NASA SnowEx 2023
Experiment Plan
Draft (August 2022)

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1. Introduction

Over one sixth of the world's population relies on seasonal snow for water supply, and the earth's dynamic snow cover plays a major role in the global energy balance. Monitoring snow water equivalent (SWE) and albedo over large regions, however, especially in northern latitudes, remains a challenge. NASA SnowEx is a multi-year effort to improve snow water equivalent (SWE) and snow-surface energy balance characterization through extensive, coincident airborne and field-based measurements. The goal is to determine an optimal approach for monitoring snow, to identify pathways to accurate space-borne snow measurements, and to enable the fusion of remote sensing, modeling, and in-situ observations. Advancements in remote sensing capability combined with state-of-the-art modeling efforts, will yield a next-generation snow satellite mission concept, and demonstration of a global snow monitoring strategy.

In 2023, the NASA SnowEx campaign focuses on the tundra and boreal forest regions of Alaska to collect observations of snow in these unique environments. This effort takes place over the winter season starting in the fall of 2022 through spring 2023, and includes a no-/low-snow data acquisition in October 2022, and a snow-on campaign in March 2023 with airborne radar, radiometer, LiDAR and stereophotogrammetry observations, and a snow melt campaign to collect hyperspectral data in April 2023.

SnowEx 2023 activities will occur at multiple sites to measure diverse snow conditions. This campaign leverages sites with ongoing snow, vegetation and meteorological measurements, in both tundra and boreal forest environments. SnowEx incorporates scientists and students from multiple organizations and universities, and aims to train participants in measurement protocol to ensure rigorous scientific data. In addition, the NASA/CUAHSI Snow Measurement Field School will continue to provide training every year for the community, with a goal of increasing the pool of experienced observers for future SnowEx campaigns.

Many factors may compromise chances of a successful and safe experiment, especially in cold, harsh, winter environments. A paramount objective of SnowEx 2023 is safety. Risk reduction in this experiment is a constant and overarching theme; sufficient training and improvements in navigation and communication to prevent accidents and limit injury have been implemented and are described in the SnowEx 2023 Safety and Operations Plan.

1.1. SnowEx Science Plan Gaps & Priorities Addressed

The SnowEx Experiment was designed to directly respond to the current ***Gaps*** and ***Priorities*** identified in the THP16 Science Plan (Durand et al. 2019). The Science Plan identifies remote sensing measurement challenges that must be addressed to advance global science related to seasonal snow. These measurement challenges are related to the specific measurement techniques and the snow properties in various environments.

The NASA Terrestrial Hydrology Program Snow focus group developed a list of eight science questions for a SnowEx tundra and boreal forest focused campaign, which can be divided into three classes: measurement science, snow science and information science.

1. Snow depth/SWE: How does microstructure model accuracy and scaling issues impact use of models to inform microwave retrievals in tundra snow? Taiga snow: How much do microwave signals penetrate forest canopies in boreal forests?
2. Snow depth/SWE: How well do snow depth retrieval methods (e.g., lidar and SfM) work where in the variable permafrost, water, and vegetation characteristics ubiquitous at high latitudes?
3. Snow depth/SWE: How does the L-band interferometric SAR approach perform where "bare earth" surfaces change?
4. Snow albedo: What is the nature of spatial variability of snow reflectance/albedo and physical properties in the Boreal/taiga/ tundra regions of North America?
5. Snow albedo: How does the spatial variability of snow reflectance/albedo change with scale?
6. Snow process: How do vegetation and snow cover processes impact the "zero curtain" or freeze-thaw status of the surface layer and active layer transitions over seasonal time scales, and how does this affect remote sensing?
7. Snow process: What factors control variability in snow cover and physical properties across latitudinal, topographic, vegetation and disturbance gradients during the accumulation and melt seasons?
8. Data assimilation: How well do methods that integrate multiple types of data with process-based models help to fill in observational gaps given the uncertainties with bare earth elevations and other factors?

In 2023 the SnowEx campaign will focus on collecting data to address these questions, within the cost and timing constraints allowed.

1.1.1. Tundra Snow

The tundra is a biome defined by cold temperatures that limit forest growth and promote permafrost development. It covers approximately 9% of the Earth's land surface area (13.7 x M km^2) and experiences a long snow season each winter. Seasonal snow in tundra regions is typically shallow (0.2 - 0.8m), except in drifts which can be 1 to 8 m deep (Sturm & Liston, 2021). Due to strong temperature gradients within the snowpack, significant grain growth at the base of the snowpack, or depth hoar, is common. At the surface a wind-hardened snow slab is often present. This results in a two-layer snowpack, with high density, small grain size snow at the surface and low density, large grain snow at the base. The vegetation in tundra includes tussocks and small shrubs, which are pervasive and influence the snow distribution and characteristics. These plants help trap snow and initiate drifts, and also create voids in the snow and promote depth hoar at the base (Bennett et al. 2022).

A key question with regard to X- and Ku-band radar backscatter remote sensing of tundra snow is how accurately grain size needs to be estimated in order to enable an accurate SWE retrieval. SnowEx will address this by making simultaneous measurements of SWE, snow specific surface area (an objective measurement of snow grain size) and X- and Ku-band radar backscatter.

Altimetry methods which estimate snow depth using differencing techniques between snow-on and snow-off observations, can be impacted by unique and variable permafrost, water, and vegetation characteristics that exist in tundra landscapes. SnowEx will help address the question of how well we can characterize the spatial variability of snow depth and density needed for accurate SWE estimates in the tundra, by measuring snow depth, density and vegetation characteristics.

1.1.2. Boreal Forest Snow

The boreal forest (taiga) is the extensive forested region in northern latitudes that experiences freezing temperatures and snow for a majority of the year. The boreal forest covers approximately 8% of the Earth's land surface area (12.2 M km^2), and snow plays a critical role in the ecological and biogeochemical health of this biome. Snow depth is generally shallow to moderate (0.3 to 1.3 m), and densities are typically low given the strong temperature and vapor gradients that promote large grain growth and depth hoar[2]. Tree species are primarily coniferous and can be very dense, leading to snow interception and spatial variability which can be difficult to quantify. Large spread between modeled estimates of both in SWE and albedo has been found in boreal forests.

A key question with regard to X- and Ku-band radar backscatter remote sensing of boreal forest snow is at what forest density SWE can be estimated. Earlier research suggested SWE retrievals were only possible in areas with less than 20% forest fraction, though that value has not been rigorously demonstrated, and more recent work has suggested it may be possible to leverage gaps in the forest canopy. SnowEx will address this by making simultaneous measurements of SWE, forest structural properties based on lidar, and X- and Ku-band radar backscatter.

While lidar and stereophotogrammetry techniques have been shown to provide accurate snow depth measurements in many forested areas, the dense boreal forest canopy may pose additional problems. SnowEx 2023 aims to address the question of how well we can characterize the spatial variability of snow depth and density needed for accurate SWE estimates in the boreal forest, by measuring snow depth, density and vegetation characteristics.

Snow-forest interactions are a major source of uncertainty in modeled albedo estimates over boreal forest regions, yet there are surprisingly few spatially distributed measurements of albedo during the winter season. To address this gap, SnowEx will collect airborne hyperspectral data during the snowmelt coincident with ground snow observations.

1.2. Campaign Objectives

This document describes the overall SnowEx 2023 observational strategy, which include the collection of airborne active/passive microwave data, lidar, optional stereo imagery and hyperspectral data, as well as coincident ground observations, to meet the following campaign objectives.

1. Quantify the impact of boreal forest on microwave SWE retrievals
2. Evaluate accuracy of modeled microstructure and snow spatial distribution in a tundra environment and the impact on SWE retrievals
3. Quantify the accuracy of spaceborne lidar and stereo-photogrammetry snow depth retrievals in boreal forest and tundra environments
4. Quantify the spatial variability of snow physical properties in the boreal forest and tundra regions
5. Quantify the temporal and spatial variability of snow reflectance/albedo in the boreal forest region

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2. Management

The SnowEx 2023 campaign is funded under the NASA Terrestrial Hydrology Program, directed by Dr. Jared Entin. The Project Scientist is Carrie Vuyovich (NASA GSFC), and the Deputy Project Scientist is Svetlana Stuefer (University of Alaska, Fairbanks). Dan Hodkinson (NASA GSFC/SSAI) is the Operations Lead. HP Marshall (Boise State University), Kelly Elder (USFS), Michael Durand (OSU), Batu Osmanolgu (NASA GSFC), Dragos Vas (ERDC CRREL), Arthur Gelvin (ERDC CRREL), Elias Deeb (ERDC CRREL), Stine Pedersen (Colorado State University), Chris Larsen (University of Alaska, Fairbanks), Megan Mason (NASA GSFC/SSAI), Anne Nolin (University of Nevada Reno) and Kelly Gleason (Portland State University) bring essential expertise to the leadership team that includes sample design, snow characterization, ground-based and airborne remote sensing, and campaign execution. The SnowEx 2023 Science team and the THP Snow Group provide overall guidance. Albert Wu (NASA GSFC/SSAI) provides expert guidance for the airborne science program.

2.1. SnowEx 2023 Organization Chart

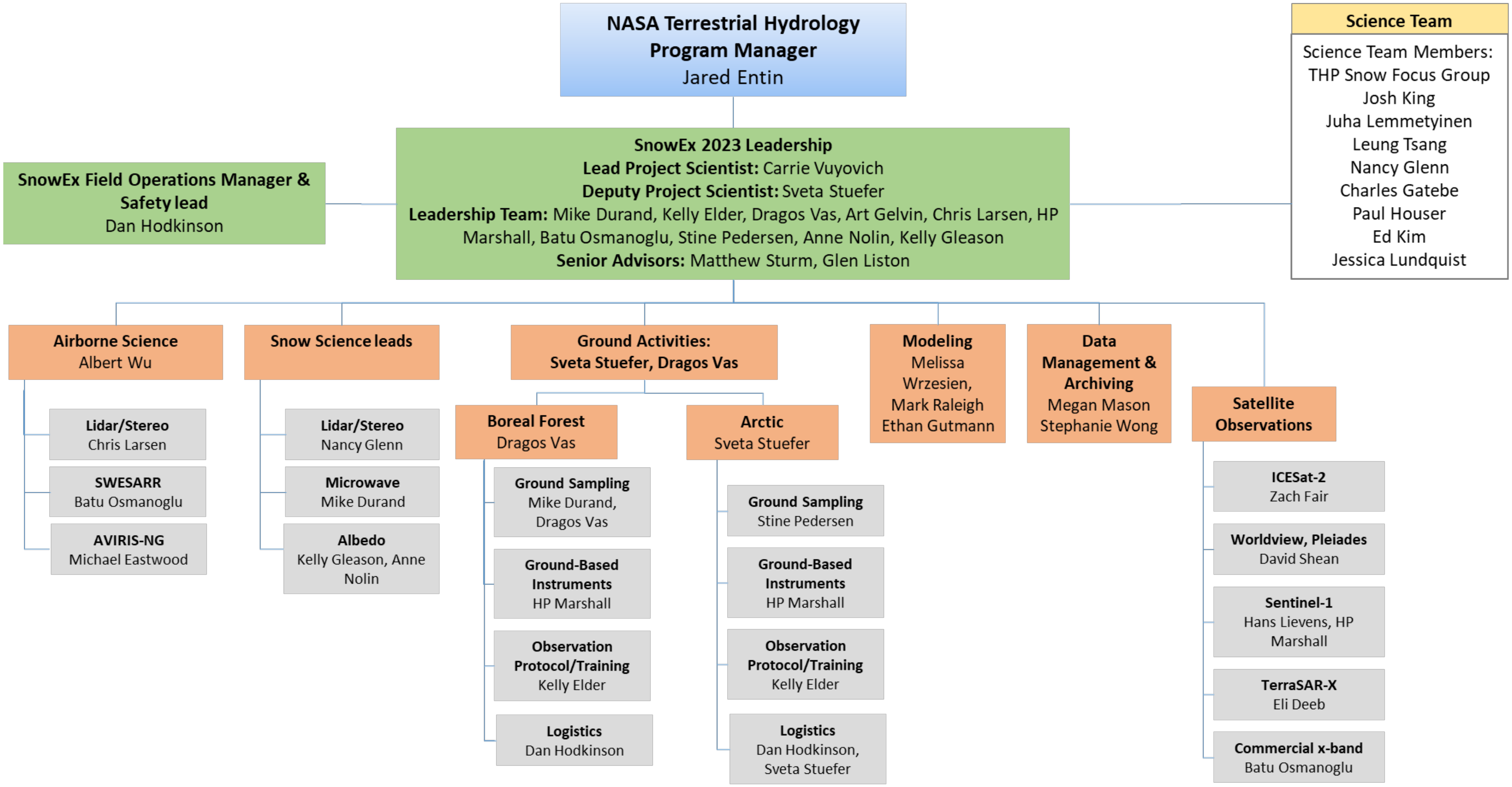


Figure 2.1: SnowEx2023 Management Structure

2.2. Roles and Responsibilities

SnowEx Project Leadership Team

The highest priority of SnowEx is safe collection of high-quality snow science data to fulfill the Project's objectives. Leadership team responsibilities include contributing to the Experimental Plan, Operations Plan, and Campaign summary documents; developing the sampling strategy and measurement protocol for aircraft and ground measurements; coordinating airborne and ground activities; developing a communications plan for ground and airborne activities; participant training; and providing status reports.

There are additional responsibilities for specific roles.

Project Scientist: Ensure SnowEx project/science goals are being met, final decision on all planning decisions, ensure that team members have what they need, troubleshooting, team communication, reporting, overall direction, schedule and budget, and interfacing with community and NASA management.

Deputy Project Scientist: Support lead project scientist to ensure SnowEx project/science goals are being met, ensure that team members have what they need, troubleshooting, team communication, reporting, overall direction, schedule and budget, interfacing with community and NASA management, and step in for PS if needed to make final decisions.

Operations Manager and Safety Lead: Execute contracts, purchase equipment, manage shipping of equipment for field experiments, participate in weekly calls with leadership team, interface with Program Manager.

Leadership Team: Participate in weekly planning discussions, help develop experiment plan, sampling strategy, flight plans, and field activities. Design and implement complex field experiments involving large groups of field observers.

Airborne Instrument Leads: Responsible for overall flight planning and daily schedule for their instruments/aircraft; provide status updates every day during campaign for team meetings and summary of flights; Provide quick-look data products in the field; Submit SOFRS reports daily (coordinate with aircraft POCs). Process all data and work to archive data at NSIDC within 6 months of the end of the campaign.

Snow Science Leads: Organize and lead the design and implementation of consistent observations for the airborne flights to achieve science objectives. Determine where and when to implement flight sampling protocol based on past experience and flight hours.

Ground Activity Leads: Design and implement field experiment to achieve science objectives. Leads will determine where and when to implement ground sampling protocol based on past experience and site access, and will work with the snow science leads to coordinate ground and airborne activities.

Data Management Lead: Develop online form for data entry for time series, coordinate data entry during Grand Mesa IOP, archive and backup data in secure location, develop metadata for each type of data, facilitate data archival for all instruments and observations, provide data access to community

Modeling Leads: Responsible for assessing the value of modeling efforts before and during the campaign. Will work with ground and airborne science leads to coordinate model domains, data and provide input on valuable validation data.
Satellite Observation Leads: Responsible for any tasking requirements for collecting data during the campaign. Will work with ground and airborne science leads to coordinate optimal locations and times for observations and provide input on valuable validation data.
Science Advisors: Provide input on science goals of experiment plan, provide overall goals and priorities (Science Plan), and connection to long term SnowEx goals.

2.3. Communication

Four levels of communication are required as part of SnowEx 2023. Project updates will be delivered to NASA HQ monthly by the Project Scientist and Deputy Project Scientist. Site Leads and Project Leadership will participate in bi-weekly phone calls to discuss data collections, data protection, and progress. Members of the SnowEx and Snow International (SINTER) communities will be briefed on the campaign regularly, through community forums. Public and science community communications will be enhanced with help from NASA Goddard's Public Affairs to utilize social media and the press. The SnowEx website (https://snow.nasa.gov/campaigns/snowex) will also be updated during the campaign.

In addition, a detailed plan for communication during the campaign is described in the SnowEx 2023 Safety and Operations Plan.

2.4. SnowEx 2023 Timeline of Activities

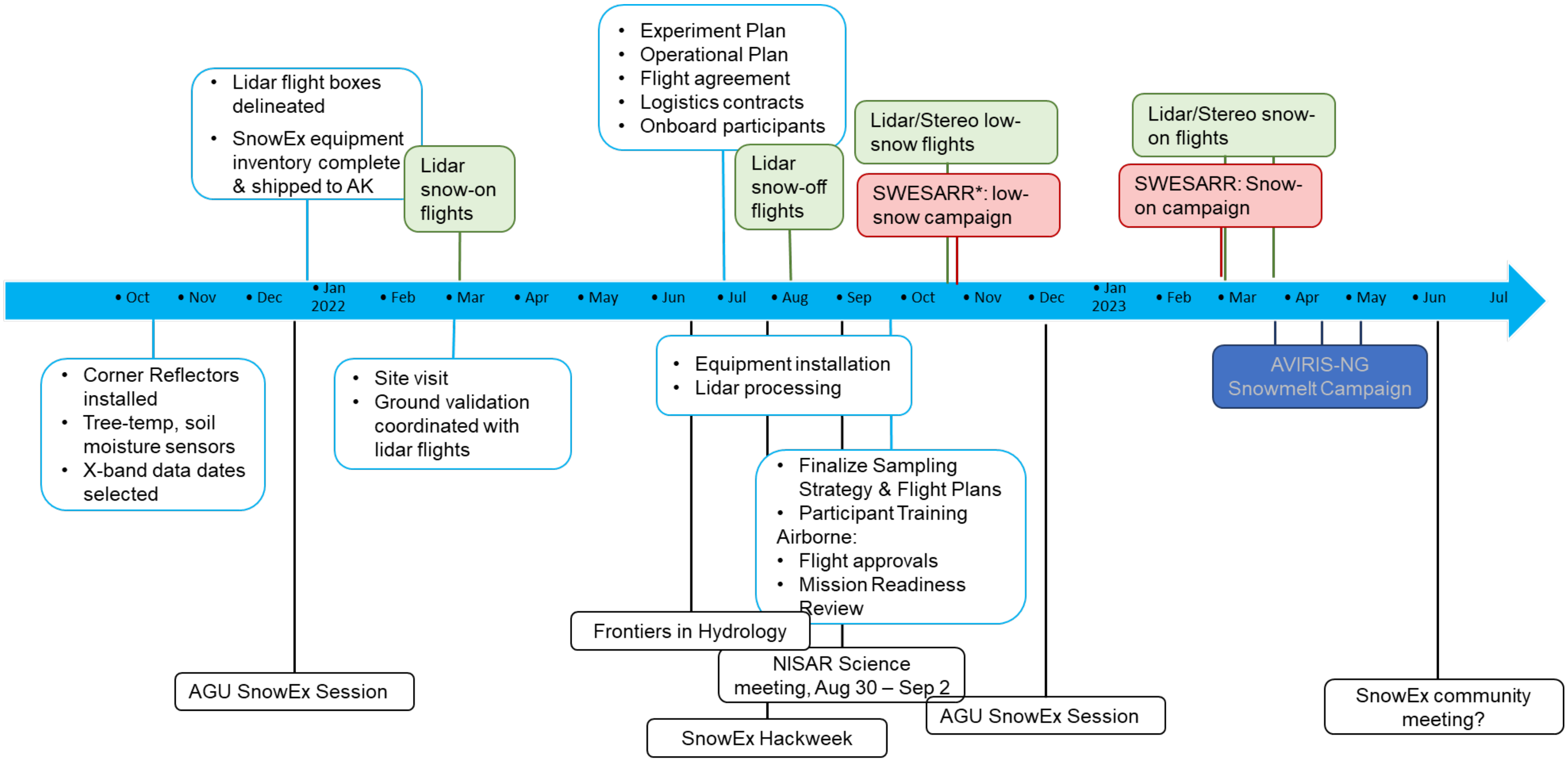


FIGURE 2.2: SNOWEX2023 TIMELINE OF AIRCRAFT AND GROUND ACTIVITIES

3. Partnerships

SnowEx 2023 welcomes non-NASA partnerships and seeks to leverage other airborne and field activities. Partners are defined as activities external to SnowEx, but co-located over our sites and sharing goals of improved snow measurement techniques, along with willingness to share data. With partnerships, more comprehensive snow observation datasets will exist across various landscapes and throughout the winter season, with a wider range of airborne sensors. Appendix A lists contributing SnowEx 2023 participants and organizations. Partners are contributing to experimental planning and design, and bringing crucial airborne and modeling resources to this effort. Importantly, investigators on existing NASA and non-NASA projects will be coordinating their field plans with SnowEx, providing additional value and experienced observer resources to SnowEx at little to no cost.

3.1. NWS Fairbanks

3.2. NWS AK Pacific River Forecast Center, Anchorage

3.3. Outreach and Education: WWA SnowSchool

3.4. Outreach and Education: MAIANSE

4. Airborne Activities

Four separate airborne instruments, used on three different aircraft, comprise the core SnowEx 2023 instruments (Fig. 2.2). Snow-free and snow-on acquisitions are planned with lidar, stereophotogrammetry, radar and radiometry observations for the five sites. These instruments will fly over Bonanza Creek, Creamer's Field and Caribou-Poker Creek sites near Fairbanks, as well as two separate sites near Toolik and Prudhoe Bay. Hyperspectral observations are planned during the snow melt period in April 2023 over multiple sites in the Fairbanks area: Creamer's Field, Caribou-Poker Creek and Delta Junction.

4.1. Airborne Sensor Descriptions

4.1.1. SWESARR

Figure 4.1. SWESARR Instrument

The airborne SWE Synthetic Aperture Radar and Radiometer (SWESARR) instrument was developed at NASA Goddard Space Flight Center (Fig. 4.1). SWESARR has three active (including a dual Ku band) and three passive bands (Table 4.1). Radar data is collected in dual polarization (VV, VH) while the radiometer makes single polarization (H) observations. The combination of all these microwave measurements will provide an important data set to develop and to enhance SWE retrieval algorithms.

Radar and radiometer observations are sensitive to snow properties (e.g., microstructure, wetness) and vegetation and soil characteristics (e.g., state, moisture, roughness). To account for vegetation and soil contributions in the SWE algorithms, it is important to collect snow-off observations. Snow-off flights are scheduled for late October 2022. Ground measurements like soil samples will be collected along with corner reflectors. Snow-on data collection will occur during March 2023. SWESARR will be flown on a twin otter aircraft. At a flight altitude of 2 km, the SAR swath width ranges from 250 m to 450 m, as frequency decreases.

Table 4.1. SWESARR microwave bands collected

	Band	**#**	**Freq. (GHz)**	**BW (MHz)**	**Pol.**
Active	X	1	9.65	200	VV,VH
Passive	X	2	10.65	200	H
Active	Ku-Lo	3	13.60	200	VV,VH
Active	Ku-Hi	4	17.25	100	VV,VH
Passive	K	5	18.70	200	H
Passive	Ka	6	36.50	1000	H

4.1.2. Airborne LiDAR and Optical stereo imagery – Coming soon

4.1.3. AVIRIS-NG – Coming soon

4.2. Flight Lines and Flight Plans

Flight lines and flight plans were chosen to address the gaps and priorities in the Science Plan. These include flight lines that sample a range of vegetation and topography, a wide range of snow climatology, and a wide range of snow conditions, from dry snowpacks to wet snow conditions.

