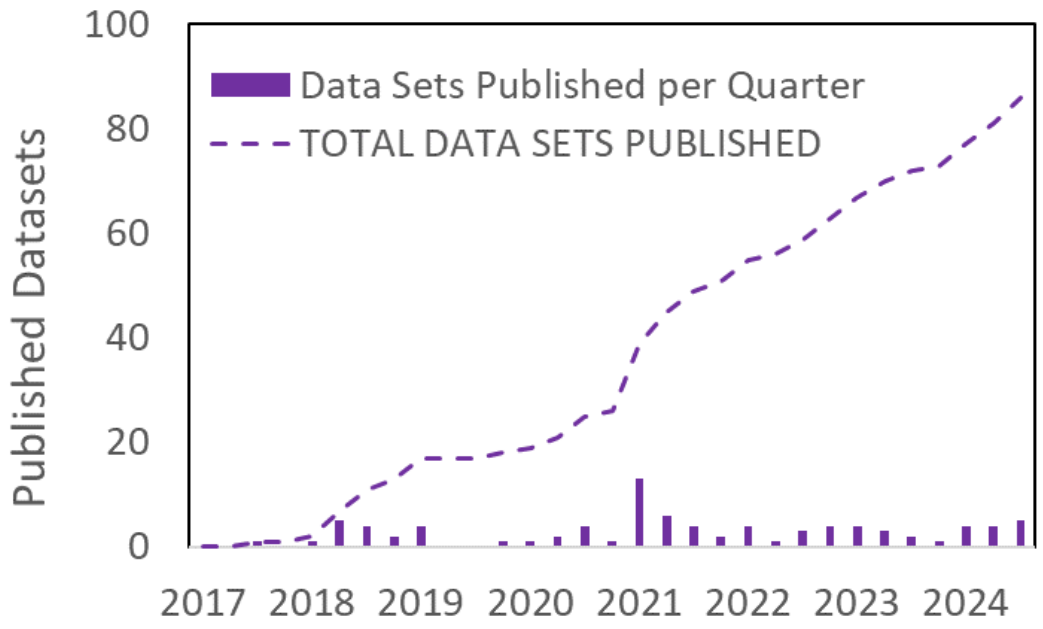
Derived (Level 2)
S: n/a
P: snow depth from HR satellite image pairs, derived snowpack relative permittivity and density, spatially distributed SWE/density.

