# NASA SnowEx 2020

# Experiment Plan

## Draft (August 2019)


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# Document Change Record

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| 2019-07 | Initial draft in review by SnowEx Leadership |
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# Table of Contents

# 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. However, monitoring snow water equivalent (SWE) and albedo over large regions, especially in mountains, remains a challenge. NASA SnowEx is a multi-year effort to improve snow water equivalent (SWE) and snow-surface energy balance measurements and estimates. The multi-year SnowEx campaign's goal is to fuse remote sensing, modeling, and in-situ observations to determine the optimal approach for monitoring snow, and to identify a pathway to accurate space-borne snow measurements. Extensive coincident airborne and field-based experiments, 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.

The NASA SnowEx2020 Campaign integrates expansive and frequent airborne and field-based experiments in the Western U.S., from fall 2019, through spring 2020. This effort includes three major campaigns:

1) a **Time Series** experiment at thirteen sites, spanning five states, from December 2019 to May 2020, with L-band InSAR, and LiDAR;
2) a Ka-band InSAR experiment over the **Mammoth/Lakes Basin** in California which includes two flights in March and April coincident with ASO LiDAR flights; and
3) An **Intensive Observation Period (IOP)** at Colorado's Grand Mesa that includes LiDAR observations in September 2019, no/low snow radar/radiometer acquisitions in November 2019, and a 10-day campaign in late January-early February 2020 with airborne radar, radiometer, thermal IR, and LiDAR observations.

Rather than one focused multi-week effort in one small area, as was done in the 2017 SnowEx Campaign (SnowEx17), SnowEx2020 activities encompass Winter 2019-2020 over the western United States. The time series approach leverages local experienced field observers and sites with ongoing snow measurements, allowing for increased temporal and expansive investigation within the constraints of a smaller budget than SnowEx17. SnowEx2020's campaign incorporates over 100 scientists from over 20 government organizations and universities. Moreover, recently the 6$^{th}$ NASA/CUAHSI Snow School was completed to train students, and several participants from this 3-day course will be involved in the SnowEx2020 time-series experiment. The NASA/CUAHSI Snow 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 2020 is safety. Risk Reduction in this experiment is a constant and overarching theme; improvements in navigation and communication to prevent accidents and limit injury have been implemented and are described in each site's safety plan. For these details, see the SnowEx2020 Safety and Operations Plan.

### 1.1.1 Western U.S. Time Series Campaign

The Time Series Campaign will focus on calibration and validation of a new SWE retrieval approach using L-band InSAR, leveraging the NASA JPL airborne UAVSAR. While this NASA asset has been used primarily for studying vegetation structure, and surface deformation due to earthquakes and volcanic activity, the change in phase from this sensor can be related to changes in snow depth and SWE. There have been few studies using L-band InSAR for measuring snow depth and SWE [e.g. Deeb et al, 2013; Gunnerison et al, 2001], largely due to the dynamics of the seasonal snow cover, which require repeat intervals on the order of weeks. Current spaceborne InSAR systems have repeat frequencies of 90 days, however the upcoming 2022 launch of NISAR provides an exciting opportunity for snow monitoring (11-day repeat globally).

During SnowEx17, remarkably little change in SWE (~5cm) occurred during its three-week duration, which was challenging for change-detection approaches. However, the UAVSAR change in snow depth retrievals for the period February 6-22 show the technique has promise, with InSAR depth change retrievals agreeing with corresponding LiDAR depth change over a similar period (Feb 8-25) to within 5cm, over a dynamic range of 25cm [Marshall et. al, in prep]. This technique needs to be tested under a wider range of snow conditions, for larger changes in SWE, and during the transition from dry to wet conditions, in order to understand the limitations, and evaluate the potential to leverage the upcoming NISAR mission for global snow monitoring.

From December 2019 through May 2020, UAVSAR will fly 13 flight paths across five states (Figure 1.1), at weekly to biweekly temporal resolution. These sites span a range of snow climates and conditions, elevations, aspects, and vegetation. Flight paths were designed to include sites with ongoing snow research projects, existing ground-based remote sensing infrastructure (e.g., radar and LiDAR), snow-off and planned snow-on aerial LiDAR, scheduled ground snow measurement campaigns, and locations with experienced local field observers performing regular observations coincident with UAVSAR (weekly to biweekly temporal resolution). To aid modeling activities, sites with energy balance observations were chosen.