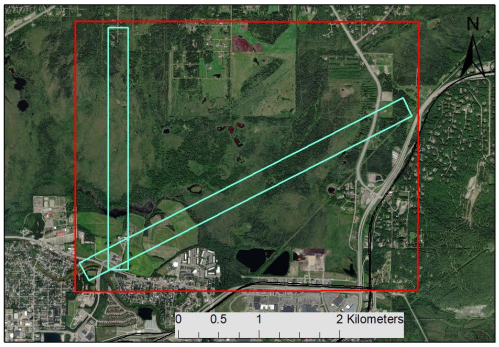
4.2.1. Low/No-Snow and Snow-On Intensive Observing Periods

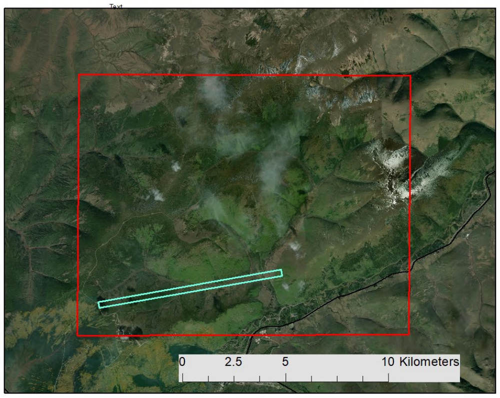
SWESARR, lidar and an optical stereo imagery system (Section 4.1.1) were identified as core airborne instruments for the low/no-snow and snow-on SnowEx 2023 intensive observing periods. For SWESARR, twenty-five kilometers of transects can be flown with ten hours of science flight time. This includes two to three replicates of the flight lines occurring during each flight to ensure measurement overlap with ground measurements. Considering a flight altitude of 2 km, the SWESARR SAR swath width is about 450 m at the lowest frequency, and the exact ground-segment repeat with the Twin Otter aircraft is not possible, the ground sampling areas were designed with a width of 650 m. Flights with LiDAR and stereo imagery will include both snow-free and snow-on flights to cover the SWESARR flight lines and additional area over each of the sites. To be aligned with the SnowEx Science Plan, planned observations are composed of a mix of vegetation and snow types, which can be achieved in the Interior and Arctic Alaska (Figure 4.2.1). Several lakes and rivers are also included in the flight lines (Fig. 4.2.1). It was also desirable to have relatively easy summer/winter road/trail access to aid in ground data collections.

The flight lines in the BCEF area (Figure 4.2.1) are oriented northwest-southeast, following an access road. The line to the south of the road encompasses the “corner reflector experiment”, an array of 20 radar corner reflectors positioned behind trees, and will be a focus of in situ forest structural measurements via terrestrial lidar scanning (TLS). The line to the north of the road is very similar snowpack and forest as the line to the south of the road, and will be a location with in situ snow measurements. Both lines along the access road are in a predominantly black spruce forest. The north-south line in BCEF overlaps an area of mixed forest, with several clearings, and including a snow pillow which will provide a SWE time series.

The FLCF site includes two flight lines, both of which span transects with long-term history maintained by CRREL. The north-south line includes an area with sparse forest cover towards the north, and mixed forest in the south. The southwest-northeast line includes mixed forest with clearings throughout, across a permafrost gradient. The CPCRW line spans a river valley with thin black spruce forest and open area, along with some thicker mixed forests. These three lines span a range of forest density and types.

The three lines at Kuparuk, and the line in the ACP together span a range of conditions for tundra snow. At Kuparuk, the north-south oriented lines span a range of elevation and snow depth conditions. The east-west line overlaps with past measurements, including the CLPX-II campaign. The ACP line spans tundra snow over frozen lakes.





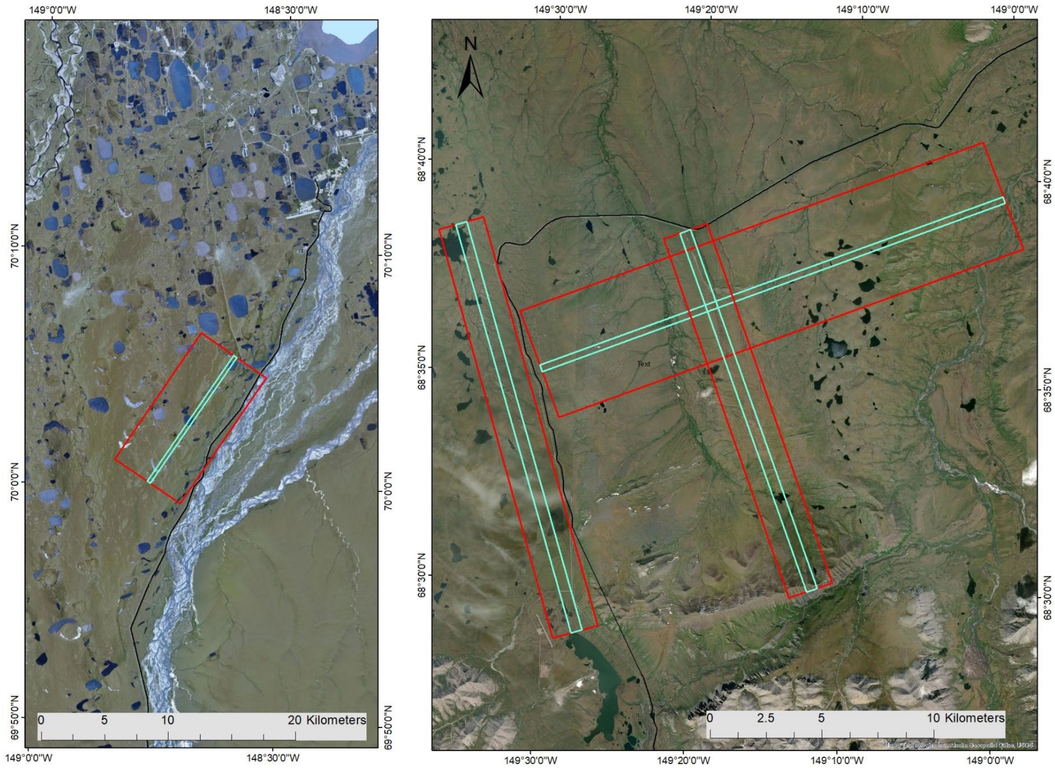


Figure 4.2.1. The flight lines for SWESARR (blue areas) and lidar/stereo (red boxes) for the Alaska IOP include boreal forests and tundra locations. Clockwise from top left: Bonanza Creek Experimental Forest (BCEF), Farmer's Loop and Creamer's Field (FLCF), Caribou-Poker Creek Research Watershed (CPCRW), Kuparuk, and Alaska Coastal Plain (ACP).

4.2.2. AVIRIS-NG – Coming soon

5. Ground Activities

5.1. Study Locations

Five study sites were selected across Northern Alaska to cover a range of terrain, permafrost, and environmental conditions (Figure 5.1). Three study sites represent boreal forest snow class and two study sites are selected in the Arctic tundra snow class (Table 5.1).

Table 5.1: Alaska SnowEx 2022-2023 sites

SITE	SITE ID	SITE NAME	SNOW CLASS
1	BCEF	Bonanza Creek Experimental Forest	Boreal forest (taiga) snow
2	FLCF	Farmers Loop and Creamer's Field	Boreal forest (taiga) snow
3	CPCRW	Caribou Poker Creek Research Watershed	Boreal forest (taiga) snow

4	Kuparuk	Upper Kuparuk and Toolik-Galbraith, Northern Foothills of the Brooks Range	Arctic tundra snow
5	ACP	Arctic Coastal Plain	Arctic tundra snow

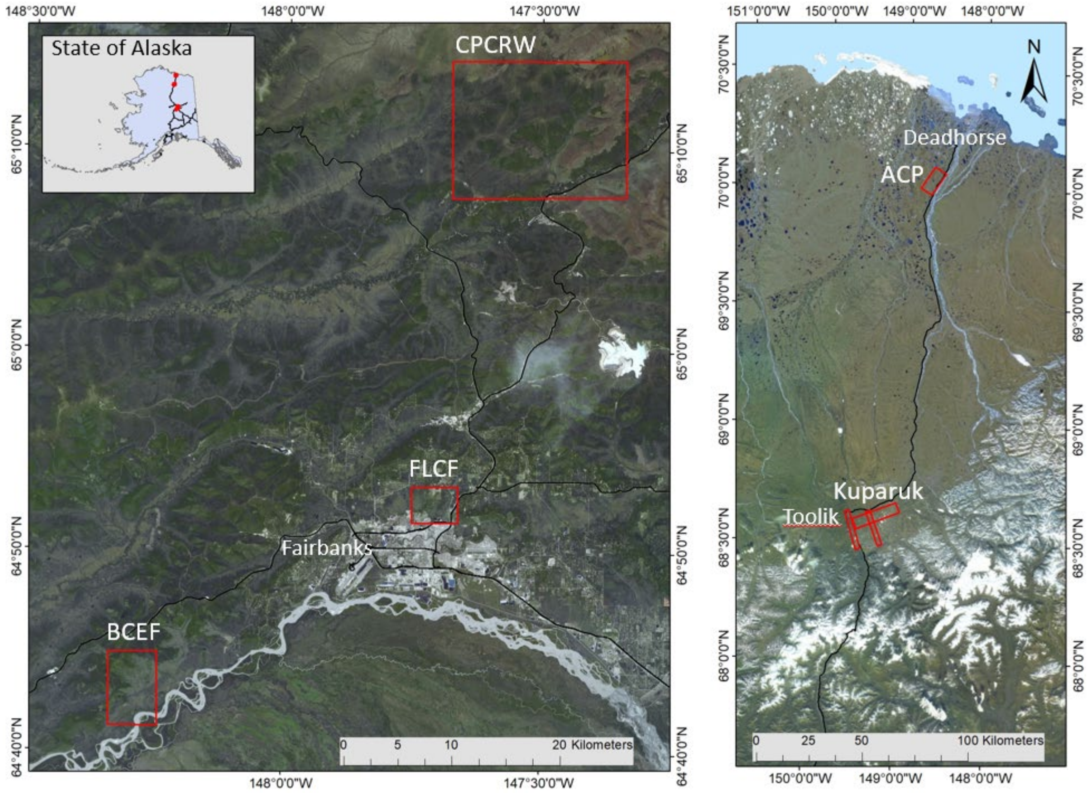


Figure 5.1: SnowEx 2023 site locations in Interior Alaska and on the North Slope of Alaska.

The specific locations of the field experiments were chosen based on existing ground-based infrastructure, previous remote sensing experiments, and access. Priority was given to long-term snow observation sites, which provide climatological perspective, and sites with previous lidar acquisitions and available data. Additional detailed information about each study site is provided in Appendix B.

5.1.1. Bonanza Creek Experimental Forest (BCEF)

The Bonanza Creek Experimental Forest (BCEF) is located 20 km southwest of Fairbanks Alaska. It was established in 1963 and in 1987 joined the Long Term Ecological Research Network (LTER) as a research program to study boreal forests in changing landscapes. It consists of lowlands along the Tanana River floodplain as well as uplands, the rolling hills north of the floodplain. Permafrost is discontinuous and a few oxbow lakes exist in the floodplain.

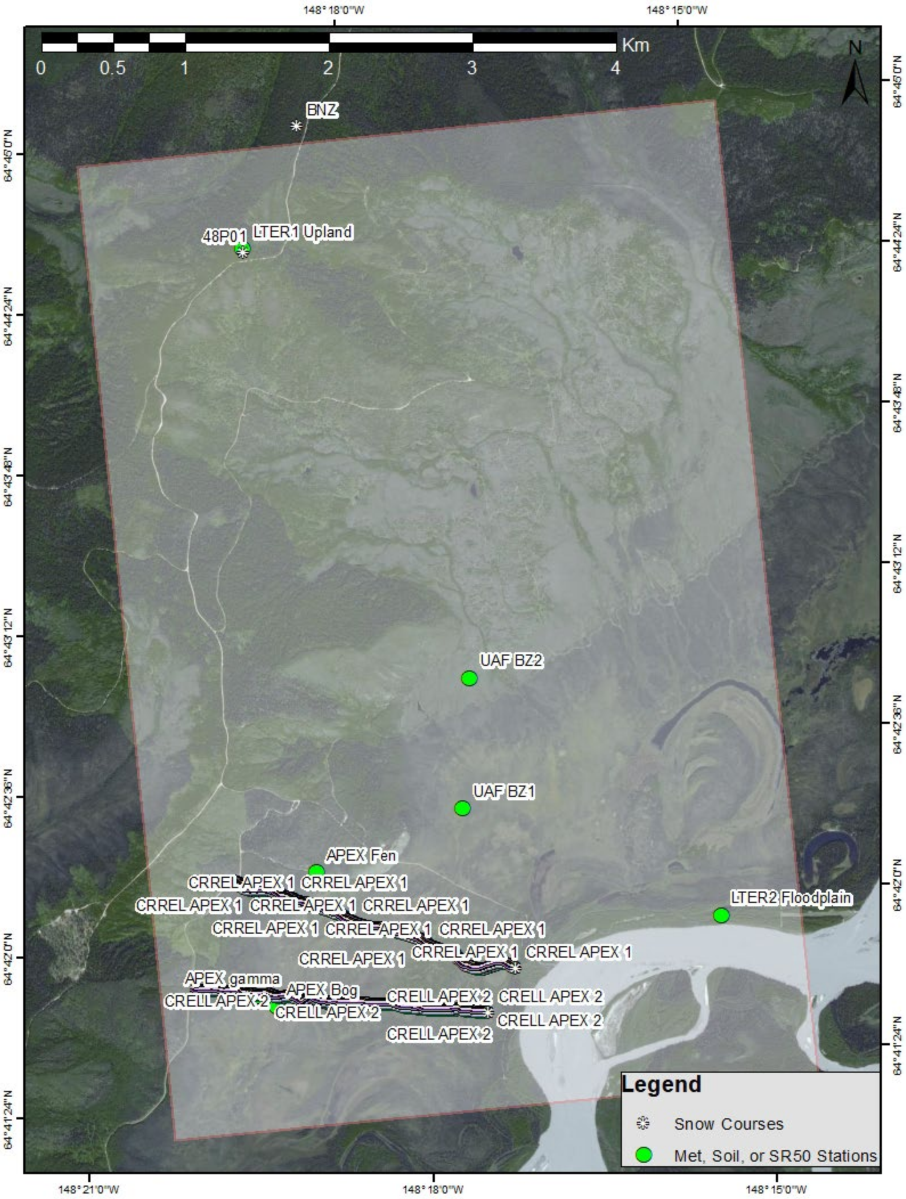


Figure 5.1.1: Location of existing meteorological, soil, and snow observation sites in BCEF.

5.1.2. Farmers Loop and Creamer's Field (FLCF)

The site consists of Farmer's Loop and Creamer's Field, located in the Fairbanks North Star Borough, and is in an area of discontinuous permafrost. CRREL operates the Farmer's Loop permafrost experimental test site with meteorological, soil, and snow studies. They also have a research site at the Creamer's Field Migratory Waterfowl refuge.

Creamer's Field Site (6 W 465013 7193916): One CRREL research site is located at the Creamer's Field Migratory Waterfowl Refuge, and it is composed of a 500 m long transect.

Farmers Loop site: Past CRREL research efforts at this site are focused along two transects: Farmers Loop Transect 1 (6 W 468051 7194877), 400 m and Farmers Loop Transect 2 (6 W 467948 7194614), 500m. These two transects are part of the Cold Regions Research and Engineering Laboratory Farmers Loop permafrost experimental test site.

Figure 5.1.2: Location of existing meteorological, soil, and snow observation sites in Farmer's Loop and Creamer's Field.

5.1.3. Caribou-Poker Creek Research Watershed (CPCRW)

Caribou-Poker Creek Research Watershed (CPCRW) is a 104 km^2 subarctic research basin located in the uplands northeast of Fairbanks. It is in an area of discontinuous permafrost, with hydro-meteorological monitoring since 1969. The ecology of the watershed has been monitored to assess the role of disturbance to the landscape (wildfire, herbivory, logging). Ongoing research occurs throughout the watershed and several meteorological stations and ecological research sites.

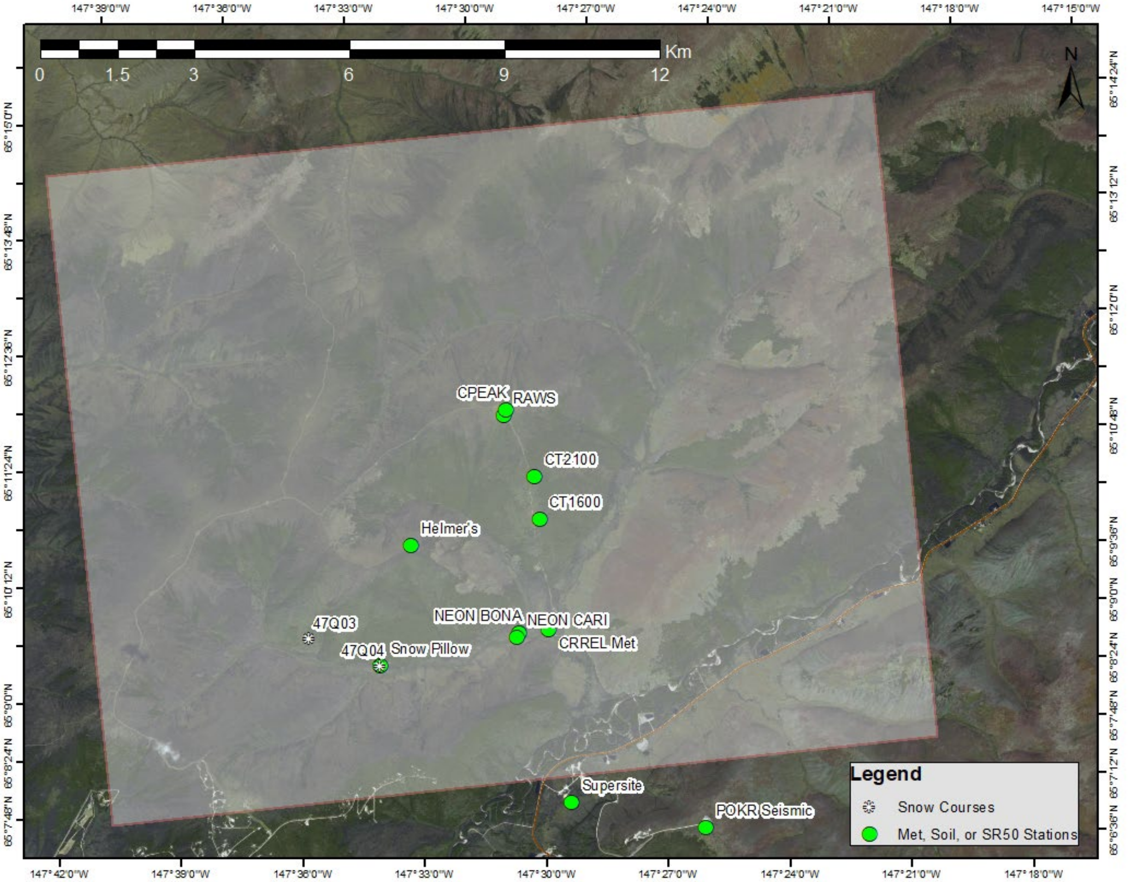


Figure 5.1.3: Location of existing meteorological, soil, and snow observation sites in CPCRW.

5.1.4. Toolik Field Station and Upper Kuparuk (Kuparuk)

The Upper Kuparuk and Toolik-Galbraith study areas are located in the vicinity of Toolik Field Station, in the northern foothills of the Brooks Range. It consists of rolling hills and valleys and is underlain with continuous permafrost. The first swath is along the west side of the Dalton Highway (MP273 to MP285) from Toolik Lake at the north end to the northern tip of Galbraith Lake in the south. The second swath is located south of the Dalton Highway near MP290 in the Upper Kuparuk River watershed. A few lakes exist in each swath.

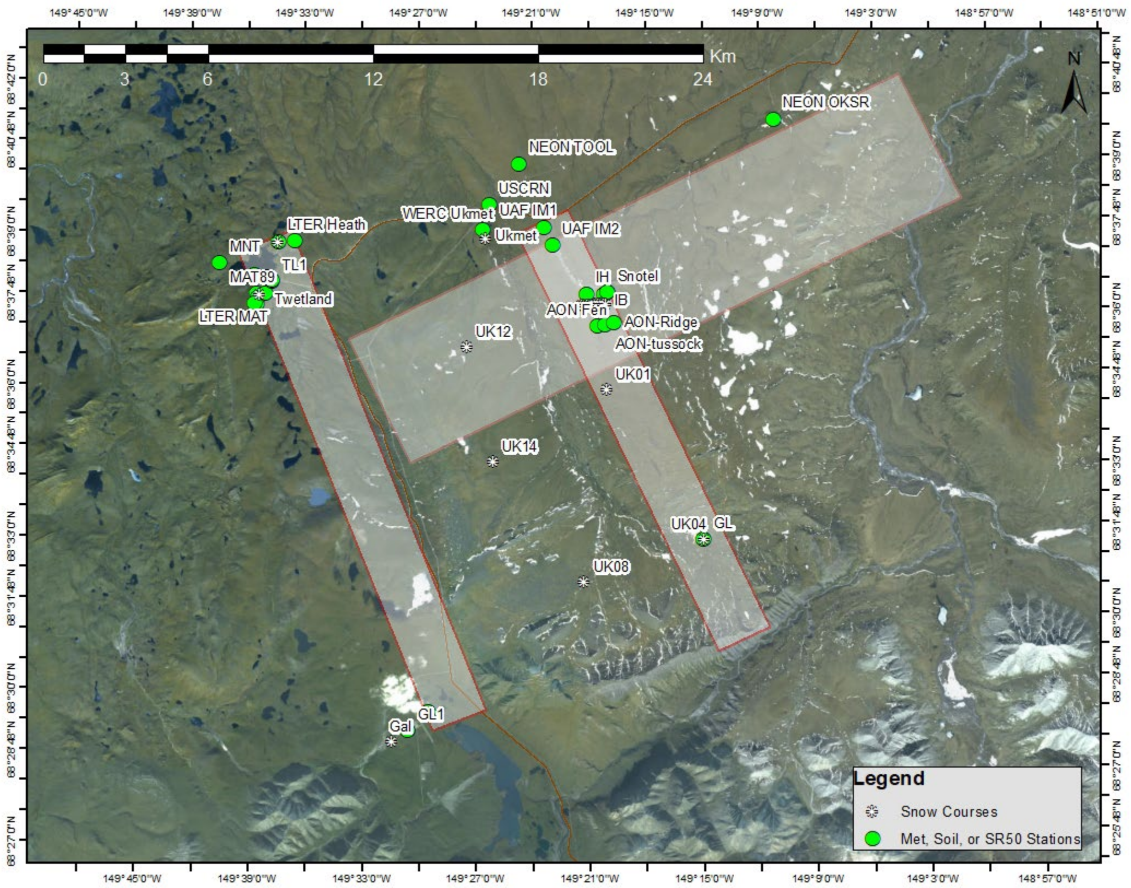


Figure 5.1.4: Location of existing meteorological, soil, and snow observation sites in Toolik and Upper Kuparuk.