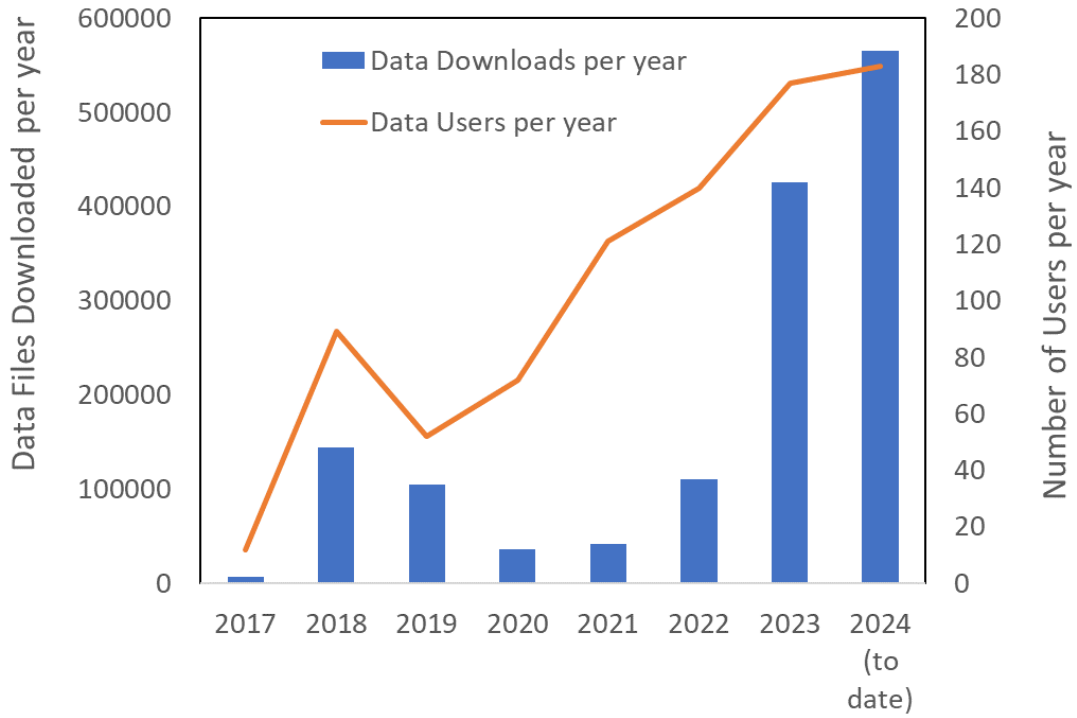


SnowEx Data Inventory

Provided by Megan Mason, NASA GSFC

SnowEx User metrics (NSIDC)