While the schedule of flights is subject to change, the current UAVSAR flight schedule consists of a Dec 18 flight, then weekly flights from January 8th until the end of February (Jan 8, Jan 15, Jan 20, Jan 29, Feb 5, Feb 12, Feb 19, Feb 26) and then biweekly flights in March and April (Mar 11, Mar 25, Apr 8, Apr 22, May 6). See Figures 1.1,1.4.

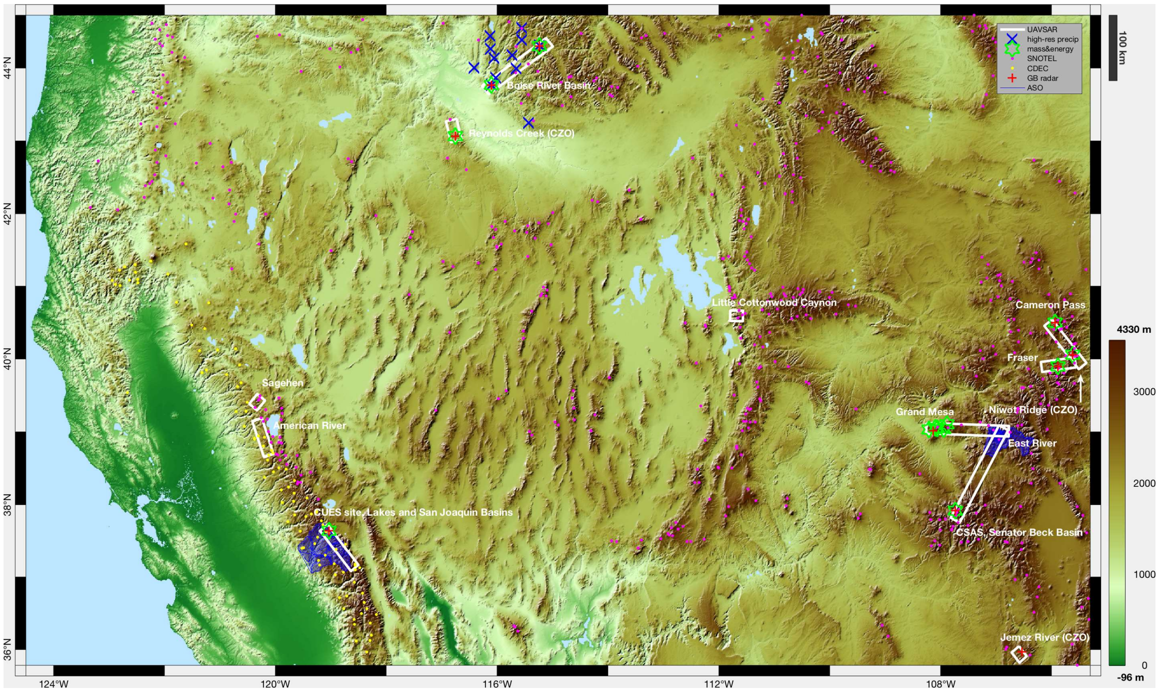



**FIGURE 1.1: SNOWEX 2020 TIME SERIES SITES. WHITE BOXES SHOW THE LOCATION OF BI-WEEKLY L-BAND INSAR ACQUISITIONS, BLUE HATCHED AREAS SHOW ASO TARGETS.**

Airborne LiDAR provides high-resolution snow depth maps, and when combined with energy balance modeling, spatially distributed SWE estimates can be made (Painter et al., 2016). These data will be reliable sources of validation data, particularly for InSAR snow depth retrievals as well as a powerful constraint for InSAR retrieval of snow density and SWE. Airborne LiDAR acquisitions will be obtained from planned ASO surveys over some of the California and Colorado sites. A separate helicopter-based LiDAR and thermal IR campaign, funded by the U.S. Army Cold Regions Research and Engineering Laboratory, will take place at the two Idaho sites. Additional LiDAR acquisitions over a subset of sites in Idaho and Colorado will be collected to augment those planned acquisitions. Exact locations and number of flights are still to be determined pending a contract for these data, and may include both snow-free and snow-on collections, depending on quality of existing snow-free data.