5.1.5. Arctic Coastal Plain (ACP)

The Arctic Coastal Plain (ACP) extends from the northern Brooks Range foothills to the Beaufort Sea. The study area is a low-gradient region in the northern part of the ACP, 13 km (8 miles) south of the Deadhorse airport to the west of Franklin Bluffs. The area is underlain by continuous permafrost. The area of interest lies within the Putuligayuk and Sagavanirktok River basins along the Dalton highway. Lakes, ponds, and wetlands are common, as well as topographic features such as drained thaw lakes and ice wedge polygons.

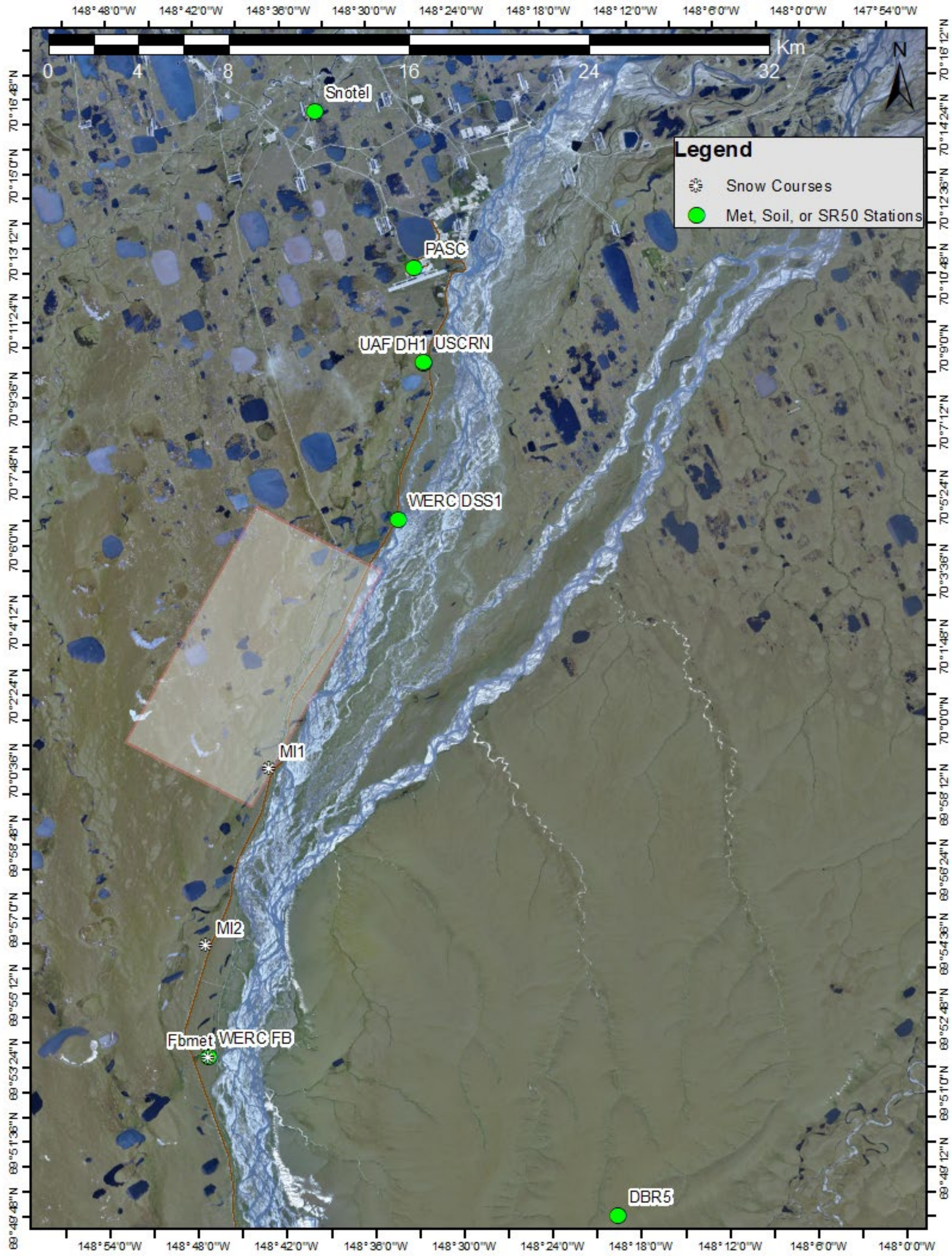


Figure 5.1.5: Location of existing meteorological, soil, and snow observation sites in Arctic Coastal Plain.

5.2. Sampling Strategy

Representative *in situ* measurements of snow characteristics are critical field experiment components. Our ground data collection objective is to provide high-quality, geospatially-referenced data sets coincident with airborne acquisitions (Section 4) to address the SnowEx Science Plan. Ground data collection objectives include quantifying the mean, variance, and distribution of snow properties at the five sites in Alaska. A snow field campaign strives to balance and optimize cost, instruments used (air and ground), a desired range of snow conditions, and to satisfy measurement gaps. It considers safety, ground assets (e.g., meteorological towers, SNOTEL, radar corner reflectors), terrain, access, and land ownership and management.

A major requirement of ground data collection is that ground measurements represent a wide range of snow conditions at the time of the airborne remote sensing overflights. Risks of significant changes in ground conditions increase with each passing day, therefore the ground data collection strategy is to complete all measurements in a given location within the campaign period centered on the overflights. This requires field personnel to be divided into three groups to perform ground measurements simultaneously in Interior Alaska near Fairbanks, in northern Brooks Range near Toolik Field Station and on Arctic Coastal Plain near Prudhoe Bay.

Within the campaign period, risks of significant change are not equal for different variables. First, new snow accumulation and deposition can affect snowpack depth, density, and surface reflectance. Second, evolutions of internal snowpack (grain size and stratigraphy) as well as soil and vegetation characteristics, while much less dynamic than surface characteristics, also influence the microwave remote sensing signal. Third, snow surface wetness and roughness at the time of the overflight can strongly influence the remote sensing signals (microwave), and can also be dynamic, changing on time scales of minutes to hours. These changes in snow characteristics often can be detected from snow pit and snow trench measurements,but are more difficult to identify from snow depth observations alone. Therefore, the ground data collection strategy takes into account a variety of measurement techniques, environmental characteristics, safety, field crew size and experience, and also prioritizes measurements to be made on the target day for airborne data collection in the study area.

Ground measurement locations are chosen randomly within snow and land cover classes to capture a range of snow depths, vegetation, and topography (Figure 5.2.1 and Figure 5.2.2.). For the purpose of SnowEx ground sampling design, snow cover is classified based on SWE mean and standard deviation using four classes: average, below average, above average, and snow drifts. This snow cover classification relies on modeled spatially-distributed SWE maps produced with SnowModel. SnowModel (Liston and Elder, 1998) simulations are performed on a 30 m grid using USGS National Elevation Dataset, North American Land Change Monitoring System Land Cover Class Definition Level 2 classification, and MERRA-2 reanalysis forcing to produce daily SWE, snow depth, and snow density simulation during SnowEx planning phase (2021–2022). In addition, lidar snow-on and snow-off data acquisitions occur in March, May, and July, 2022 over ACP, BCEF, CPCRW, and FLCF study areas. Lidar data are processed to produce snow depth and canopy height at 1-meter spatial resolution (see Section 4.2.2 for more details). Lidar-derived snow depth and vegetation map will be instrumental datasets to refine sampling design.

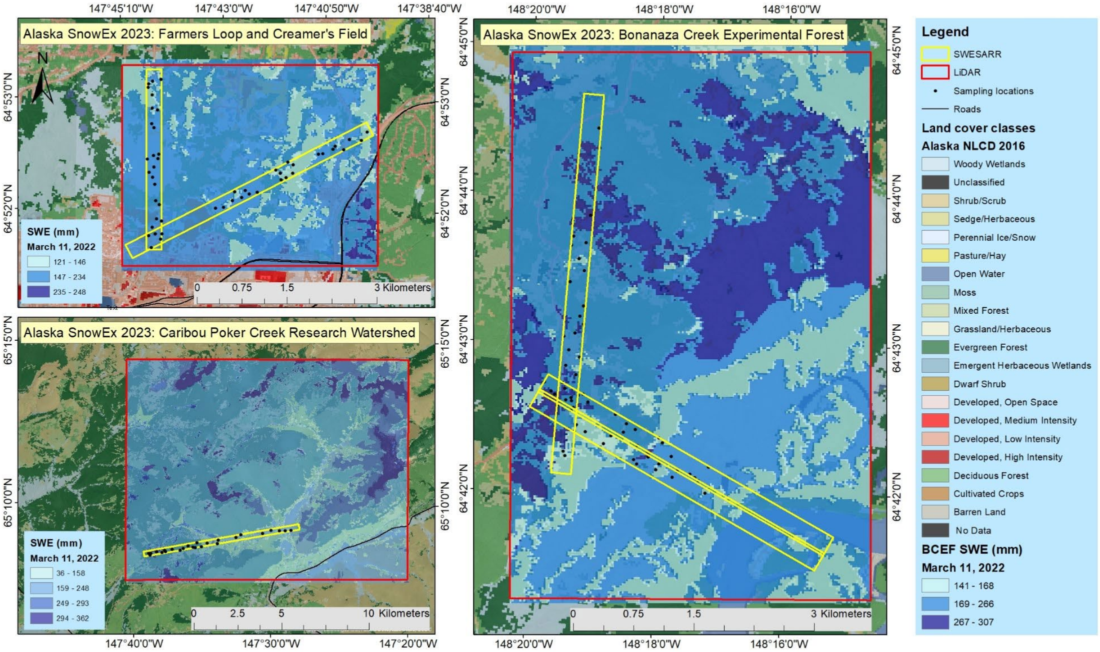


Figure 5.2.1 SWESARR (yellow lines) and lidar (red lines) swaths with preliminary sampling locations (black dots) represent a range of snow and land cover conditions in the Interior Alaska. Modeled SWE distributions overlay National Land Cover Dataset in the BCEF, CPCRW, and FLCF study areas.

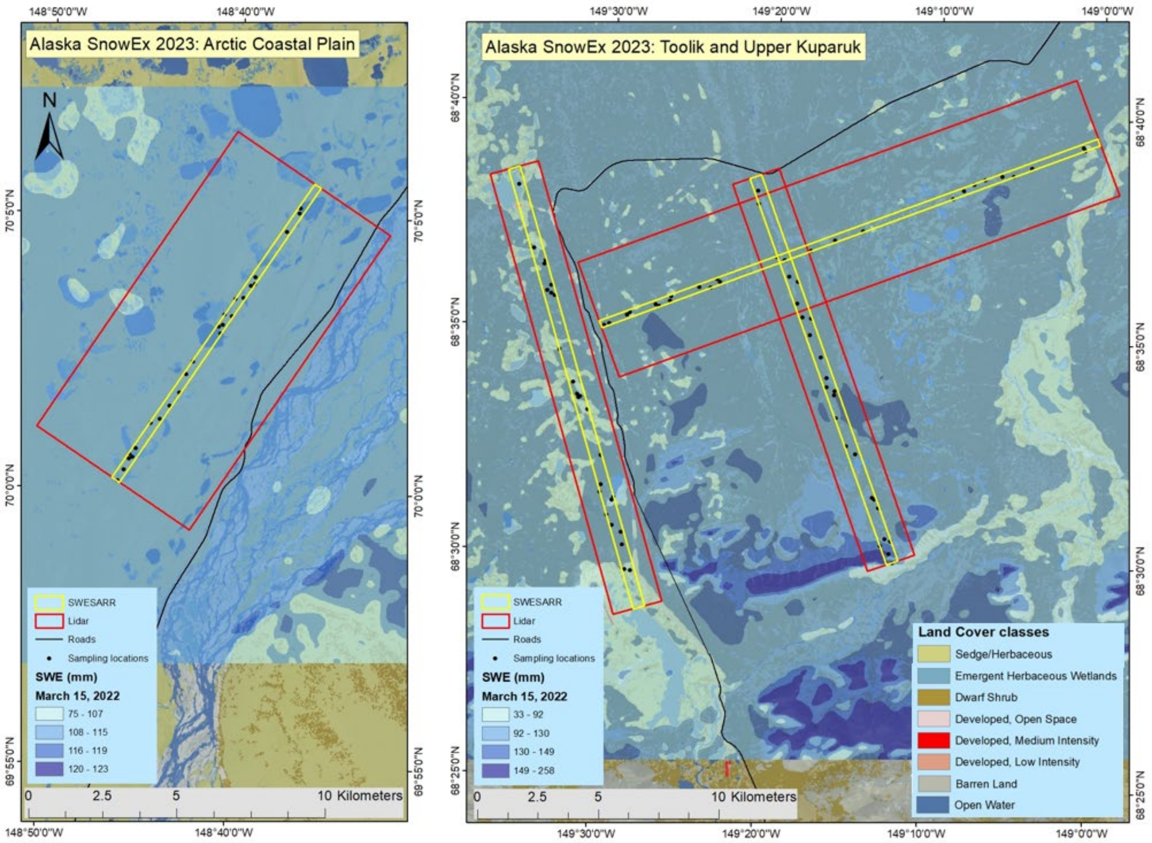


Figure 5.2.2 SWESARR (yellow lines) and lidar (red lines) boxes with preliminary sampling locations (black dots) represent a range of snow and land cover conditions on the North Slope of Alaska. Modeled SWE distributions overlay National Land Cover Dataset in the ACP and Kuparuk study areas.

Nested approach? Planning team discussed the possibility of identifying a small area with intensive ground sampling. Possibly at BCEF and Toolik/Kuparuk?

5.3. Core Observations

Details on the field sampling protocol are available in Appendix C. The following core observations will be collected at each site:

- Snow depth transects (probing)
- Snow interval boards
- SWE Tubes
- Snow Pits
    - Depth
    - Density
    - Temperature
    - Wetness
    - Stratigraphy
    - Grain Size
- Substrate properties (roughness, vegetation, frozen state)

5.4. Ground-Based Instruments

Ground-Based Instruments (GBI) for snow measurements include sensors to quantify snow properties from the snow pit wall, and non-destructive ground-based remote sensing sensors.

5.4.1. Tree Temperature

Two sensors are installed in BCEF to measure tree temperature directly. These measurements will aid in interpretation of radar measurements over the trees, since radar transmissivity of forests is sensitive to tree temperature.

5.4.2. Snow Microstructure

Snow microstructure controls and influences microwave radiative transfer through the pack. Quantifying it is key to understand the observations from SWESARR and assess the performance of radiative transfer models used in SWE retrieval algorithms. Microstructure will be characterized using three methods: 1) infrared reflectance from a laser operating at 1310 nm to quantify specific surface area (SSA) (e.g., IceCube (Gallet et al., 2009) and IRIS (Montpetit et al. 2012)); 2) microcomputed tomography (micro-CT) of snow samples to obtain three-dimensional (3-D) structure (e.g., Heggli et al., 2009); and 3) snow penetrometer (SMP) measurements of force to characterize the stratigraphy, and possibly to derive correlation length, density, and SSA (e.g., Proksch et al., 2015). It is anticipated that there will be vertically continuous SSA measurements in every pit, at least dozen SMP measurements around each pit, and snow casts from only a few pits.

5.4.3. Snow Surface Temperature

Snow surface temperature measurements are important for surface energy balance calculations and modeling.

5.4.4. Liquid Water Content (WISe)

SnowEx 2023 microwave observations are sensitive to the presence of liquid water in the snow pack. Vertical profiles of Liquid Water Content (LWC) will be measured in snow pits during the Time Series Campaign and the Grand Mesa IOP Campaign using WISe, the LWC probe commercialized by A2 Photonic Sensors (http://www.a2photonicsensors.com/medias/A2PS_WISe_EN.pdf). WISe was originally developed by Météo France and provides an easy and reliable means to obtain field LWC.

To obtain LWC estimates at a given depth, measurements of snow density are required for that depth. Either density value is entered manually to the WISe unit in the field, or a post-calculation is done. LWC can be expressed as volumetric or mass fractions. Field observers will utilize the SnowEx 2023 pit sheet to record values of permittivity and volumetric LWC. LWC may vary quickly as soon as the snow pit is opened, therefore LWC will be measured as soon as the snow pit is opened. Then, simultaneously temperature and stratigraphy will be recorded, followed by a visual inspection of grain type and size. Finally, the snow pit wall will be refreshed and snow density will be measured (Appendix C).

Measurement Characteristics. WISe measures the resonant frequency of the snow sample in the capacitor and uses the relation between snow permittivity in the MHz range and snow density to derive LWC. Given the above protocol, density values will not be available at the time of the measurement; the observer should record the permittivity on the data sheet. The WISe User Manual specifies the equations and parameters used to obtain LWC from snow permittivity and density.
LWC measurement range: 0-20 vol.
Typical measurement uncertainty: 1% vol.
Acquisition time: <1s
The WISe Quick Start Guide is available in Appendix XXX.

5.4.5. GPS snow-depth probes

All SnowEx 2023 snow depths will be tied to GPS positions around every pit location, while pit observations are on-going. The sampling design protocol will strive to have a high number of observations and remove user subjectivity to represent snow depth conditions in the area around the pit. Depth measurements will be made after radar acquisitions (Section 5.2.6.5) to ensure the availability of spatially overlapping data sets. For IOP measurements, it is anticipated that there will be two kinds of snow-depth probes deployed. MagnaProbes (Sturm and Holmgren, 2018) will be used where snow is shallower than 120 cm and GPS accuracy of ~3 m is acceptable. A 3-m long manual probe will also be used in concert with a rugged Juniper Mesa2 tablet, connected to a sub-meter accuracy Geode GPS antenna.

5.4.6. Radar

Radar systems offer the opportunity to survey depth/SWE over long distances, contributing to the assessment of depth/SWE retrievals from airborne observations. Ground penetrating radar (GPR) observations will first be collected around snow pits, where manual depth observations will be made along the radar tracks to calculate radar velocity, followed by larger spatial surveys to gain spatial coverage.

5.4.7. Terrestrial laser scanners (TLS)

TLS surveys give the community access to surface elevation and roughness, snow depth, and stand scale forest structure characteristics. It offers an opportunity to assess snow depth data from manual measurements and radar retrievals. Also, it will provide highly accurate surveys of the corner reflectors. Two TLS teams will be conducting site surveys during an October snow-free campaign at Bonanza Creek, and repeating them during the IOP (Table 5.2). This area encompasses black spruce forest on the relatively level part of Bonanza Creek, and the sites are located within the flight lines to bolster chances of coincident airborne data collection.

5.4.8. Radar Corner Reflectors

Engineering corner reflectors are needed to ensure 1) accurate geolocation of the radar images, and 2) assess radar backscatter measurements. Engineering corner reflectors differ from the science corner reflectors deployed at BCEF to infer radar scattering properties of forests. Corner reflectors must be oriented such that they are pointed perpendicular to the flight line, at the incidence and elevation angles appropriate for the airborne sensor. Coordination between airborne radar teams and the ground teams deploying these calibration targets is required. Approximately five engineering corner reflectors will be deployed in both the Fairbanks area, and the Toolik area.

Table 5.2. Tentative ground-based instruments to be deployed during SnowEx 2023 and current point of contact (POC).

Suggested Instrument	Observing Characteristics	POC/ Institution	Deliverables	Data Format	Personnel/ additional equipment Needed
Microstructure					
IceCube	laser reflectance at 1310 nm	Mike Durand Ohio State Univ.	SSA profiles in all snow pits	csv	1 person
IceCube	laser reflectance at 1310 nm	Juha Lemmetyinen FMI	SSA profiles in all snow pits	csv	1 person
IceCube	laser reflectance at 1310 nm	HP Marshall Boise State Univ.	SSA profiles in all snow pits	csv	1 person
IRIS	laser reflectance at 1330 nm	Paul Billecocq Univ. of Sherbrooke	SSA profiles in all snow pits	csv	1 person
Snow Casting for MicroCT	3-D snow structure	Zoe Courville ERDC-CRREL			1 person
Snow MicroPenetrometer	Penetration force	H.P. Marshall Boise State Univ.	Hardness vertical profiles, microstructural parameter profiles (e.g., SSA, structural element length, microscale strength, microscale elastic modulus)	csv, pnt format	1 person
SnowSurface Temperature					
Liquid Water Content					
WISe	LWC	Carrie Vuyovich GSFC	LWC profiles, permittivity profiles		6 people (pit observers)
GPS Snow-Depth Probe					
Depth probe, Mesa2, Geode	Depth		Coordinates, depths	csv	3 people (1p/sensor/pit team)
MagnaProbe	Depth		Coordinates, depths	csv	
Radar					
Multiband FMCW Radar	6-18 GHz, coherent	H.P. Marshall Boise State Univ.	Amplitude vs. time over FMCW sweep. Processed results include snow travel-time, depth, SWE, layer thickness,		1 person

			geolocated and time-stamped.		
GPR	1 GHz	Ryan Webb, Univ. of New Mexico Dan McGrath, Colorado State Univ.	Travel-time through snow, depth, SWE		2 people
Stratigraphy hardness probes					
		Kelly Elder, HP Marshall			added to pit equipment
Terrestrial Laser Scanners (TLS)					
Leica ScanStation C10	532 nm	Art Gelvin ERDC-CRREL	RTK Opus corrected GPS points, Geo-located TLS scans		2 people

5.5. Corner Reflector Experiment

Radar-tree interactions are to be assessed by placing twenty corner reflectors in the Bonanza Creek Experimental Forest study site within the SWESARR flight line. The ratio of the measured power to the measured power expected if no trees had been present will provide insight to the ability of future spaceborne missions to measure SWE in presence of forest cover. The sampling strategy is to place reflectors behind individual trees of a range of height and canopy density, focusing primarily on the range of forest cover less than 50%, as it is unlikely that radar at X- and Ku- frequencies will penetrate thick canopies. As there is likely to be significant variability in the radar response among trees of fairly similar canopy structural characteristics, our strategy is to have multiple corner reflectors in similar conditions. Due to the fairly low number of corner reflectors it is practical to install, we will focus on a single tree species, the black spruce (*picea mariana*). Black spruce is one of the most common trees in the boreal forest, and so is of wide relevance. Because it tends to grow in resource-limited areas, it tends to be both shorter in height and have less extensive canopies. Information on the radar response of the black spruce canopies will be used to 1) support retrieval of SWE under similar canopies across BCEF using SnowEx23 data; and 2) more broadly support better mapping of the expected fraction of SWE in boreal forest that may be visible to X- and Ku- radar.

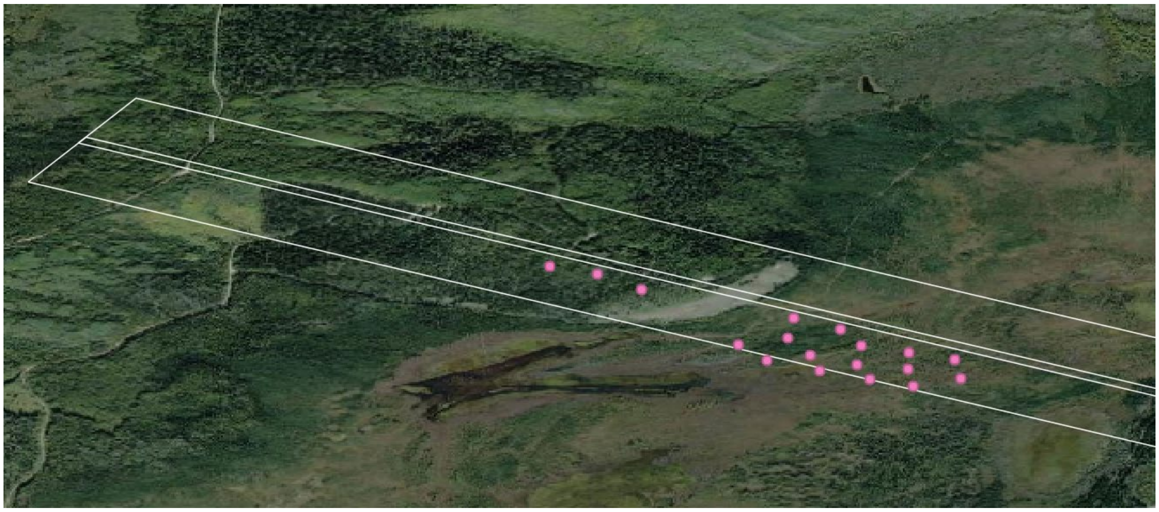


Figure. Example layout of SWESARR flight lines and corner reflector locations (to be updated after CR locations are finalized).