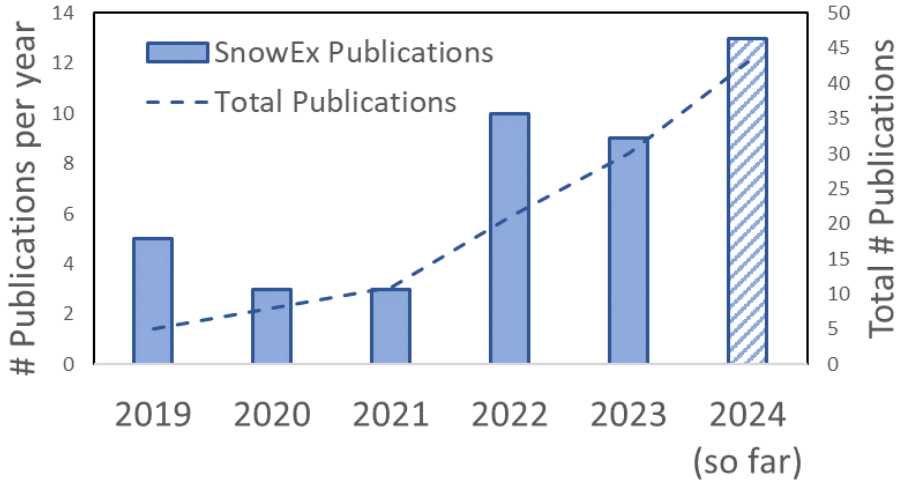




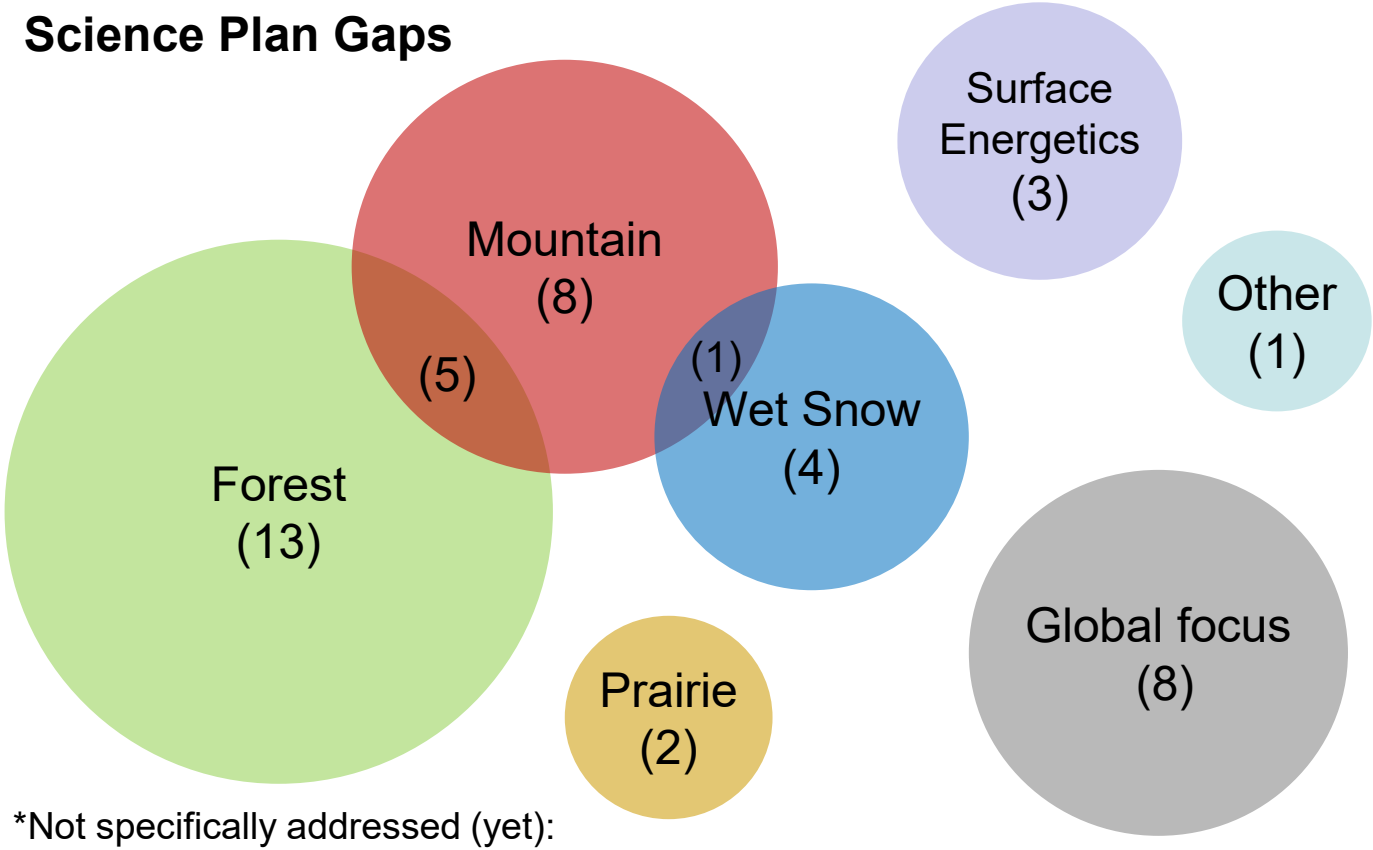
Provided by Stephanie Wong, NSIDC

SnowEx Publications – Gaps Addressed

- Uncertainty estimates focused on specific gaps
- Strong focus on forest questions (18) address main objectives of SnowEx
- Several algorithm development and basic measurement studies can be broadly applied



Science Plan Gaps

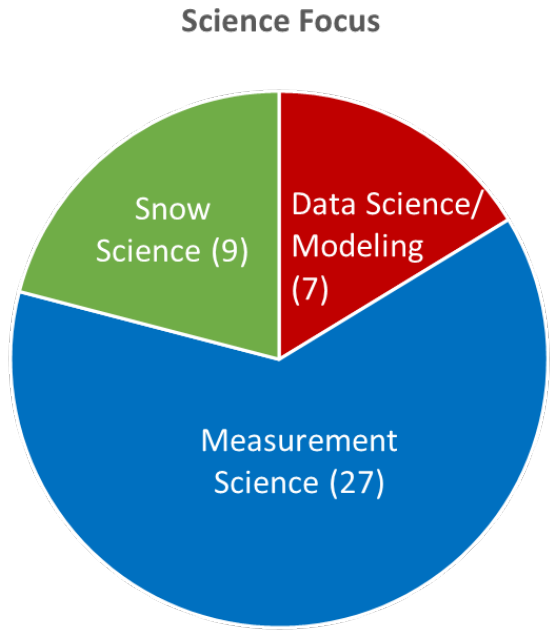


*Not specifically addressed (yet):

- Maritime
- Tundra

SnowEx Publications - Technique

SWE and Snow Depth		
Type	**Snow Sensing/Estimation Technique**	
SWE via Snow Depth	Spaceborne Lidar	1
	Ka-band InSAR	
	Dual band Ku/Ka altimetry	
	SfM/Stereo	4
	Wideband Radiometer	
Volume scattering	X-/Ku-band SAR	5
	Passive Microwave	1
	C-band SAR	7
Signal interferometry	L-Band/C-band InSAR	4
	SoOP	1
Surface Energetics	Imaging Spectrometer	3
	BRDF	
	Thermal IR	3
Modeling	Physical Modeling	6
	Radiative Transfer Modeling	4
	Data-driven modeling/ Machine Learning	3
Airborne / Ground Only	Ground Obs (snow pits, depth, etc)	16
	Airborne Lidar	17
	GPR	6
	Time Lapse Cameras	2
	TLS	3
	SSA, SMP Cosmic Ray Neutron Sensor (1 each)	3



SnowEx Collaborations & Partnerships

Snow science is a team sport!

NASA Snow Community Meeting
14-15 August 2024, Boulder, CO