Most of the CRs are 18” in size, and trihedral in shape, with a theoretical radar response of 23 dB. Several CRs are 36” in size, with a theoretical response of 35 dB. The size refers to the smaller dimension of the isosceles right triangles that make up the CRs. Both 18” and 36” reflectors are expected to be clearly visible in SWESARR imagery, despite background radar clutter.

CR are installed to be oriented such that their inclination angles (degrees down from nadir) is equal to the angle at which SWESARR is looking. They are to be installed above the level of snow accumulation, and are fixed to the ground via the tripod legs and sandbags if necessary.

Three-dimensional models of each CR and the trees it sits behind will be created with a terrestrial lidar scanner (TLS). TLS measurements will be made prior to the campaign. The TLS data will be used to estimate structural properties of the canopy, such as biomass, tree dimensions etc., following the approach of Hojatimalekshah et al., 2021.

Figure. 18” (left) and 36” (right) corner reflectors deployed in BCEF as part of a March 2022 experiment.

6. Satellite Observations

6.1. Tasked Satellites

6.1.1. Maxar WorldView 1,2, and 3 (Formerly DigitalGlobe)

Thanks to improvements in satellite image resolution and pointing accuracy, DEM co-registration techniques, and processing software, stereo photogrammetry shows promise for mapping snow depths (Shean et al. 2016, Stereo2SWE THP-17 Project). Automated processing software can provide high-resolution (2-m posting) digital elevation models from stereo satellite imagery acquired during snow-free and snow-covered conditions. These DEM products can be differenced to yield snow thickness with vertical accuracy of better than 0.2-0.3 m, approaching that of airborne LiDAR at a fraction of the cost. However, this technique has not been widely applied or tested for snow depth measurements, especially in areas where extensive coincident ground measurements are going to be collected.

For SnowEx 2023, snow accumulation and melt during a time series is the focus. Bi-weekly high-resolution commercial imagery will be requested to synchronize with aerial and ground snow data collection efforts. Based on past experience, a subset of the sites centered on ground-based and aerial lidar measurements for all 5 areas will be the main priority. Snow-free mid- and late-summer collections in 2022 or 2023 are required over the same areas to generate "bare earth" snow-free DEMs for different vegetation growth states.

Repeat stereo imagery will be used to generate high-resolution DEMs and maps of snow depth for each time period. Snow depth ground observations and lidar data, collected by collaborators, will serve as validation datasets. The results of this effort may demonstrate that high-resolution satellite stereo imagery can be used to calculate snow distributions over broad and remote areas inexpensively compared with other techniques.

6.1.2. TerraSAR-X

Observations with multiple polarizations and high spatial resolution will be performed with X-band radar from TerraSAR-X, for a subset of the SnowEx2023 sites. These observations will be used to test for sensitivity to volume scattering from larger grains within the snowpack, by comparing co- and cross-polarization observations.

6.1.3. ALOS-2 PALSAR

6.1.4. Commercial x-band

6.2. Operational Satellites

In addition to satellite acquisitions specifically tasked for SnowEx 2022, there are a number of operational, globally observing satellite sensors that are relevant to the goals of SnowEx 2022. These are briefly described below, along with their relevance for snow property estimates.

6.2.1. Sentinel 1A, 1B

6.2.2. ICESat-2

7. Modeling

Advances in numerical simulation of snow and data assimilation techniques are needed to improve our global snow estimation capabilities, through data-merging of multiple remotely sensed and ground-based observations, gap-filling narrow-swath observations, and improved uncertainty estimation (NASA SnowEx Science Plan). Ongoing modeling efforts will support the SnowEx 2023 activities through the planning phase, during the campaign, and in analyzing the results.

7.1. Modeling over Alaska domains – Coming soon

8. Data Management Plan

The NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC), part of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder, will be the primary NASA data center for SnowEx data management and distribution. While this responsibility includes a wide range of tasks, this document specifically addresses the data management plan for the field campaigns and the data generated during them.

NSIDC support staff will be stationed in Fairbanks, AK and will support both the Fairbanks and North Slope field sites with data collection, entry, and first level QA/QC steps. The goal is to shorten the time it takes to publish the data and reduce the number of errors in the data, including typos, missing fields, undecipherable entries. Secondly, support staff will provide the means to back up raw data from various instruments prior to the end of the campaign periods. It remains the job of the PI and/or SnowEx leadership team to process data and prepare data submissions for any of the backed-up campaign data.

Campaign preparation

NSIDC SnowEx Team Lead (Stephanie Wong) and the SnowEx Data Support Scientist (Megan Mason) will develop a data entry tool that mimics the snow pit field books. They will coordinate with the ground sampling team to have a predefined location, site, and pit ID names and codes. Lastly, as part of the field training, NSIDC will provide instruction on data management protocol for field teams.

Data from field books

- NSIDC will provide and maintain a data input tool to be used for data entry at the base lodge in Fairbanks.
    - Provide personnel to assist with data management. They will be responsible for checking and entering data collected by field crews each evening, with support from the field crews as necessary. Any remaining questions will result in a follow-up with field teams the following day.
    - Travel in the field with the team to help with QC and other activities, and observe the data collection process in an effort to help streamline the data management and ingest processes.
- PIs and their field crews will be responsible for making their field books available each evening, and assisting NSIDC in the data entry steps, including clarification of missing data, unreadable text, etc.
- NSIDC will then generate the required file-level metadata and handle the data through its standard ingest processes.

Data from other ground-based instruments

Data from sources other than the field books will be handled on a case-by-case basis. In general NSIDC will be available for the following support needs:

- Backup data from additional instruments on a daily or end of campaign basis.
- Advise on data products and the submission process to support PI data collection.

Following campaign periods

- PIs will process and prepare data and upload data submission forms (https://nsidc.org/data/submit-data/submit-nasa-data-nsidc-daac/assigned-data)
- PIs will support NSIDC in the generation of the User Guides, metadata and other information necessary to support the distribution of data.
- NSIDC will work to ingest, archive, and make data available to the public in a timely manner given complete data submissions.

Data management assumptions

- SnowEx data product formats, with the exception of Level-0 or raw data, will conform to one of the NASA Earth Science Division (ESD) approved formats.
- All data will be managed within the ECS system and stored on ECS hardware.
- The MetGen software will be leveraged to produce file-level metadata for ingest and discovery purposes.
- An NSIDC developed data entry system will be used during the field campaigns

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Appendix A – List of Participants & Organizations

Appendix B – Detailed description of Study Sites

Bonanza Creek Experimental Forest (BCEF)

The Bonanza Creek Experimental Forest (BCEF) is located 20 km southwest of Fairbanks Alaska. It was established in 1963 and in 1987 joined the Long Term Ecological Research Network (LTER) as a research program to study boreal forests in changing landscapes. It consists of lowlands along the Tanana River floodplain as well as uplands, the rolling hills north of the floodplain. Permafrost is discontinuous and a few oxbow lakes exist in the floodplain.

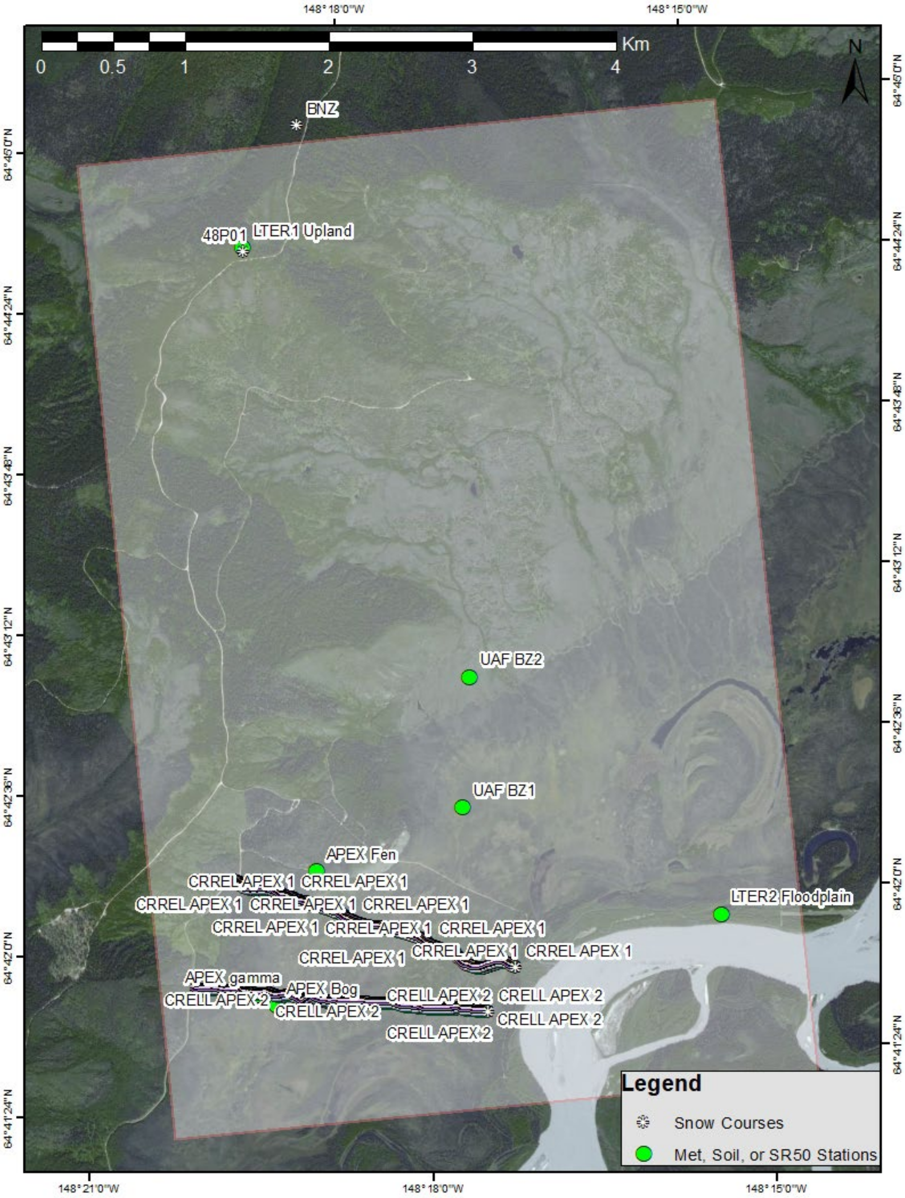


Figure 5.1.1: Location of existing meteorological, soil, and snow observation sites in BCEF.

Elevation range (m): The elevation ranges from 120 m above sea level (ASL) at the Tanana River floodplain to over 400 m ASL in the uplands.

Canopy: Taiga forest consists of deciduous (birch, aspen) and conifer (black spruce, white spruce), as well as wetlands/bogs, tundra, and shrubs in the sub-canopy.

Ownership: State of Alaska. Request permission to conduct research from the BCEF manager.

Brief historical background: Ecology and forestry studies have been conducted at BCEF since the 1950s. Snow surveys have been conducted at one NRCS location (site 48P01) since 1968.

Synergistic Activities in 2022-2023: LTER measures SWE and snow depth at two sites on a monthly basis (sites LTER1 [48P01] and BNZ). Alaska Peatland Experiment (APEX) and LTER collects soil and meteorological data at several sites in the study area. CRREL has two snow survey transects near the APEX study area.

Infrastructure

Numerous research projects are ongoing at BCEF, with several meteorological stations and snow courses.

Meteorological Sensors:

- LTER1 Upland; 64.7429558, -148.3163468 (air temp./rel. humidity, soil moisture, soil temp., wind speed, wind direction, snow depth) https://www.lter.uaf.edu/data/current-weather
- LTER2 Floodplain; 64.69889576, -148.2549125 (air temp./rel. humidity, soil moisture, soil temp., wind speed, wind direction, snow depth) https://www.lter.uaf.edu/data/current-weather
- APEX Black Spruce Forest Eddy Covariance Station; 64.69635, -148.3235 (air temp., rel. humidity, soil moisture, net radiation, soil temp, sonic anemometer)
- APEX Thermokarst Collapse Scar Bog Eddy Covariance Station; 64.69555, -148.3208 (air temp., rel. humidity, soil moisture, net radiation, soil temp, sonic anemometer)
- APEX Rich Fen Eddy Covariance Station (BZF); 64.703733, -148.313333 (air temp., rel. humidity, soil moisture, net radiation, soil temp, sonic anemometer)

Snow Sensors:

- LTER1 Upland; 64.7429558, -148.3163468 (snow depth, snow weighing bucket, snow pillow) https://www.lter.uaf.edu/data/data-detail/id/177 and https://www.lter.uaf.edu/data/data-detail/id/183 and https://www.lter.uaf.edu/data/data-detail/id/161

- LTER2 Floodplain; 64.69889576, -148.2549125 (snow depth, snow weighing bucket) https://www.lter.uaf.edu/data/data-detail/id/183 and https://www.lter.uaf.edu/data/data-detail/id/161
- Bonanza Creek 1 unburned (BZ1) UAF Permafrost Lab; 64.706944, -148.291281 (snow depth) https://permafrost.gi.alaska.edu/site/bz1

Snow Courses:

- Bonanza Creek NRCS snow survey site (48P01) near LTER1 Upland; 64.74273, -148.3161 http://www.lter.uaf.edu/data/site-detail/id/52
- LTER Bonanza Creek (BNZ) Snow Transect, 64.75034, -148.30675 http://www.lter.uaf.edu/data/site-detail/id/1268
- CRREL Snow Courses near APEX sites (ABOVE); see APEX coordinates https://catalog.data.gov/dataset/above-end-of-season-snow-depth-at-crrel-sites-near-fairbanks-alaska-2014-2019

Soil Sensors:

- LTER1 Upland; 64.7429558, -148.3163468 (soil temp./moisture)
- LTER2 Floodplain; 64.69889576, -148.2549125 (soil temp./moisture)
- Bonanza Creek 1 unburned (BZ1) UAF Permafrost Lab; 64.706944, -148.291281 (soil temp./moisture, snow depth) https://permafrost.gi.alaska.edu/site/bz1
- Bonanza Creek 2 burned (BZ2) UAF Permafrost Lab; 64.714997, -148.288546 (soil temp./moisture) https://permafrost.gi.alaska.edu/site/bz2
- APEX Black Spruce Forest Eddy Covariance Station; 64.69635, -148.3235 soil temp./moisture)
- APEX Thermokarst Collapse Scar Bog Eddy Covariance Station; 64.69555, -148.3208 (soil temp./moisture)
- APEX Rich Fen Eddy Covariance Station (BZF); 64.703733, -148.313333 (soil temp./moisture)

Time-lapse cameras:

- Bonanza Creek FP5C webcam; 64.71361, -148.147263 https://www.lter.uaf.edu/data/current-weather
- APEX Rich Fen Flux Tower; 64.7037, -148.3133 https://phenocam.sr.unh.edu/webcam/sites/bnzrichfen/
- APEX Black Spruce Flux Tower; 64.6963, -148.3235 https://phenocam.sr.unh.edu/webcam/sites/bnzblackspruce/
- APEX Thermokarst Bog Tower; 64.6955, -148.3208 https://phenocam.sr.unh.edu/webcam/sites/bnzthermokarstbog/

Ground-based remote sensing instrumentation:

Additional nearby stations: LTER operates numerous additional ecological research sites at BCEF. See their website for more information: https://www.lter.uaf.edu/data/data-catalog and https://www.lter.uaf.edu/data/current-weather

Field Logistics

Travel to site: Drive south ~27 km (~17 miles) on Parks Highway to BCEF turnoff on the south side of the highway near Mile Post (MP) 339.

Site Access: Snowmachine to BCEF from Parks Highway in winter months.

Avalanche/Other hazards: Dangerous winter driving conditions (snow and ice). Extreme cold temperatures are common (-20 to -40 F). Frostbite may occur on exposed skin. Animals (moose, bears) may be present.

Training: Wilderness first aid, Arctic field training, snowmobile orientation and safety, bear awareness, driver's safety and awareness).

Communication options: Cellular service is intermittent at BCEF. Iridium satellite phones or Garmin Inreach devices may be necessary to communicate where cellular coverage is poor. In the field, two-way radios may be helpful.

Farmers Loop and Creamer's Field (FLCF)

The site consists of Farmer's Loop and Creamer's Field, located in the Fairbanks North Star Borough, and is in an area of discontinuous permafrost. CRREL operates the Farmer's Loop permafrost experimental test site with meteorological, soil, and snow studies. They also have a research site at the Creamer's Field Migratory Waterfowl refuge.

Creamer's Field Site (6 W 465013 7193916). One CRREL research site is located at the Creamer's Field Migratory Waterfowl Refuge, and it is composed of a 500 m long transect.

Farmers Loop site: Past CRREL research efforts at this site are focused along two transects: Farmers Loop Transect 1 (6 W 468051 7194877), 400 m and Farmers Loop Transect 2 (6 W 467948 7194614), 500m. These two transects are part of the Cold Regions Research and Engineering Laboratory Farmers Loop permafrost experimental test site.

Figure 5.1.2: Location of existing meteorological, soil, and snow observation sites in Farmer's Loop and Creamer's Field.

Elevation range (m): Elevation ranges from 130 m (Creamer's Field) to 165 m ASL (Farmer's Loop).

Canopy: The transects cross a variety of ecotypes including mixed forest, deciduous forest, black spruce forest, wetland, moss, tussock, and disturbed tussock.

Ownership: The land ownership in the study area is a mix of private, Fairbanks North Star Borough, State of Alaska, University of Alaska, Bureau of Land Management, and Department of Defense. The Farmer's Loop meteorological station and snow survey transects are owned by the U.S. Army (Ft Wainwright) and operated by U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL). A portion of the study area is within the Creamer's Field Migratory Waterfowl Refuge. Numerous privately owned residences and businesses exist in the study area. The Alaska Dog Musher's Association (ADMA) maintains an extensive winter trail system throughout the study area. A low cost permit may be purchased from ADMA to use the trail system. (https://alaskadogmushers.com/trail-pass-and-membership/)

Brief historical background: The USACE ERDC Farmer's Loop Permafrost Research Site was originally established as the Fairbanks Permafrost Experiment Station in 1945. The 134-acre test facility is located just outside of Fairbanks, Alaska, on Farmers Loop Road with road and electric access. The site consists of subarctic taiga forest with black and white spruce with wetland soils underlain by ice-rich permafrost. This experimental area was intended as a test site for the design and development of new infrastructure construction techniques in cold climates.

Creamer's Field was operated as a dairy farm until 1966. The State of Alaska now manages the farm and the wildlife refuge. The extensive trail system in the study area is used by snowmobiles, cross-country skiers, skijorers, and dog mushers. Dog mushing races are frequent in February and March.

Synergistic Activities in 2022-2023: CRREL has several research areas at Farmers Loop/Creamer's Field study areas. A SNOTEL site was established at Creamer's Field in 2021.

Infrastructure

Meteorological Sensors:

- CRREL Farmer's Loop 6 meter tower; 64.875167, -147.673247 (air temp., rel. humidity, wind speed/direction, radiometer, Pluvio precip gauge, SR50 snow depth, soil temp., soil moisture)
- SNOTEL Creamer's Field; 64.86534, -147.73617 (air temp., rel. humidity, snow depth, SWE) https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=1302

Snow Sensors:

- CRREL Farmer's Loop 6 meter tower; 64.875167, -147.673247 (Pluvio precipitation gauge, SR50 snow depth)
- CRREL Farmer's Loop A-C (FLAC); 64.875838, -147.671457 (SR50 snow depth, above ground snow temp, soil temp./moisture)
- SNOTEL Creamer's Field (1302); 64.86534, -147.73617 (snow depth, SWE) https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=1302
- Aurora NWS (COOPBAURA2); 64.8552, -147.7216 (snow depth)

Snow Course:

- SNOTEL Creamer's Field; 64.86534, -147.73617 https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=1302
- CRREL Farmer's Loop; 64.877945, -147.682276 https://catalog.data.gov/dataset/above-end-of-season-snow-depth-at-crrel-sites-near-fairbanks-alaska-2014-2019

- CRREL Creamer’s Field; 64.86772, -147.738249 https://catalog.data.gov/dataset/above-end-of-season-snow-depth-at-crrel-sites-near-fairbanks-alaska-2014-2019

Soil Sensors:

- CRREL Farmer’s Loop A-C (FLAC); 64.875838, -147.671457 (SR50, above ground snow temp, soil temp./moisture)
- CRREL Farmer’s Loop thermosyphon site; 64.875404, -147.671687 (soil temp.)
- CRREL Farmer’s Loop 6 meter tower; 64.875167, -147.673247 (soil temp., soil moisture)
- CRREL Creamer’s Field (soil temp.)
- CRREL Boreal sites (soil moisture/temp.)
- CRREL Tom Douglas sites (soil temp.)

Time-lapse cameras:

- CRREL Farmer’s Loop wingspan timelapse camera

Ground-based remote sensing instrumentation:

Additional nearby stations:

- Fairbanks International Airport NWS/FAA (PAFA); 64.80389, -147.87611 (air temp., relative humidity, wind speed and direction, precipitation)
- Aurora NWS (COOPBAURA2); 64.8552, -147.7216, 443 ft. (snow depth, air temp.)
- College Observatory; 64.8603, -147.8484 (air temp., snow depth, daily precipitation)
- Fort Wainwright NWS/FAA (PAFB) (air temp., relative humidity, wind speed/direction) https://www.ncei.noaa.gov/access/search/data-search/global-hourly

Field Logistics

Travel to site: The CRREL sites at Farmer’s Loop are located 4 km north of Fairbanks off Farmer’s Loop Road. The Creamer’s Field SNOTEL site is located on College Road at the Creamer’s Field Migratory Bird Refuge. Access to the north side of the study area can be reached from Dog Musher’s Hall on Farmers Loop.

Site Access: Parking is available at Creamer’s Field off College Road and Dog Musher’s Hall off Farmer’s Loop. An extensive winter trail system exists throughout the study area and a low-cost permit to use the trails may be purchased from ADMA.

Avalanche/Other hazards: Dangerous winter driving conditions exist in the Fairbanks area (snow and ice on roadways). Extreme cold temperatures are common (-20 to -50 F). Frostbite may occur on exposed skin. Animals (moose, bears, dogs) may be present. Dog mushing and skijoring teams may be present on trails throughout the study area (Dog Musher's, Farmer's Loop, and Creamer's Field). Two large dog mushing races will be conducted March 10-12, 2023 and March 17-19, 2023 on the trails throughout the study area, contact the race directors for more information about avoiding the race course during these times.

Training: Wilderness first aid, snowmobile orientation and safety, bear awareness, driver's safety and awareness.

Communication options: Cellular service is available throughout the study area.

Caribou-Poker Creek Research Watershed (CPCRW)

Site Description

Caribou-Poker Creek Research Watershed (CPCRW) is a 104 km^2 subarctic research basin located in the uplands northeast of Fairbanks. It is in an area of discontinuous permafrost, with hydro-meteorological monitoring since 1969. The ecology of the watershed has been monitored to assess the role of disturbance to the landscape (wildfire, herbivory, logging). Ongoing research occurs throughout the watershed and several meteorological stations and ecological research sites.

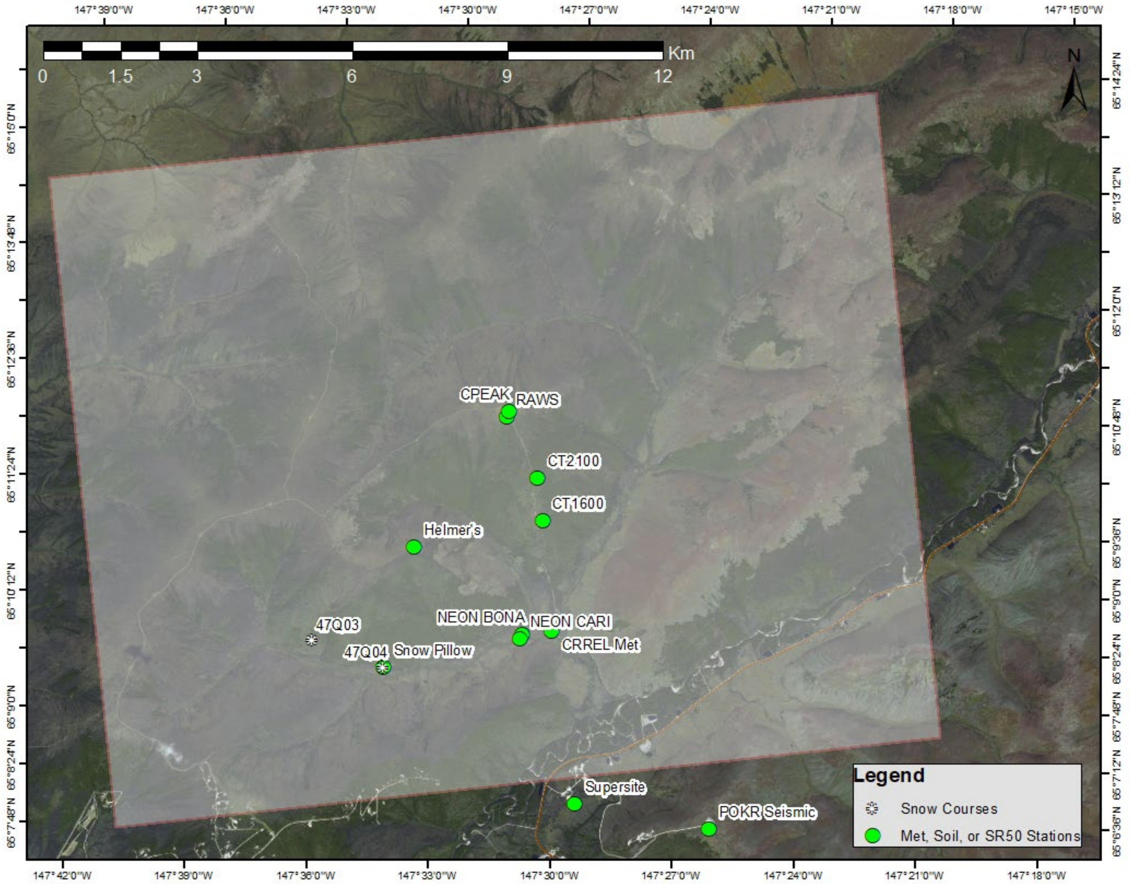


Figure 5.1.3: Location of existing meteorological, soil, and snow observation sites in CPCRW.

Elevation range (m): The elevation ranges from 200 m ASL in the valley bottoms to 800 m ASL at the ridgetop.

Canopy: The canopy consists of both deciduous (aspen, alder) and evergreen (mostly black spruce, some white spruce), as well as wetlands with tussock tundra in valley bottoms.

Ownership: State of Alaska. For access, contact the CPCRW manager prior to research.

Brief historical background: Caribou and Poker Creeks were established in 1969 as a research watershed. In 1993, the watershed was added to the Bonanza Creek Experimental Forest (LTER) monitoring program. Snow surveys have been conducted at two NRCS locations (Caribou Creek 47Q03 and Snow Pillow 47Q04) since 1970. In the late 1990s and early 2000s, UAF-WERC conducted end of winter and ablation snow and runoff measurements in the watershed.

Synergistic Activities in 2022-2023: Summer runoff measurements continue to be collected by UAF-Institute of Arctic Biology and NEON researchers. NEON collects various aquatic and hydro-meteorological data, as well as high resolution airborne remote sensing data in the watershed. Additionally, JAMSTEC/UAF-IARC has a 16-meter eddy flux tower collecting snow depth and other meteorological variables in nearby Poker Flats.

Infrastructure

Several hydro-meteorological stations and snow courses exist in the watershed.

Meteorological Sensors:

- Caribou Peak LTER; 65.19275, -147.499058 (air temp., rel. humidity, wind speed/direction, snow bucket, rain) https://www.lter.uaf.edu/data/current-weather
- Caribou Peak RAWS (CPKA); 65.1918, -147.5002 (air temp., rel. humidity, wind speed/direction), https://download.synopticdata.com/#a/CPKA2 and https://explore.synopticdata.com/CPKA2/metadata
- Helmer's Ridge LTER (offline/discontinued?); 65.17092, -147.543574 (air temp., rel. humidity, wind speed/direction) https://www.lter.uaf.edu/data/current-weather
- NEON BONA; 65.15401, -147.50258 (air temp., rel. humidity, wind speed/direction, weighing precipitation gauge) https://www.neonscience.org/field-sites/bona
- NEON CARI; 65.153224, -147.5039 (air temp., rel. humidity, wind speed/direction, net radiometer, summer runoff) https://www.neonscience.org/field-sites/cari
- CRREL Met LTER; 65.154, -147.490167 (air temp., rel. humidity, wind speed/direction, snow depth) https://www.lter.uaf.edu/data/current-weather
- Snow Pillow LTER; 65.15066, -147.56067 (air temp., rel. humidity, wind speed/direction, snow depth, rain) https://www.lter.uaf.edu/data/current-weather
- CT2100 LTER; 65.18078, -147.4897317- discontinued/manual downloads? (air temp., weighing rain gauge) https://www.lter.uaf.edu/data/site-detail/id/10
- CT1600 LTER; 65.17328, -147.4893991- discontinued/manual downloads? (air temp., weighing rain gauge) https://www.lter.uaf.edu/data/site-detail/id/9

Snow Sensors:

- Snow Pillow LTER; 65.15066, -147.56067 (SWE, snow depth) https://www.lter.uaf.edu/data/current-weather and https://www.lter.uaf.edu/data/data-detail/id/386 and https://www.lter.uaf.edu/data/data-detail/id/384
- Caribou Peak LTER; 65.19275, -147.499058 (snow bucket) https://www.lter.uaf.edu/data/current-weather and https://www.lter.uaf.edu/data/data-detail/id/384
- CRREL Met LTER; 65.154, -147.490167 (snow depth) https://www.lter.uaf.edu/data/current-weather

- NEON BONA; 65.15401, -147.50258 (weighing precipitation gauge) https://www.neonscience.org/field-sites/bona

Snow Courses:

- Caribou Creek Snow Survey Site NRCS/LTER (47Q03); 65.15642, -147.589 (snow depth, density) https://www.nrcs.usda.gov/wps/portal/nrcs/ak/snow/
- Snow Pillow Snow Survey Site NRCS/LTER (47Q04) CARSNOW; 65.15066, -147.56067 (snow depth, density) https://www.nrcs.usda.gov/wps/portal/nrcs/ak/snow/

Soil Sensors:

- NEON BONA; various to west-southwest of tower (soil temp./moisture) https://www.neonscience.org/field-sites/bona
- Snow Pillow LTER; 65.15066, -147.56067 (soil temp./moisture) https://www.lter.uaf.edu/data/current-weather
- Caribou Peak LTER; 65.19275, -147.499058 (soil temp./moisture) https://www.lter.uaf.edu/data/current-weather
- CRREL Met LTER; 65.154, -147.490167 (soil temp./moisture) https://www.lter.uaf.edu/data/current-weather
- Caribou-Poker Creek C4new, Poker1 (CPR) UAF Permafrost Lab; 65.180000, -147.440000 -discontinued? https://permafrost.gi.alaska.edu/site/cpr

Time-lapse cameras:

- CRREL Met LTER; 65.154, -147.490167 Webcam http://bnznet.iab.uaf.edu/vdv/vdv.php/webcam/5
- NEON BONA; 65.1540, -147.5026 https://phenocam.sr.unh.edu/webcam/sites/NEON.D19.BONA.DP1.00033 and https://phenocam.sr.unh.edu/webcam/sites/NEON.D19.BONA.DP1.00042 (snow cover)
- NEON CARI; 65.1531, -147.5025 https://phenocam.sr.unh.edu/webcam/sites/NEON.D19.CARI.DP1.20002
- Supersite IARC/JAMSTEC; 65.1237, -147.4876 http://monitors.iarc.uaf.edu/poker-flat-research-range/cameras.php

Ground-based remote sensing instrumentation:

Additional nearby stations:

- Poker Flat US Seismic ARRAY; 65.1171, -147.4335 (air temp., rel. humidity, wind speed/direction) http://www.usarray.org/alaska/met-sensors and https://download.synopticdata.com/#a/POKRX
- Supersite IARC/JAMSTEC; 65.1237, -147.4876 (air temp., rel. humidity, snow depth, wind speed/direction, soil temp., radiation.

http://monitors.iarc.uaf.edu/poker-flat-research-range/data.php and https://ameriflux.lbl.gov/sites/siteinfo/US-Prr

- Fairbanks USCRN; 64.97333,-147.50972 https://www.ncei.noaa.gov/access/crn/sensors.htm?stationId=1799 and https://www.atdd.noaa.gov/u-s-crn-groups-map/alaska-and-hawaii_group_map/ak-fairbanks/
- Cleary Summit Snow Course (47Q01) NRCS; 65.048, -147.4315 https://www.nrcs.usda.gov/wps/portal/nrcs/ak/snow/
- Steese Highway at Cleary Summit MP20.9 ADOT RWIS; (65.04703, -147.4465)

Field Logistics

Travel to site: Research watershed is located near MP30 of the Steese Highway, 48 km (30 miles) northeast of Fairbanks. At the town of Fox, turn east onto the Steese Highway.

Site Access: Access the site by turning north off the Steese Highway near MP30 and crossing the bridge over the Chatanika River (bridge access is locked and request permission from watershed manager).

Avalanche/Other hazards: Dangerous winter driving conditions (snow and ice). Extreme cold temperatures are common (-20 to -40 F). Frostbite may occur on exposed skin. Animals (moose, bears) may be present.

Training: Wilderness first aid, Arctic field training, snowmobile orientation and safety, bear awareness, driver's safety and awareness).

Communication options: Cellular service is intermittent. Iridium satellite phones or Garmin Inreach devices may be necessary to communicate where cellular coverage is poor. In the field, two-way radios may be helpful.

Toolik Field Station and Upper Kuparuk (Kuparuk)

Site Description: The Upper Kuparuk and Toolik-Galbraith study areas are located in the vicinity of Toolik Field Station, in the northern foothills of the Brooks Range. It consists of rolling hills and valleys and is underlain with continuous permafrost. The first swath is along the west side of the Dalton Highway (MP273 to MP285) from Toolik Lake at the north end to the northern tip of Galbraith Lake in the south. The second swath is located south of the Dalton Highway near MP290 in the Upper Kuparuk River watershed. A few lakes exist in each swath.

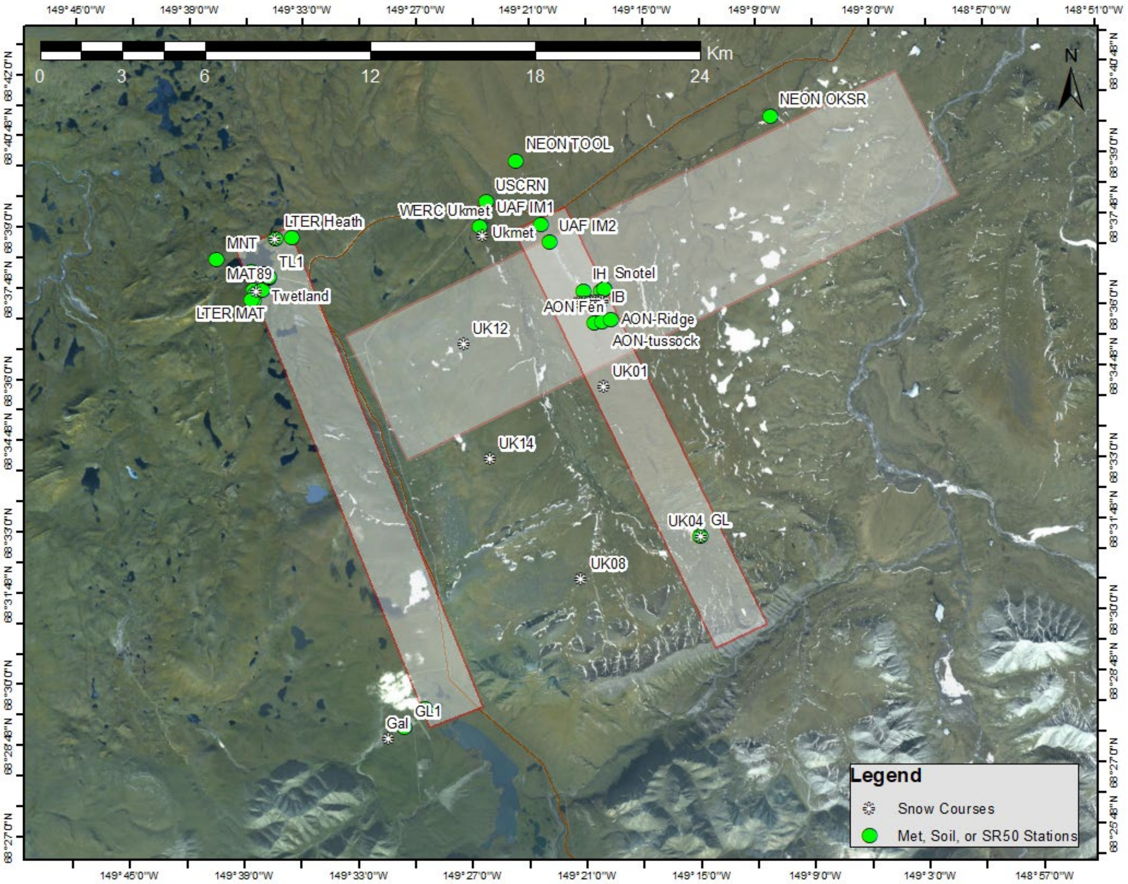


Figure 5.1.4: Location of existing meteorological, soil, and snow observation sites in Toolik and Upper Kuparuk.

Elevation range (m): The elevation of the Toolik-Galbraith swath ranges from 700 m to 800 m ASL. The elevation of the Upper Kuparuk swath ranges from 700 m to 1500 m ASL. The Brooks Range, located just south of the two swaths has elevations exceeding 1500 m ASL.

Canopy: Vegetation in the area consists of tundra (tussock, dwarf shrub, sedge, shrub, lichen), however at the highest elevations in the Upper Kuparuk watershed, the landcover may be bare soil or bedrock.

Ownership: Land at both Upper Kuparuk and Toolik-Galbraith areas are managed by BLM. Data collection will operate under existing UAF-WERC permits (F93768 and/or F97125). Note that an active airport exists at Galbraith Lake, within the Toolik-Galbraith swath. UAF (for National Science Foundation) operates Toolik Field Station located within the Toolik-Galbraith swath.

Brief historical background: Imnavait Creek began as a research watershed in the early 1980s. Toolik Camp was established in the mid-1970s during the construction of the Trans-Alaska Pipeline. Nearby airport is at Galbraith Lake which serves Alyeska Pipeline Service Company Pump Station 4. End of winter snow surveys have been conducted in the Upper Kuparuk (1997-2022) and Imnavait (1985-2022) watersheds by UAF-WERC and the NRCS SNOTEL site is in Imnavait Creek.

Synergistic Activities in 2022-2023: NRCS operates a SNOTEL station in Imnavait Creek. UAF-WERC measurements of end-of-winter snowpack, ablation, and streamflow at Upper Kuparuk and Imnavait watersheds. NEON collects high resolution airborne remote sensing data in the region and Oksruikuyak Creek is a NEON aquatic monitoring site.

Infrastructure

Several meteorological stations within the Upper Kuparuk and Imnavait watersheds, as well as at Toolik Field Station. Several stations also collect soil and snow variables.

Meteorological Sensors:

- Imnavait Met (IB) UAF-WERC; 68.616278, -149.303611 (HMP45C air temp., rel. humidity, RM Young and Met One wind speed/direction, SR50 snow depth, Eppley radiation). https://ine.uaf.edu/werc/werc-projects/imnavait/current-data/meteorological-stations/imnavait-met/
- Imnavait SNOTEL (968); 68.62, -149.3 (YSI thermistor air temp., Judd snow depth, automated storage precipitation gauge, Hydra Probe digital thermistor soil temp, Hydra Probe II soil moisture, LiCor LI200 solar radiation, RM Young 05103 wind speed/direction) https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=968
- Imnavait Creek CRREL (old Snownet site will be re-established August 2022). (snow depth, SWE sensor, soil temp./moisture, wind speed/direction, air temp., rel. humidity)
- AON Imnavait Eddy Flux towers; Fen-wet sedge 68.605833, -149.311014; tussock 68.606333, -149.304078; Ridge-dry heath 68.606808, -149.295805 (air temp., wind speed/direction, sonic anemometer, soil heat flux, net radiometer, soil moisture, soil temp., snow depth) http://aon.iab.uaf.edu/data_access and http://aon.iab.uaf.edu/project_sites?q=imnavait and https://ameriflux.lbl.gov/data/download-data/
- Upper Kuparuk Met UAF-WERC; 68.640139, -149.406500 (HMP45C air temp, rel. humidity, RM Young and Met One wind speed/direction, SR50 snow depth, Eppley radiation) https://ine.uaf.edu/werc/werc-projects/imnavait/current-data/meteorological-stations/upper-kuparuk-met/
- Green Cabin Lake Met UAF-WERC; 68.533611, -149.229833 (HMP45C air temp, rel. humidity) https://ine.uaf.edu/werc/werc-projects/imnavait/current-data/meteorological-stations/green-cabin-lake-met/

- US Seismic Array Toolik Field Station; 2012-present; 68.64080, -149.57240 (air temp., rel. humidity, wind speed/direction) http://www.usarray.org/alaska/met-sensors and https://download.synopticdata.com/#a/TOLKX
- UAF Toolik Field Station Met LTER; 68.6283, -149.5958; 1988-present (air temp. rel. humidity, wind speed/direction, snow depth) https://www.uaf.edu/toolik/edc/monitoring/abiotic/met-data-query.php
- UAF Toolik Moist Acidic Tussock LTER; 68.6241, -149.6067; 2017-present () https://www.uaf.edu/toolik/edc/monitoring/abiotic/met-data-query.php
- UAF Toolik Lake LTER
- NEON Toolik Lake (TOOK) (68.63069, -149.61064), (Air temp. rel. humidity, precipitation (weighing gauge), radiation, soil temp., soil moisture) https://www.neonscience.org/field-sites/took
- Galbraith Lake Airport (PAGB) NWS/FAA; 68.48333, -149.4833 (air temp., rel. humidity, wind speed/direction) https://download.synopticdata.com/#a/PAGB and https://www.ncei.noaa.gov/access/search/data-search/global-hourly

Snow Sensors:

- Imnavait SNOTEL (968); 68.62, -149.3 (snow depth, storage precipitation gauge) https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=968
- AON Imnavait Eddy Flux towers ; Fen-wet sedge 68.605833, -149.311014; Ridge-dry heath 68.606808, -149.295805 (snow depth) http://aon.iab.uaf.edu/data_access and http://aon.iab.uaf.edu/project_sites?q=imnavait and https://ameriflux.lbl.gov/data/download-data/
- Imnavait Creek CRREL (old Snownet site will be reestablished August 2022). (snow depth, SWE sensor) https://www.uaf.edu/toolik/edc/monitoring/abiotic/met-data-query.php
- Imnavait Weir UAF-WERC; 68.6167, -149.3187; (SR50 snow depth)
- Imnavait 1 (IM1) UAF Permafrost Lab; 68.639656, -149.352341; 2006-present (SR50 snow depth) https://permafrost.gi.alaska.edu/site/im1 and http://lapland.gi.alaska.edu/vdv/
- UAF Toolik Field Station Met LTER; 68.6283, -149.5958; 1988-present (snow depth) https://www.uaf.edu/toolik/edc/monitoring/abiotic/weather.php
- NEON Toolik Lake (TOOK); 68.63069, -149.61064; (precipitation weighing gauge, radiation) https://www.neonscience.org/field-sites/took

Snow Courses

- Green Cabin Lake UAF-WERC snow survey site; 68.533611, -149.229833, (manual snow depth, density, SWE) https://ine.uaf.edu/werc/werc-projects/imnavait/
- East Headwaters UAF-WERC snow survey site; 68.568778, -149.309 (manual snow depth, density, SWE) https://ine.uaf.edu/werc/werc-projects/imnavait/

- Imnavait Creek Transect UAF-WERC snow survey sites; (manual snow depth, density, SWE) https://ine.uaf.edu/werc/werc-projects/imnavait/
- Galbraith UAF-WERC snow survey site; 68.4780, -149.5030 (manual snow depth, density, SWE)

Soil Sensors:

- Imnavait 1 (IM1) UAF Permafrost Lab; 68.639656, -149.352341; 2006-present (soil temp./ moisture,) https://permafrost.gi.alaska.edu/site/im1 http://lapland.gi.alaska.edu/vdv/
- Imnavait 2 (IM2) UAF Permafrost Lab; 68.633592, -149.345909 (soil temp./ moisture) https://permafrost.gi.alaska.edu/site/im2 http://lapland.gi.alaska.edu/vdv/
- Imnavait Creek Met (IB) UAF-WERC; 68.616278, -149.303611 (soil temp.) https://ine.uaf.edu/werc/werc-projects/imnavait/current-data/meteorological-stations/imnavait-met/
- AON Imnavait Eddy Flux towers; Fen-wet sedge 68.605833, -149.311014; tussock 68.606333, -149.304078; Ridge-dry heath 68.606808, -149.295805 (soil heat flux, soil moisture, soil temp.) http://aon.iab.uaf.edu/ and https://ameriflux.lbl.gov/data/download-data/
- Imnavait Creek CRREL (old Snownet site will be reestablished August 2022). (soil temp./moisture)
- Galbraith Lake (GL1) UAF Permafrost Lab; 68.477413, -149.502416 (soil moisture/temp.) https://permafrost.gi.alaska.edu/site/gl1
- UAF Toolik Field Station Met LTER; 68.6283, -149.5958; 1988-present (soil temp.) https://www.uaf.edu/toolik/edc/monitoring/abiotic/weather.php
- Toolik Lake 1 (TL1) UAF Permafrost Lab; 68.628015,- 149.595377 soil moisture, soil temp.) https://permafrost.gi.alaska.edu/site/tl1
- NEON Toolik Lake (TOOK); 68.63069, -149.61064; (soil temp., soil moisture)

Time-lapse cameras:

- Various cameras at Toolik Field Station and Upper Kuparuk/Imnavait: https://www.uaf.edu/toolik/edc/monitoring/abiotic/time-lapse.php
- NEON (Upper Kuparuk camera) https://phenocam.sr.unh.edu/webcam/sites/NEON.D18.TOOL.DP1.00033 and https://phenocam.sr.unh.edu/webcam/sites/NEON.D18.TOOL.DP1.00042
- NEON (Toolik camera) https://phenocam.sr.unh.edu/webcam/sites/NEON.D18.TOOK.DP1.20002
- NEON (Oksrukuyik Creek camera) https://phenocam.sr.unh.edu/webcam/sites/NEON.D18.OKSR.DP1.20002/

Ground-based remote sensing instrumentation:

- NEON Toolik Field Station (TOOL); 68.66109, -149.37047; in Upper Kuparuk – (radiation sensors throughout array; airborne data includes remote sensing spectrometer and lidar flightlines/mosaics)

Additional nearby stations:

- NEON Toolik Field Station (TOOL); 68.66109, -149.37047; eddy covariance tower and soil pits in Upper Kuparuk
- NEON Oksrukuyik Creek (OKSR); 68.66975, -149.14302; aquatic monitoring, air temp.
- USCRN Toolik Lake; 68.64833, -149.39889 (Thermometrics PRT air temperature, Vaisala relative Humidity, Met One wind speed, Kipp and Zonen net radiation, Geonor T-200BM3 weighing bucket with double alter shield) https://www.ncei.noaa.gov/access/crn/sensors.htm?stationId=1799 and https://www.atdd.noaa.gov/u-s-crn-groups-map/alaska-and-hawaii_group_map/ak-toolik/
- ITEX-AON has sites in the Toolik and Imnavait Creek area to monitor soil conditions, NDVI, phenocam, and also a seasonally operated mobile instrumented sensor platform (MISP): https://www.gvsu.edu/itex-aon/weekly-field-season-updates-55.htm

Travel to site: The site is located in the northern foothills of the Brooks Range near Toolik Field Station, approximately 595 km (370 miles) north of Fairbanks. To reach the area, fly to Fairbanks and drive a 4-wheel drive truck to site. Alternatively, Alaska Airlines also flies to Deadhorse and the site is 205 km (128 miles) south of Deadhorse. Dalton Highway capable truck rentals are available in Fairbanks and Deadhorse and usually include spare tires and CB radio. Accommodations are available in Deadhorse or Toolik Field Station. Toolik Field Station has strict COVID-19 mitigation and quarantine requirements for entry (as of June 23, 2022 https://www.uaf.edu/toolik/news/covid-19.php).

Site Access: These areas may be accessed on foot by walking/skiing/snowshoeing or snowmobiles if sufficient snow cover is present (according to State of Alaska DNR tundra travel regulations). The Toolik-Galbraith swath is located near MP273-285 of the Dalton Highway, and encompasses the UAF Toolik Field station at the north. The northern end of the swath can be accessed from Toolik Field Station, and the southern end can be accessed from the Galbraith Airport road. The Galbraith area typically has low snow cover and can also be accessed by walking or skiing off the highway.

The northern end of the Upper Kuparuk swath is located off the Dalton Highway near MP290.5. If accessing the Upper Kuparuk swath from Toolik Field Station, drive 8 km (5 miles) north to the Imnavait Creek access road at MP290.5. There may be a pullout in the vicinity of the Alyeska gate. Do not block Alyeska gate access. Depending on road and snow conditions, the area can be accessed in early winter by driving or walking the access road 3.2 km (2 miles) into the Imnavait Creek watershed, however, the access road is unmaintained and not plowed.

Avalanche/Other hazards: Dangerous driving conditions, use CB radio on channel 19 to communicate with other drivers and follow all speed limits (50 mph) for Dalton Highway. Vehicle should be 4-wheel drive and have at least 1-2 spare tires and a jack for changing spare tires. Winter tires are necessary. Avalanche danger exists at Atigun Pass in the Brooks Range. Extreme cold temperatures are common (-20 to -40 F), high winds (20-30 mph) and blowing snow frequently causes whiteout conditions. Foggy conditions may be present resulting in difficult navigation. Frostbite may occur on exposed skin. Animals (caribou, moose, bears) may be present.

Training: Wilderness first aid, Arctic field training, snowmobile orientation and safety, bear awareness, driver's safety and awareness (geared toward Arctic/oilfields/Dalton Highway).

Communication options: Cellular service is available through AT&T and GCI at the southern end of Galbraith Lake only. Iridium satellite phones and/or Garmin Inreach devices are necessary to communicate while in the field. In the field, two-way radios may be helpful.

Arctic Coastal Plain (ACP)

Site Description The Arctic Coastal Plain (ACP) extends from the northern Brooks Range foothills to the Beaufort Sea. The study area is a low-gradient region in the northern part of the ACP, 13 km (8 miles) south of the Deadhorse airport to the west of Franklin Bluffs. The area is underlain by continuous permafrost. The area of interest lies within the Putuligayuk and Sagavanirktok River basins along the Dalton highway. Lakes, ponds, and wetlands are common, as well as topographic features such as drained thaw lakes and ice wedge polygons.

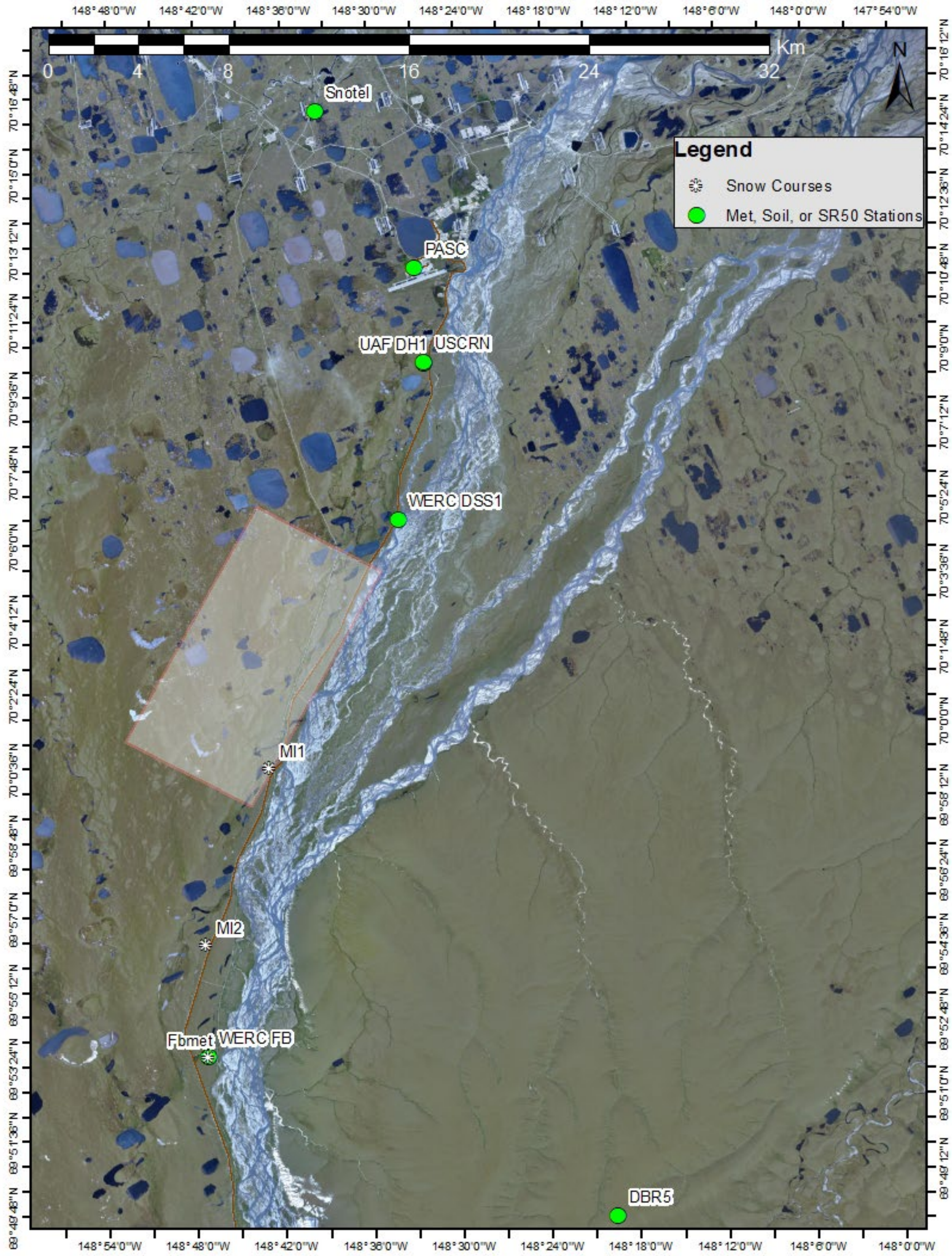


Figure 5.1.5: Location of existing meteorological, soil, and snow observation sites in Arctic Coastal Plain.

Elevation range (m): The elevation in the study area ranges from 45 m ASL at the southern boundary to 20 m ASL at the northern boundary.

Canopy: Vegetation consists of tussock tundra (including sedges and dwarf shrubs).

Ownership: The study area is managed by the State of Alaska Department of Natural Resources and SnowEx will operate under existing UAF-WERC permit ADL 420615.

Brief historical background: The area is approximately 13 km (8 miles) south of the Prudhoe Bay oil fields. Numerous ecological and hydrological studies have been conducted in the Prudhoe Bay area in support of private (oil-related) and public (primarily transportation/roads) development projects. Two historical UAF-WERC snow surveys sites exist in the swath, but are no longer active sites.

Synergistic Activities in 2022-2023: NRCS has a SNOTEL site to the west of Prudhoe Bay. Academia, private industry, and State of Alaska researchers may collect additional snow and meteorological measurements in the Deadhorse area.

Infrastructure

Several meteorological sites exist near the ACP study area, but none within the swath itself.

Meteorological Sensors:

- Franklin Bluffs Met UAF-WERC; 69.8886, -148.775; 1986-2017 (HMP45C air temp, RM Young 10 m wind speed/direction, SR50 snow depth) https://ine.uaf.edu/werc/werc-projects/teon/stations/franklin-bluffs/)
- Sagavanirktok River near MP405 (DSS1) UAF-WERC; 70.0991, -148.5085; (air temp., rel. humidity, wind speed/direction, tipping bucket, camera) https://ine.uaf.edu/werc/projects/sagdot/dss1.aspx and https://ine.uaf.edu/werc/projects/sagdot/Default.aspx
- USCRN Site at Deadhorse 3S; 70.16167,-148.46472; 2014-2022 (Thermometrics PRT air temperature, Vaisala relative Humidity, Met One wind speed, Kipp and Zonen net radiation, Geonor T-200BM3 weighing bucket with double alter shield) https://www.ncei.noaa.gov/access/crn/sensors.htm?stationId=1793&date=2021-11-18+1400+Local) and https://www.atdd.noaa.gov/u-s-crn-groups-map/alaska-and-hawaii_group_map/ak-deadhorse/
- Deadhorse Airport (PASC) NWS/FAA; 70.2, -148.4667; 1972-2022; (air temp, rel. humidity, wind speed/direction, snow depth); https://www.ncei.noaa.gov/products/land-based-station and https://www.ncei.noaa.gov/access/search/data-search/global-hourly
- Prudhoe Bay SNOTEL (1177);70.26666, -148.5666; 2011-2022; (YSI thermistor air temp, Judd snow depth, automated storage precipitation gauge, Hydra Probe digital thermistor soil temp, Hydra Probe II soil moisture, LiCor LI200 solar radiation) https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=1177
- Franklin Bluffs UAF Permafrost Lab FBW (wet site) and FBN (new site); 69.6739, -148.7219; 2016-2022; air temp, soil temp, soil moist, SR50 snow depth) https://permafrost.gi.alaska.edu/site/fbn and https://permafrost.gi.alaska.edu/site/fbw

- Deadhorse (DH1) UAF Permafrost Lab;70.1613, -148.4653; 2007-2022 (air temp, soil temp, soil moisture, SR50 snow depth) https://permafrost.gi.alaska.edu/site/dh1

Snow Sensors:

- Prudhoe Bay SNOTEL (1177); (snow depth, automated storage precipitation gauge) https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=1177
- USCRN site Deadhorse (Geonor weighing bucket gauge), https://www.ncei.noaa.gov/access/crn/sensors.htm?stationId=1793&date=2021-11-18+1400+Local), https://www.atdd.noaa.gov/u-s-crn-groups-map/alaska-and-hawaii_group_map/ak-deadhorse/
- Deadhorse Airport (PASC) NWS/FAA; 70.2,-148.4667; 1972-2022; (snow depth) https://www.ncei.noaa.gov/products/land-based-station and https://www.ncei.noaa.gov/access/search/data-search/global-hourly
- Deadhorse (DH1) UAF Permafrost Lab;70.1613, -148.4653; (snow depth) https://permafrost.gi.alaska.edu/site/dh1
- Franklin Bluffs (FBW, FBN) UAF Permafrost Lab; 69.6739, -148.7219; (snow depth) https://permafrost.gi.alaska.edu/site/fbn and https://permafrost.gi.alaska.edu/site/fbw

Snow Courses:

- MI1 UAF-WERC snow survey site; 70.0032, -148.6792 (manual snow depth, density, SWE)

Soil Sensors:

- Deadhorse (DH1) UAF Permafrost Lab;70.1613, -148.4653; (soil temp./moisture) https://permafrost.gi.alaska.edu/site/dh1
- Franklin Bluffs (FBW, FBN) UAF Permafrost Lab; 69.6739, -148.7219; (soil temp./moisture) https://permafrost.gi.alaska.edu/site/fbn and https://permafrost.gi.alaska.edu/site/fbw

Time-lapse cameras:

- Sagavanirktok River near MP405 (DSS1) UAF-WERC webcam; 70.0991, -148.5085; https://ine.uaf.edu/werc/projects/sagdot/dss1.aspx
- Deadhorse Airport (PASC) NWS/FAA webcam; 70.2,-148.4667; https://weathercams.faa.gov/

Ground-based remote sensing instrumentation:

Additional nearby stations:

- Alaska Department of Natural Resources Snow Survey Sites (monthly field measurements October to ~December each year of snow depth, SWE, and soil temp.)

Field Logistics

Travel to site: The site is approximately 800 km (500 miles) north of Fairbanks. To reach the ACP, fly to Fairbanks and drive a 4-wheel drive truck to site. Alternatively, Alaska Airlines also flies to Deadhorse. Dalton Highway capable truck rentals are available in Fairbanks and Deadhorse and usually include spare tires and CB radio. Accommodations are available in Deadhorse.

Site Access: The site is accessed by driving approximately 13 km (8 miles) drive south of Deadhorse. Site is located along the Dalton Highway between MP397 to MP405. Site may be accessed on foot by walking/skiing/snowshoeing or use snowmobiles if sufficient snow cover is present (according to State of Alaska DNR tundra travel regulations).

Avalanche/Other hazards: Dangerous driving conditions, use CB radio on channel 19 to communicate with other drivers and follow all speed limits (50 mph) for Dalton Highway. Vehicle should be 4-wheel drive and have at least 1-2 spare tires and a jack for changing spare tires. Winter tires are necessary. Cold temperatures are common (-20 to -40 F); high winds (20-30 mph) and blowing snow frequently cause whiteout conditions. Foggy conditions may be present resulting in difficult navigation. Frostbite may occur on exposed skin. Animals (caribou, musk ox, bears) may be present.

Training: Wilderness first aid, Arctic field training, snowmobile orientation and safety, bear awareness, driver’s safety and awareness – geared toward Arctic/oilfields/Dalton Highway).

Communication options: Cellular service is available through AT&T, GCI, and Verizon within 8 km (5 miles) of Deadhorse. Outside of Deadhorse, Iridium satellite phones and/or Garmin Inreach devices are necessary. In field, two-way radios may be helpful.

Appendix C – Field Sampling Protocol

C.1. Snow Depth Measurements (Probing)

Snow depth (HS), or height of snowpack, will be measured at locations identified on the map. Locations will be identified in tabular (UTM) form, and loaded onto GPS units in the form of searchable waypoints. Relative locations will be identifiable on a site map for approximate location by field teams. Three different probing tools will be employed based on location and need:1) manual depth probe (1 m sections attachable into 10 m+ probes), 2) digital Magnaprobe, and 3) folding avalanche probe (3.2 m). These tools will allow for four different recording and measurement methods: 1) 1 m probe with Mesa2 digital tablet, 2) Magnaprobe with datalogger and notebook for site beta and anomalies, 3) 1 m probe with notebook and handheld GPS, and 4) avalanche probe with notebook. Method 1 and 2 will be preferred methods, with method 3 used for failure of digital equipment and method 4 used with Magnaprobe when instrument maximum depth is exceeded.

Depth will be measured to the nearest 1 cm (0.01 m) by probing vertically into the snowpack (plumb to Earth's center - not perpendicular to local slope).

The following steps outline the general procedure for sampling snow depth with the manual probe and Mesa2 tablet:

1. Locate initial sampling point using visual aids (marked stake), maps, photographs and GPS.
2. Record sample depth in appropriate location on the data tablet or field book to the nearest centimeter. Use centimeters rather than meters to avoid decimal points for field notes.
3. Locate direction of the next sample point from the field map. It will be one of the four cardinal directions and the distance and direction will be listed in an adjacent column in the field book. Use a compass (corrected for local declination, e.g. 9.5^{O} E for Grand Mesa, CO) to determine the direction of the next pit on the ground
4. Use the 5-m probe to mark off the appropriate distance in the correct direction. If the distance to the next point is more than 5-m, be careful to measure the distance accurately. If a probe that is more or less than 5-m is being used to measure the horizontal distance, be careful to compute the correct distance as it is measured on the ground.
5. Repeat the depth measurement and recording as in steps 2 and 3 above.

Figure B.1 This stake has an ablation cone or hollow next to the metal stake on the south side and a wind-scoured depression around the PVC stake on the north side. Snow measurements should be made outside of these disturbed areas in the uniform snow cover.

Notes on Sampling Snow Depth

The snow depth probes have marks every centimeter, with lines at five centimeter increments. Each ten centimeter increment is labeled numerically, and all probe extensions are labeled identically. Since the probes are all marked numerically from 10 to 90 cm, it is very easy to be 1.00 m off by miscounting the number of extension sections in the snowpack. For example, it is easy to record 313 cm when the depth is actually 213 cm. This mistake has obvious and serious consequences to our sampling scheme. Be sure to keep track of the depths closely, the number of sections that are included in the total probe, and question the measurements. If they seem odd, they may well be mistakes.

Most of the depths that will be encountered at most of the sampling locations will be less than 5 m. The easiest method for sampling and measuring distances between samples is achieved with a 5 m pre-assembled probe length. This length will allow sampling of most depths, and will allow easy measurement of the distance between the original stake position and subsequent point to be sampled. Since the points are all at distances that are increments of 5 m, it is simple to use the 5 m probe to mark off horizontal distances. When sampling in heavy timber, use a 5 m probe to measure horizontal distances and a 1 or 2 m probe to sample depths. It is sometimes difficult to get the 5 m probe upright in forested areas due to canopy and branches. Do not move the sampling point to make the collection easier as it will bias the sampling and affect depth statistics.If the horizontal measurement puts the measurement location in a tree well do not adjust it to obtain a sample in the deeper snow. Record in the comment section for that point that it was a tree well. If it is suspected that the probe hit a fallen tree, stump, boulder or other surface anomaly, do not resample elsewhere. Record the suspicion in the comment section. Basically, no subjective decisions should be made to alter the sampling scheme that will bias the sample. If the sample location falls exactly on a tree, record zero depth and note that it was a tree location.

Check the compass bearings regularly. In heavy timber it is easy to turn slightly at each measurement. If the compass is checked often for bearing, then more accurate locations will be obtained. The locations of the measurements, as well as the snow depths, are critical to the research objectives.

Snow depth will be sampled with collapsible snow probes. The probes have one cm (0.01 m) increments and snow will be measured to the nearest 0.01-m. Probes are constructed in 1.00 m long sections and can be joined together to sample snow depth up to about 14 m. It is more difficult to carefully insert the probe vertically if there is more than 5-m of probe attached. The probes are easy to use in shallow or low-density snowpacks. A number of factors make the simple measurement more problematic.

If more than eight sections are joined before inserting in the snowpack, bending will occur in the probe sections when attempting to lift the sections vertically from the horizontal to begin the depth sample. At depths greater than 8 m, simply add additional sections one at a time to the probes already inserted in the snowpack. If it is windy or the probes are hard to handle, start with 4-5 m and add sections one-by-one as you insert the probe.These additional sections can then be removed one or two sections at a time as the probe is extracted from the snowpack. Removing a probe longer than 8-m and attempting to lay it back down can result in bending and damage of the individual probe sections. (See cautionary note below about losing sections in the snowpack.) These probes are very strong in the vertical direction, but have little strength and considerable flexibility when stressed from the side. They will simply bend under their own weight if care in handling is not exercised.

Potential Problems and Solutions in Sampling Snow Depth

Ice lenses. Ice lenses may be mistaken for the ground surface. When in doubt, lift the probe a few more times and ram it vertically down to break through a suspected ice lens. This technique will not damage the tip of the probe, even if it is hitting a rock rather than soil or ice. With experience, one can usually discern between rock, ice and snow based on the feel and sound of the probe.

Sampling too deep. In areas with soft ground, mud or duff it is possible to probe considerable depths below the snow/soil interface. Field workers will develop a feel for the difference between snow and soil or mud with time. If the probe is going too deep, the probe will come back out of the snowpack out with mud on the tip. Simply reinsert the probe next to the last measurement and be careful to find the interface. It should be close to the last depth, less the suspected amount that it penetrated the soil. Some of the sampling areas are in moist or boggy areas that will most certainly present this problem.

Sticking probes. In deep snowpacks the probes may become stuck. This usually occurs in dense snowpacks (densities greater than 400 kg m-3) or very deep snowpacks where the friction on the probe becomes great. Additionally, moisture on the probe from surface melt may refreeze at depths in the cold portion of the snowpack as the probe is inserted. Short, swift downward probing motion followed immediately by retraction of the probe 20 – 40-cm, may minimize both of these problems. This type of rapid hammering motion seems to work well in difficult snowpacks. If a rest is needed, do so with the probe lifted slightly off the bottom of the current depth and chances of icing and sticking will be minimized. A “T” handle can be fitted on the top of the probe using the same set screws that hold additional probe sections together. The T handle is useful for driving the probe down, as well as for getting a probe unstuck. Usually a rotation of the T handle will dislodge a troublesome probe. The T handle should not be used to drive the probe in when more than a meter of probe is sticking out above the snow surface. This can easily result in a bent or broken probe section above the snow since there is little lateral support for the probe shaft.

Bending probes. In order to keep from bending the aluminum shafts as they are inserted into the snowpack, the probe should be held close to the snow surface. A height of 1-m above the snow surface is usually adequate. Holding the probe higher may result in bending or breakage of the shaft section above the snow surface. In low-density, shallow snowpacks, this is usually not an issue and probes can be easily inserted holding the probe in any fashion. If a section is bent, replace it with a different one and return the bent section to the field supervisor at the end of the day. Do NOT attempt to straighten it in the field.

Losing sections below the snow surface. Care must be taken to not lose a section of the probe down the hole. There are two key reasons for this concern: 1, the equipment is needed for the rest of the day, and 2, the probes are very expensive. If a section is lost down the hole, retrieval should be attempted immediately. Keep in mind that digging time increases exponentially with increase in depth. It will take hours to reach a probe section 3 or 4-m deep. We cannot afford to use excessive time recovering equipment during the experiment. If a probe section is lost and it is determined that it cannot be recovered in a reasonable amount of time, record the location with as much accuracy as possible (point number, coordinates, description, etc.) and continue sampling. The best scenario, of course, is to take precautions that will minimize the chance of loss in the first place. Three practices will help greatly toward this end. First, on a regular basis (every five measurements) check all of the screws in the probe to make sure that they are all snuggly inserted. They will slowly work their way loose in the probe, which can allow the section to become uncoupled. Second, always use both screws when assembling probes, whether simply adding one section or assembling a longer probe. There are two screws in each section for a reason - use them. Last, if many sections are in use (greater than five) and disassembly is desired before moving to the next sampling point, remove the entire probe before disconnecting section. It is easy to drop the bottom portion of the probe as it is disassembled it if it is still vertical and in the hole. It may slide back to the base of the snowpack in this case.

General care. These probes are strong in the vertical dimension, but weak laterally as stated above. Care should be taken in transporting them. If skiing with the probes assembled, as will doubtless happen between sampling points, do NOT use the probes as ski poles or any kind of support for balance or to keep from falling. Hold the probe near one end, drag the probe behind yourself and be careful not to bind it between trees or brush that will damage the sections. If there is a slightly bent section and it cannot be replaced with an unbent one, use the bent section at the top of the probe. This will minimize drift of the probe at depths and reduce the chance of breakage deep in the snowpack.

Set screws. Be careful not to turn the set screws in too far. The screws are stainless steel and the shafts are aluminum. This means the screw material is stronger than the shaft material and the threads will eventually cut the shaft wall and enlarge the holes if the screws are turned in too far. The screws need only be screwed in until the screw tip is flush with the outside diameter of the probe.

Screws may rattle out and be lost during transport in vehicles or on snow machines. Place one meter sections in ABS/PVC tubes for transport and check to see if screws are still in place at new assembly site. If screws are missing, check the bottom of the transport tube carefully as they are easily lost in snow. Replacement screws are included in the field kit, but they are expensive and easy to lose. Take care to minimize loss as we have a limited number of replacements.

C.2. Snow Surface Roughness

Snow surface roughness will be measured using various remote sensing techniques including TLS, drone-mounted instruments, and airborne LiDAR. Not all sites will receive the high-resolution surveys, however, so basic descriptive notes on the surface characteristics should be recorded for all snowpit sites. Notes should include a basic description of the snow surface roughness, e.g. smooth and flat, very rough sastrugi with 45 cm troughs, small 10 cm dunes spaced at 3-5 m apart, 1 cm surface hoar, etc.

Screws may rattle out and be lost during transport in vehicles or on snow machines. Place one meter sections in ABS/PVC tubes for transport and check to see if screws are still in place at new assembly site. If screws are missing, check the bottom of the transport tube carefully as they are easily lost in snow. Replacement screws are included in the field kit, but they are expensive and easy to lose. Take care to minimize loss as we have a limited number of replacements.

C.3. Snow Pits

Snow pit data will be manually recorded on collated data sheets, printed on write-in-the-rain paper. An online system of identical spreadsheets, managed by NSIDC, will allow field teams and assistants to enter the manually-recorded data into the digital version, providing rapid digitization of the snow pit data, thus minimizing transcription errors. The instructions below describe the snow pit measurement techniques.

Snow pit Orientation and Excavation

1. Locate pit stake based on maps, GPS and visual information. Do not trample area by foot, ski, or snowmobile. Go to the appropriate digging site without disturbing the surface of the snow that will be sampled by the current or subsequent data collection.
2. Choose a pit wall that will be shaded for sampling (i.e. north facing, or west facing in the morning or east facing in the afternoon). Be sure not to further disturb the surface or snow structure in this direction. Throw all excavated snow form the pit away from this sampling side. Most people leave two adjacent sides of the four pit walls clean and undisturbed for sampling. If the pit is being dug on a slope greater than 4 or 5 degrees, then the samples should be taken on one of the flanks parallel to the slope. This will insure that layers in the snowpack are sampled completely throughout the entire profile.
3. Mark the pit dimensions with a probe or shovel. Check the snow depth with a probe or ski pole. If the snow depth is 1-m or less, the pit area can be as small as 1.5-m by 1.5-m. If the snow depth is 2-m, then the pit area will need to be at least 2.0-m by 1.5-m. Pits that are deeper than 2-m need a shelf in half of the pit so that the person taking samples can reach the entire pit wall profile. This extra depth requires a pit surface area of about 2-m by 2.5-m. The best method is to start digging the total needed surface area from the beginning after marking the area with the shovel blade. The areas given above are based on ease of snow removal. Such a large surface area will not be needed to take measurements, but it is difficult to remove snow if the snow pit area is not large enough. For pits with depth less than or equal to 2 m, it is easier for one person to dig at one time. Two people digging at the same time just get in each other's way. One person can dig while the other person is getting sampling equipment ready. The density sampler, thermometer, and crystal card should be placed in the snow in a shaded spot to equilibrate with the snow temperature before use. Frequently switching will keep either team member from getting too tired. In pits approaching depths of 3-m or more, both team members can dig at the same time. Once the pit gets to about 2-m, one person can dig and throw snow to the surface and the other person can move snow away from the pit.
4. After the pit has been excavated to rough dimensions as given above, carefully shave the pit wall to be sampled with a flat shovel blade. An area about 0.5 to 0.7-m wide, over the entire depth of the snowpack, should be smoothed out for sampling. Be sure that the pit wall is vertical. Very little extra time is required to prepare a clean organized pit than a sloppy pit. A sloppy pit will result in compromised measurements.

Figure B.2. Carefully shave the pit wall to obtain a smooth surface. This is a critical step for accurate snow density measurements.

5. If the site will receive additional visits for snow pit measurements (e.g. time series sites), place a marker at least one meter beyond the sampled pit wall or disturbed snow to insure that the next sampling occurs in undisturbed snow. Two or more markers may be helpful and effective for managing undisturbed sampling space at time-series site that will be used multiple times.

6. After all measurements are taken and equipment is removed, backfill the snowpit for safety and to minimize changes in the snowpack from disturbance for the next sampling. Try to place all "dirty" snow in the snow pit bottom when backfilling to minimize radiation changes due to reduced albedo.

Notes on Snow Pit Location

Snow pit locations were chosen by a random selection of grid cell locations in each 1-km cell. The same relative locations were used in all twelve 1-km cells. Two snow pits will be excavated each winter at each snow pit site. It is important that the first sampling exercise does not influence the snowpack properties for the second sampling period. The primary concern is that traffic or disturbance of the snow during the first survey will alter the site such that anomalous conditions will be sampled in the subsequent survey. To minimize the problem, we will dig the first snow pit 2-m directly down slope of the pit-marking stake. The second pit will be dug 2-m directly up slope of the stake. All snow will be thrown down slope of the pits. It flat terrain where there is no discernable slope, the first pit will be located 2-m directly south of the stake and the second pit will be located 2-m directly north of the stake.

Snow Pit Depth

Place the snow depth probe against the pit wall in the center of the smooth area that will be sampled. Be sure that the probe tip is not pushed into the ground. Recorded the total depth as measured on the probe at the snow/air interface. Leave the snow depth probe in place against the pit wall for depth reference of other snow pit measurements (e.g. snow density, temperature, etc.), or place a folding rule to accomplish the same result

Figure B.3. Folding rule placed against pit wall for measurement height reference. It is often easier to secure a folding rule than a probe section by folding the unused portion and gently inserting it into the snow surface in a location that will not interfere with other measurements. Id snowpits are deeper than 2 m, a probe is preferable and may be secured against the pit wall with small sticks or snow. Remove any unneeded sections to minimize tipping by wind.

Snow Density Profile

1. Clear a flat place with the shovel to hold the scale. In shallow pits a level place on the snow surface will work. In deep pits a hole in the side of the pit wall will need to be carved out with the shovel. Be sure to make it big enough so that there will be no interference from the roof or sides of the hole when weighing samples. Remove the digital scale from the plastic case. Close the case and place it on the snow surface. Place the scale on top of the scale and make sure that the scale is level.

Figure B.4. Excavated hole in snowpit flank to provide a flat, protected location for the scale and fieldbook. Note that there is plenty of room to bring the density sampler in and out of the hole without knocking snow onto the scale or notebook. If the hole is too big, blowing snow will accumulate on the scale and book.

2. Turn on the scale and wait for it to equilibrate to zero. Place the empty cutter (without the lid) on the scale. The scale should read within two or three grams of the weight written on the back of the cutter. If not, check to be sure there is no excess snow or water on the cutter. If the reading is still anomalous, change the battery. If the reading still seems to be in error, use the spring scale as outlined below. If the reading is acceptable, push the tare button on the scale. Snow density can now be sampled. Note that many of the digital scales have an automatic timer that shuts off the scale if a measurement is not made in a period of a few minutes. If this happens, the tare is lost and turning the scale back on will give a zero weight again. If a sample is already in the cutter when this occurs, then measure the total weight (cutter and snow), then subtract the tare weight before recording the sample in the field book. Tare the scale with the empty cutter before taking another sample.

3. The sampler may be held in either hand. The handle is held like a ski pole and the cutter inserted with the handle in the vertical position. Position the tip of the density sample at the correct depth of the sample. Carefully line up the cutter so that the back of the cutter will be flush with the pit wall after insertion. Slowly and firmly press the cutter into the snow pit wall until the back of the cutter just barely touches the snow surface. Do not insert the cutter further so that the outside of the

cutter back is flush with the pit wall. That will result in over sampling of density, as compaction will occur.

Figure B.5. Carefully line the sampler up so the back plate is parallel to the pit face in all directions when fully inserted.

4. Hold the cutter in place with the one hand while placing the cutter lid vertically at the vertical edge of the cutter. Slowly and firmly insert the lid at the appropriate and to isolate the snow density sample. It helps to begin the insertion of the lid at an exaggerated angle to ensure that the sample is correctly isolated.

Figure B.6. Hold the sample in the pit wall with one hand while inserting the lid with the other. Angle of insertion is important for the lid to avoid sample error.

5. Pull the cutter and lid out of the snowpack and rotate the sampler to a horizontal position. Remove the cutter lid and inspect the sample. If the sampler has not successfully collected a complete sample, then discard the sample and repeat the measurement. If the cutter has over sampled due to an incorrect angle of the lid, do not attempt to shave the excess off of the sample after it has been removed. Discard the sample and repeat the measurement. If the insertion angle of the cutter is incorrect, the back of the cutter will not be flush with the snowpack when it is fully inserted. Do not attempt to correct this mistake after the cutter is partially or completely inserted.

This will disturb the sample and give unreliable results. Discard the sample and repeat the measurement. The samples should be staggered back and forth across the pit face so that the snow is undisturbed for each sample.

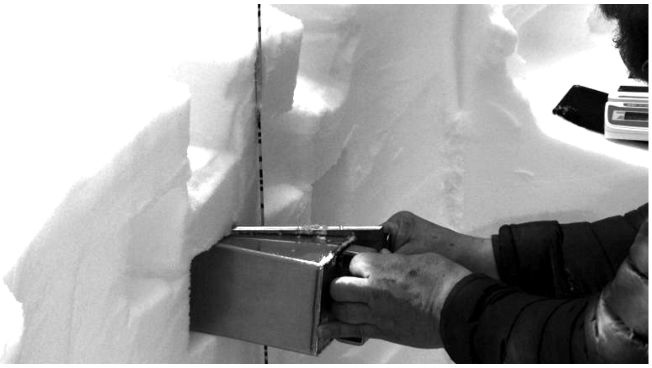


Figure B.7 Simultaneously remove both the sampler and lid to insure no snow loss from the sampler.

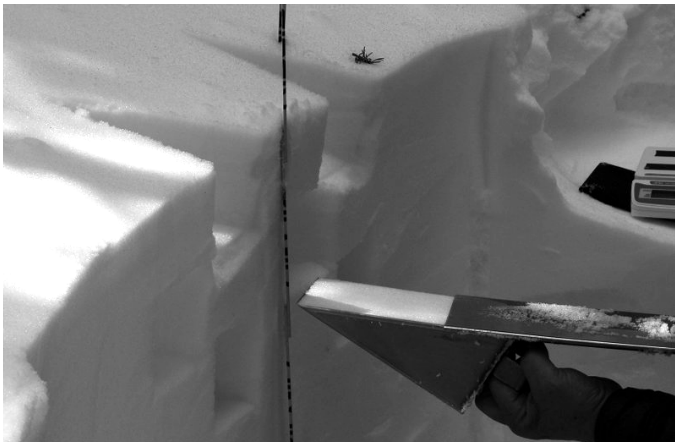


Figure B.8. Slide the lid off the sampler so snow sticking to the inside of the lid is retained in the sample. The lid can then be used to remove snow sticking to the exterior of the sampler in the sides and bottom.

6. If the sample appears to be good, clean the excess snow off the outside of the cutter, place the cutter (without the lid) on the top-loading scale. Read and record the density.

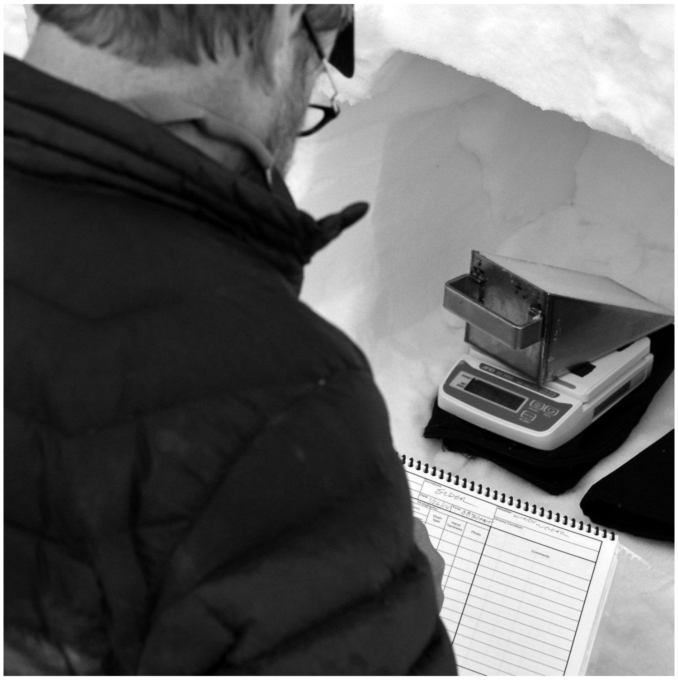


Figure B.9. Weight the clean sample and record the value in the data book.

7. Repeat the measurement as above until two full profiles are completed. If any irregularities are observed, be sure to note them in the field book. For example, if there is a high-density value and free water or ice are observed in the profile at the sample location, record the details.

Figure B.10.. Snowpit wall after density, temperature, and stratigraphy measurements have been taken

Notes on Sampling Snow Density

If the digital scale malfunctions, it will be necessary to use the backup spring scale. Place a ski pole, handle first, in the snow pit wall. Attach the spring scale to the tip of the ski pole and the plastic bag to the scale. Tare the scale with the empty bag using the adjusting knob on top of the scale. Extract density measurements as outlined above, and dump the sample carefully into the bag and weigh the sample. Be sure to dump the entire sample out before the next measurement is taken. Check that the scale tare weight is zero after every five measurements and adjust as necessary.

If the top surface of the snow (snow-air interface) is irregular, try to find a uniform area to take the surface density measurements. If such a place does not exist, insert the cutter at a level just below the irregularities so that a complete sample is obtained.

Ice lenses may make getting a good sample problematic. If the lens is too thick, sample the snow above and below it. In the field notes record the actual depths sampled and a thickness of the lens not sampled. Most continental ice lenses can be sampled if the cutter is held firmly with both hands while inserting. Some maritime ice lenses are far too thick to sample. Do not sample a lens that is too thick as the cutter may be bent.

Snow density samples should be taken in two complete profiles (Figure B.2). Start with a sample at the surface and work to the bottom of the profile, taking both samples at a given depth, and then proceeding to the next increment below. The 1000-cc density samplers take a 10-cm high so a complete profile can be taken from the surface to the ground in 10-cm increments. The samples should be taken and recorded in the field book in 10-cm increments following the first sample. For example, if the total depth in the snow pit were 217-cm, then the first two samples would be taken from 217-207-cm; the second two samples would be taken form 207-197-cm, etc. The last two samples would be taken from 17-7-cm. If possible, also take a sample from 10-0-cm, although this will often be impractical due to ground surface irregularities and vegetation. In that case, the last measurement might be 11-1-cm or 12-2-cm. Record appropriately in the field book.

In very dense snow it may be necessary to sample the snowpack using a rubber mallet to insert the cutter. This should be done with great care. The cutter should be hit only on the two corners below the handle. Excessive force should not be used with the rubber mallet and other objects should not be used to strike the cutter or damage will occur. Once the cutter is in, it may be necessary to drive the lid in with the rubber mallet as well. In this case the cutter must be held in with a wrist, hip, knee or foot depending on the sample level. Both hands are needed to hold the lid and hammer it, but pressure must be provided against the cutter or the lid will for it back out of the pit wall as the lid goes in. This may take a little practice in dense snow.

Be sure the cutter bottom is snow-free before placing it on the scale. A few snow grains will allow the cutter and sample to slide off of the scale.

Be very careful to keep the snow off of the scale. The scales are electronic and moisture does affect them. If they get too wet (this means very little moisture internally), they simply quit working. There is ample opportunity for moisture to get into the scale through the holes for the top plate.

Snow Wetness Profile

Snow wetness measurements will be taken throughout the entire pit wall profile. The assumption that all layers with temperatures colder than 0°C are dry is not valid due to thermometer error and uncertainty. It is generally safe to assume that layers with temperatures less than –2°C are dry. All other layers should be tested. Note also that it is possible, and not uncommon, for a cold layer to overlay a melting layer where preferential flow paths have introduced melt water to lower layers while leaving overlying layers cold and dry. The snowpack is sampled by taking a sample from the pit wall with a gloved hand at the location of concern. The following classification and methodology will be used to determine the wetness profiles:

Dry (D): Snow grains have little ability to adhere to one another when compressed. It is difficult to make a snowball with this snow. Temperature is usually below 0°C, but dry snow may exist at this temperature, particularly in light of thermometer accuracy. Water content by volume is 0%; data code is D.

Moist (M): Snow tends to stick together when compressed, but liquid water is not visible even with a hand lens. Temperatures are typically at 0°C. Water content by volume is <3% .

Wet (W): This snow adheres well with moderate pressure and is the perfect snow for making snowballs. Water cannot be squeezed out with moderate pressure, but can be seen in the contacts between grains with a 10X lens. The temperature is 0°C and this represents snow in the pendular regime. Water content by volume is 3-8% .

Very Wet (V): Water can be squeezed out with moderate pressure, but the snow matrix still contains a considerable amount of air. The temperature is 0°C and this represents snow in the funicular regime. Water content by volume is 8-15% .

Slush (S): The snow is saturated with water and contains only isolated air bubbles. Cohesion is minimal and actually increases as water is pressed out. Water drips freely from sample. The temperature is 0°C. Water content by volume is >15% .

Be sure to shave the pit wall back to get fresh snow unaltered by the exposed pitwall. This is particularly important on warm or sunny days. It may be necessary to shave the wall back as much as 30 cm in a narrow section to find representative snow. Snow wetness measurements should be made as soon as possible when the stratigraphic layers are identified. Note that wetness may change from one category to another (e.g. moist to dry) within a layer identified as a single layer in the stratigraphic profile. This should be noted in the field notes.

Snow Temperature Profile

Snow temperature should be measured every 10 cm over the entire snow depth profile. The thermometer should be cooled in shaded snow before measurements are made for at least 5 minutes. Once cooled, move the thermometer to a new location for the first measurement. An accurate surface temperature measurement is difficult to obtain. Solar radiation is the primary problem, but snow contact is also a problem. Even if the site is well-shaded, shade a portion of the surface with a shovel inserted handle first in the snowpack. Place the thermometer in the shaded area and record the temperature after it equilibrates. The temperature measurements should be made on the same 10 cm intervals as the density measurements over the entire profile.

Use only one thermometer so that relative differences can be measured, rather than differences between thermometers. The second thermometer is provided as a backup and should only be used if the other one is damaged. The temperature measurements should be made simultaneously with the density measurements. The thermometer should be left in place for 2-3 minutes before each measurement is taken. If snow temperature measurements are not taken simultaneously with the other measurements, then excessive time will be needed to complete the entire snow pit. It usually works best to insert the thermometer in the undisturbed snow immediately adjacent to the depth probe. This practice allows accurate depth location and does not interfere with the density samples. Be careful with the thermometers and place them in the case provided for transport between pits. Slight bending of the stem will result in incorrect measurements. Shock or bending will also change the calibration. If it is suspected that the thermometer is damaged, use the second thermometer provided. Be certain not to leave thermometers in the snow pit bottom after the last reading is taken. If any irregularities in the measurements are observed, be sure to note them in the field book.

Snow/Soil Interface temperature

Temperature should also be measured at the base of the snowpack. Insert the thermometer at the snow/soil interface on the same pit wall where other temperature measurements were taken. Be careful not to force the thermometer into frozen soil or rocks. Note the condition of the ground in the field book (i.e. hard, frozen, unfrozen, soft, muddy, etc.). Note that this is the interface temperature so the thermometer tip should not actually penetrate the soil.

Snow Grain Size and Type

Snow grain size will be measured for each homogeneous layer in the snow profile. Use a paintbrush, dry wall brush, putty knife, hand or other instrument to determine where major grain boundaries exist in the pit profile. Mark each boundary. Collect a sample from the pit wall by gently scraping the point of interest with the crystal card. Tap the card gently to distribute the grains over a thin layer that leaves distinct, identifiable individual grains. You will not be able to get accurate grain sizes from a pile of grains. Use the pocket microscope with a graduated reticule and the crystal card to determine the size of grains along their long axis. Choose the grains as randomly as possible, e.g. do not look for the largest grains or smallest grains, simply choose several and measure them. Take the mean of the observations as the layer's grain size. Check the appropriate box in the field sheet.

Grains types will be recorded for basic shapes defined by the international snow research community, but will not include subcategories. We will use the following categories: surface hoar, new snow, decomposing new snow, rounds, facets, melt forms, crusts, and ice lenses.

Surface hoar (SH) presents in a wide variety of shapes and sizes and in extreme case may vary over three orders of magnitude in length. Some sites may observe surface hoar from 1 mm to several cm. Presence or absence of surface hoar, as well as size, are critical observations as they may have a profound effect on sensors. Note that buried surface hoar layers are common in continental and intermountain snowpacks and should be recorded as they represent a distinct change in the snowpack that will affect remote sensing sensors.

Figure B.11. Surface hoar comes in many shapes and sizes.

New snow (PP, for precipitation particles) are usually obvious. While they, too, exist in an infinite variety of shapes and sizes, they are easily identifiable by their fixed geometries and sharp, intricate habits. Record the size based on the longest axes.

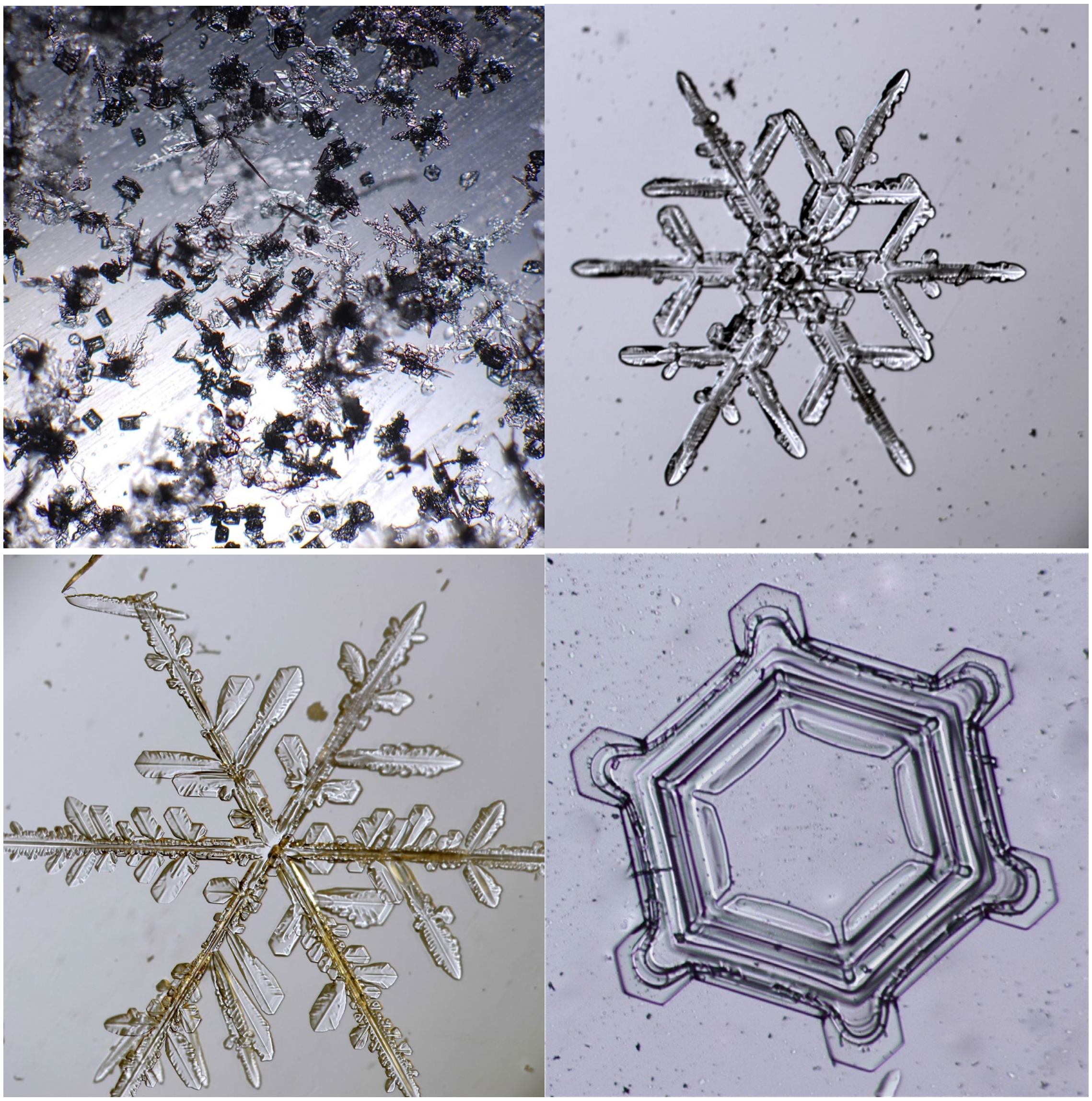


Figure B.12. New snow or precipitation particles (PP).

Decomposing new snow and fragments (DF) retains the basic shape of new snow or portions of new snow crystals, but have rounded edges and lacks the sharp nature of the atmospheric forms.

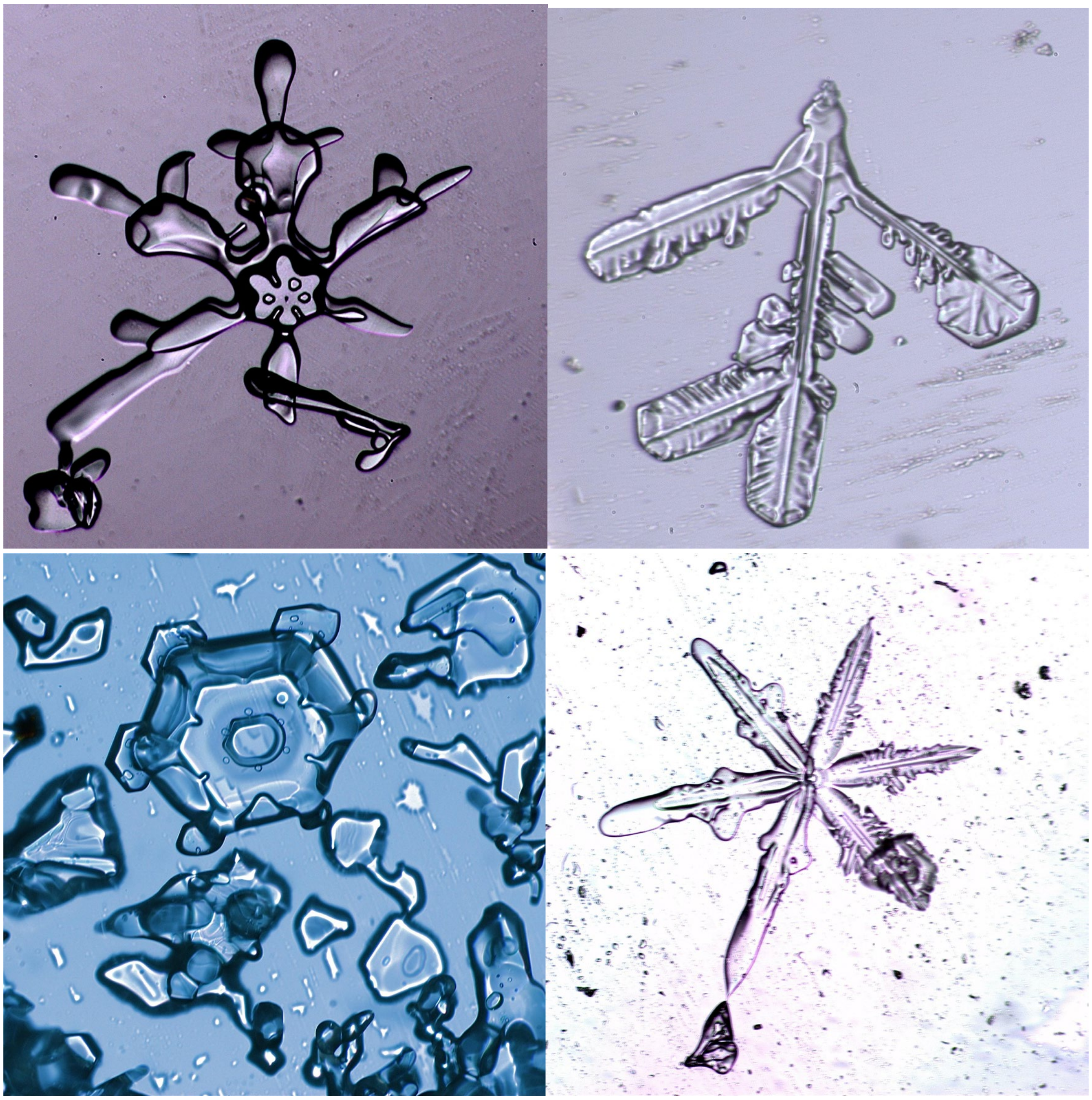


Figure B.13. Decomposing new snow or fragments (DF).

Rounds (RG) or rounded grains, are the metamorphosed grain produced under a mild temperature gradient and are typically well-bolded, oblate spheroids, unexceptional in every way to most snow enthusiasts. Rounds are the result of a metamorphic process attempting to reach an equilibrium form. They may be likened to overcooked rice or undercooked beans and are typically less than 1 mm in diameter. Rounds will be one of the grain types most commonly observed in most of the study sites.

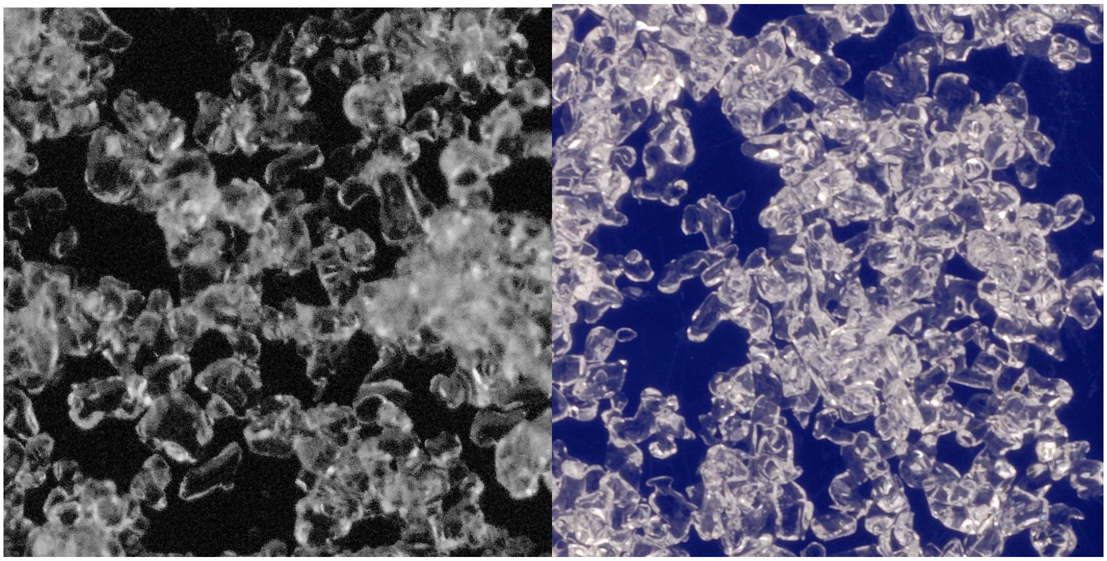
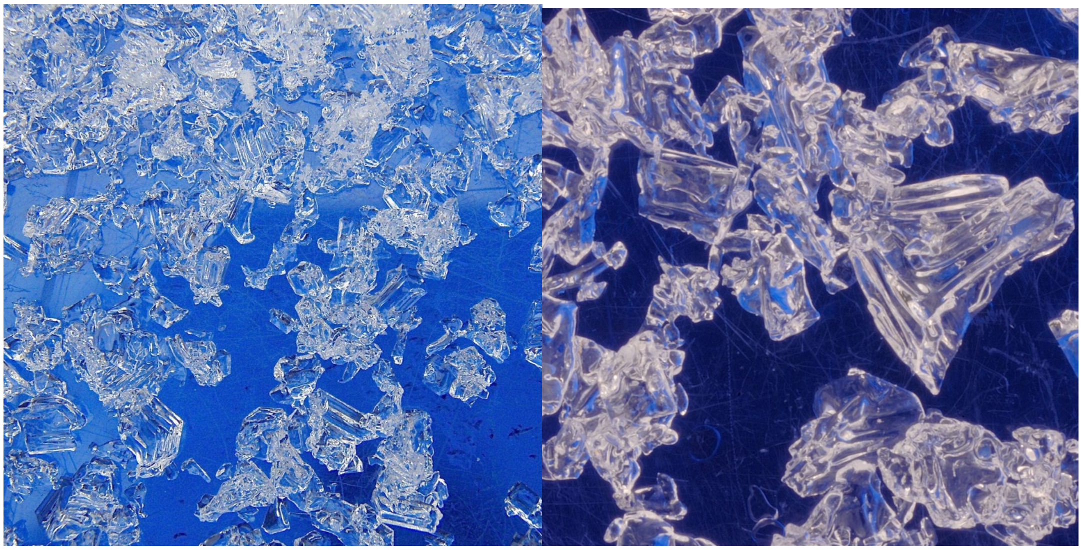


Figure B.14. Round grains (RG).

Facets (FC), or faceted crystals, are produced when strong temperature gradients within the snowpack change the metamorphic regime to a kinetic process from an equilibrium process (RG). Facets are often intricate, but in a blocky way, unlike atmospheric forms. Early faceting produced linear features on grains, as well as angular or square shapes and surfaces. Advanced facets may be cupped and striated. Faceted grains are typically 2-6 mm, but some study sites may see grains greater than 10 mm on long axes. Note that we are including the major category of depth hoar in the facetes crystals (FC) category. Depth hoar identification can be made by data users by examining the corresponding grain size and location in the snowpack profile.



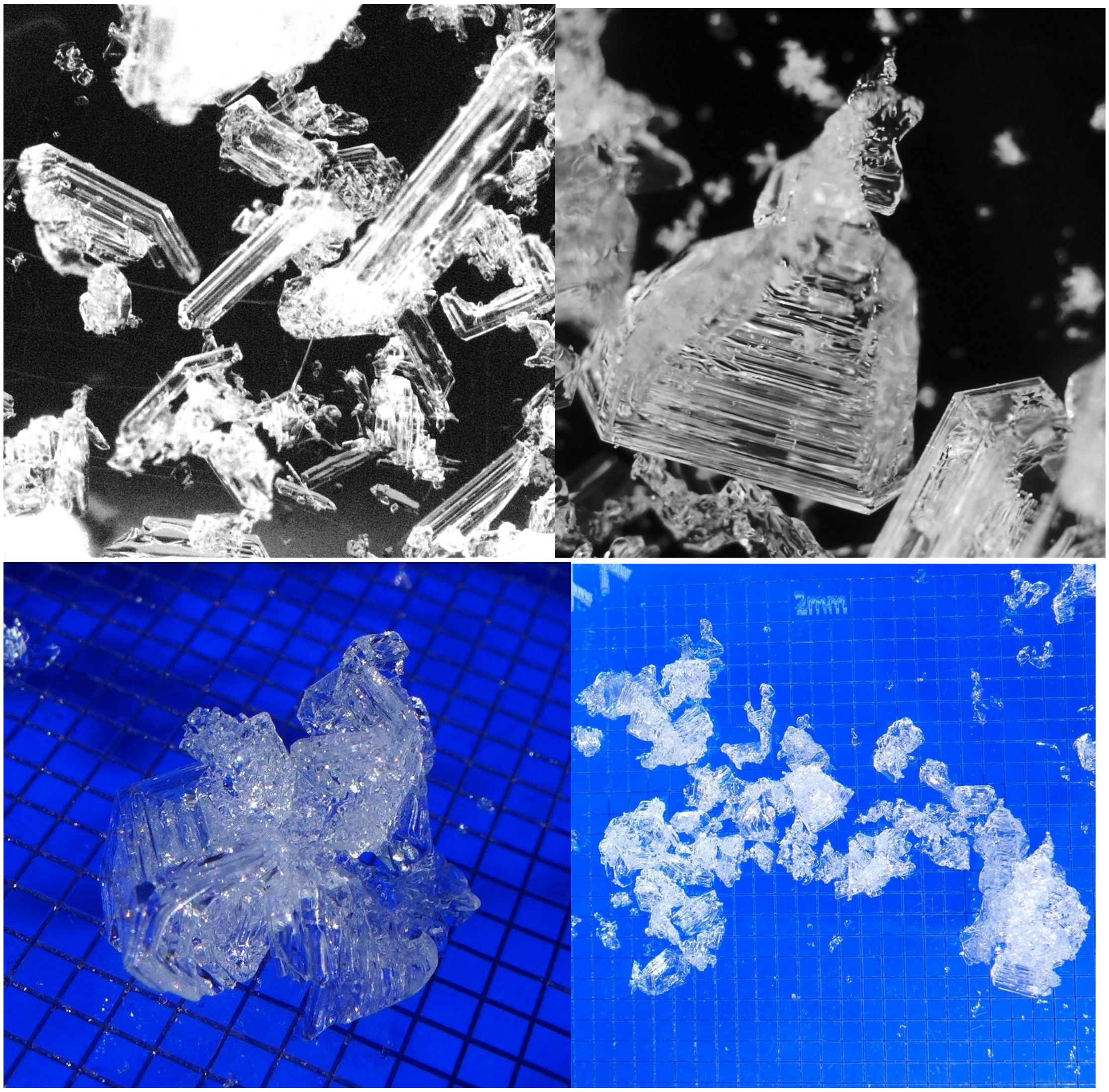


Figure B.15. Faceted crystals (FC).

Melt forms (MF) are grains that have gone through at least one period of exposure to melting temperatures. They are typically round and large. If they are in a melting phase they are not well bonded and if refrozen may be very well bonded. Melt forms include clustered round grains, polycrystals and slush. MF grains may be 0.5-2 mm and are typically large, as the larger grains grow at the expense of the smaller grains. It is unlikely that any of the snow wetness categories listed above with wetness greater than moist with be anything other that a melt form, though exceptions do exist. The category MF is often misidentified and "melt-freeze", but this is incorrect as the freezing phase only retards the process that produces these grains.

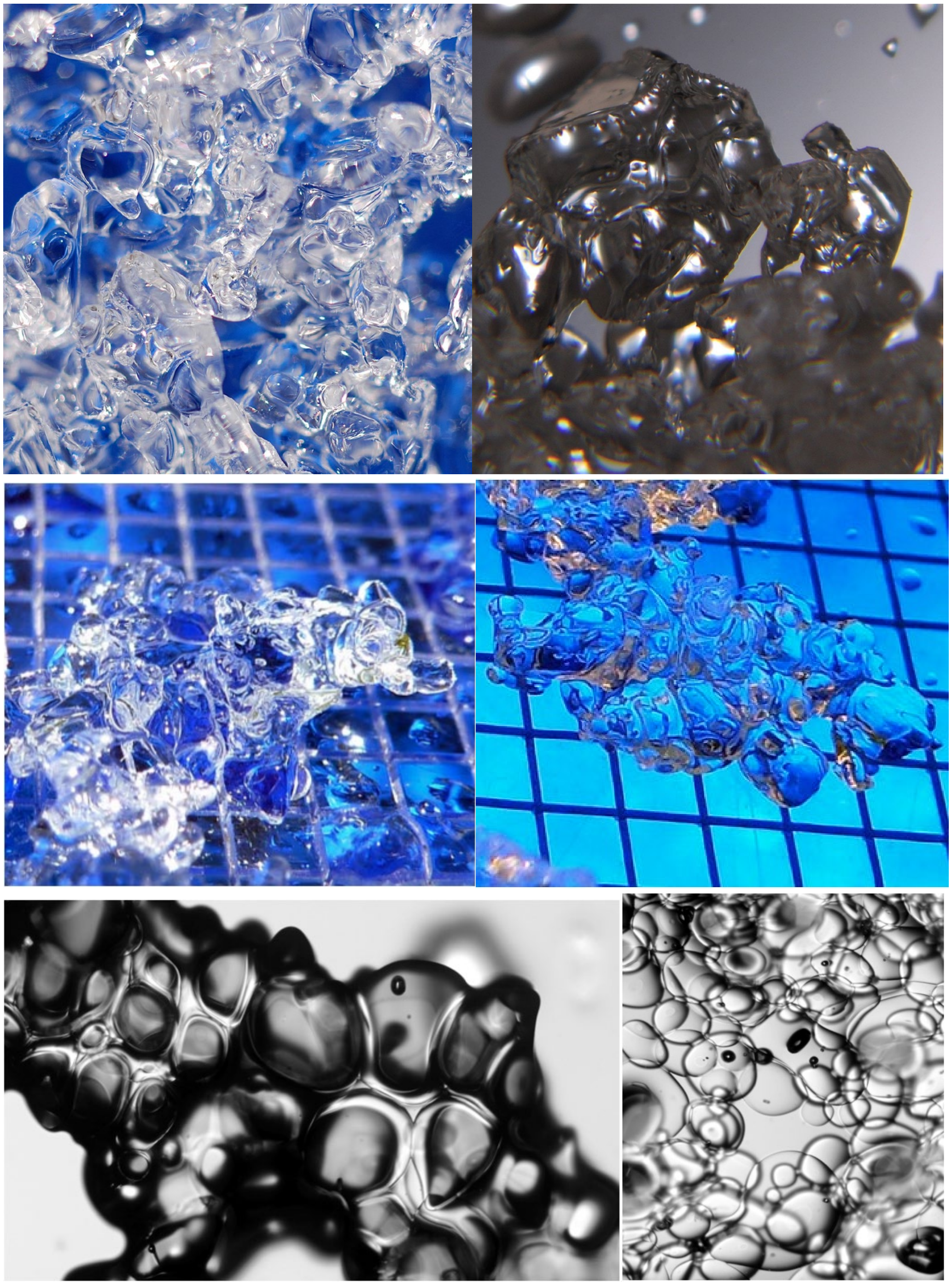


Figure B.16. melt forms (MF).

Crusts (CR) may be formed by radiation, sensible heat, wind, rain, or other process. We will define crusts by layers that are well-bonded anomalies within other more common layers or on the snowpack surface. They typically are strong and brittle at cold temperatures. Close examination will show rounded grains with many bonds per unit volume. They may show some characteristics of faceting, but not often at midlatitudes or moderate elevations. Crusts have distinct grains that can be separated and measured. A defining feature of crusts is that they retain considerable air space with in the matrix, which makes them opaque due to light scattering. Grain sizes in crusts may be very small (<0.5 mm) in wind-blown deposits, or relatively large (>2 mm) in radiation crusts. Note that these are often included as a subcategory of MF, but for our purposes we have elected to give a broader nomenclature based on remote sensing objectives. Densities of crusts may range between 300 and 700 kg m-3.

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Figure B.17. Crust (CR).

Ice lenses (IF), or ice formations, may be caused by some of the same forcings as crusts (radiation, rain, etc.) but also percolation of liquid water and subsequent lateral movement in the snowpack. In some cases, ice lenses are just the further development of crust-forming processes. A defining feature of ice lenses is that they have little air retained in the matrix and transmit visible light effectively, such that colors and even shapes may be identifiable through these lenses if they are thin. Thicknesses may be between 1 and 30 mm, with exceptional lenses even thicker. Densities may range from 700 to 900 kg m-3. Individual grains are not identifiable on the field and in this case, grain size is meaningless.

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Figure B.18. Ice lenses (IF).

Notes for Snow Grain Measurement

Be sure to keep the crystal card cold. The card should be placed in the snow in the pit wall when not in use and should be moved back and forth on a cold layer of snow between measurements when the air temperature is warm. This technique will reduce the amount of melt and crystal change that occurs during observation with the sample on the card.

Note that the card only has one grid size etched on its surface and it is 2 mm. This grid makes it easy to measure crystal sizes to the nearest one mm. There is also a graduated reticule inside the pocket microscope included in the field equipment. The reticule has both a metric and imperial scale. be careful not to use the imperial scale. The metric scale has graduations of millimeters and tenths of millimeters. We will use categories based on maximizing grain size information potentially useful for retrieval of snow properties for prioritized airborne sensors. The five categories will be <1 mm, 1-2 mm, 2-4 mm, 4-6 mm, and >6 mm.

In some layers there will be a gradual change in crystal type and size over the distance of observation. Arbitrary boundaries may be made, but should be chosen based on as much information as can be gathered, e.g. hardness, texture, paintbrush results, etc. When there is not a clear boundary within a layer, take a size sample (three measurements) at the bottom of the layer and again at the top of the layer and record all of the observations with their approximate location.

Note any irregularities or other observations in the field book. For instance, if there is a horizon with a large number of pine needles in it, or vertical ice columns, those are noteworthy.

ADD example pit sheets here?
Both blank and filled out with explanation sheets?