*[Insert zoomed in maps of California, Idaho, Colorado, to show LiDAR targets]*

### 1.1.2 Mammoth/Lakes Basin Campaign

The Mammoth/Lakes Basin Campaign is focused on the calibration/validation of snow depth retrieval from airborne Ka-band InSAR. Ka-band radar, with a wavelength of 8mm, is assumed to have the majority of its energy reflected back to the aircraft from the snow surface when snow is present, and from the ground in snow-free conditions. Using the difference between InSAR-derived DEMs during snow-free and snow-on conditions, snow depth can be retrieved, much like the snow depth mapping approach using airborne LiDAR. Penetration depth in snow is frequency dependent, with previous studies (e.g. Rignot et al, 2001) showing 10s of meters at L-band and meters at C-band. At Ka-band, penetration is also affected by snow wetness, with penetration on the order of 30-80 cm in dry snow, reducing to near 0 cm in wet snow. This effort will focus on quantifying the bias introduced due to penetration of the Ka-band InSAR signal, and the resulting difference between the snow surface and the phase center.

### 1.1.3 Grand Mesa Intensive Observation Period (IOP)

Grand Mesa will be used as a Time Series site (Figure 1.2) with bi-weekly UAVSAR and two airborne LiDAR data collections, and it will also host an Intensive Observation Period (IOP). The primary objectives of the Grand Mesa IOP are to test and validate SWE retrieval from active and passive microwave sensors, and to quantify subpixel variability in thermal IR signatures to assess the value of kilometer-scale satellite IR observations (e.g., GOES-16) for snow energy balance modeling. This component of SnowEx2020 (Section 3.2.2) primarily addresses airborne experiments with the NASA GSFC SWE Synthetic Aperture Radar and Radiometer (SWESARR; Section 3.1.3) and the University of Washington Thermal IR sensor package (Section 3.1.4).

The Grand Mesa IOP is scheduled for 27 January 2020 – 7 February 2020 (Section 4.2.2). The experiment will be performed across the range of vegetation and snow conditions that exist on the western part of Grand Mesa. A field team of approximately 22 scientists is planned for the 10-day IOP. This site was chosen for this component of the experiment because it provides gradients in vegetation and snow depth with minimal topography, is high elevation with abundant drier snow, and is conveniently located 25-35 km from Twin Otter International (TOI) at Grand Junction Regional Airport. Thanks to experience gained and local relationships developed during past campaigns, detailed knowledge of the required logistics and resources ease the implementation and execution of a safe campaign. Grand Mesa has four meteorological stations (three installed September 2016, and one existing site that was upgraded) and three SNOTEL sites. These continuous observations provide a relatively high density of available forcing data for snow models, compared to most areas in the mountains in the western U.S. Two large radar calibration targets have been permitted and maintained since 2015.

Coincident acquisitions will include the University of Alabama SnowRadar (Section 4.3) and NOAA's National Operational Hydrological Remote Sensing Center (NOHRSC) gamma sensor (Section 4.4), and these will be coordinated with SnowEx2020 activities on Grand Mesa; for this particular experiment these will take place at no cost to SnowEx2020. Coordination is mutually beneficial, as these groups will all share the data acquired during the Grand Mesa IOP.

## 1.2 THP16 Science Plan Gaps & Priorities Addressed

The SnowEx2020 Experiment was designed to directly respond to the current ***Gaps*** and ***Priorities*** identified in the THP16 Science Plan (https://tinyurl.com/ybshd54d), which was led by different THP16 investigators (Durand, Raleigh et al., 2018) than the primary authors of this Experimental Plan. This experiment responds to 6 of 7 ***Gaps***, all of the ***Mission Critical, Crucial,*** and ***Important Priorities***, and two of the ***Beneficial Priorities***. While this experiment will not necessarily resolve these Gaps and Priorities, it will be a major step forward in our understanding of snow remote sensing, with a goal of improving the snow community's readiness for a satellite mission proposal for global snow monitoring.

The ***Gaps*** identified by the THP16 Science Plan include: 1) snow climates that have not previously been the focus of intensive snow remote sensing efforts, 2) wet snow conditions, and 3) surface energy balance studies. The SnowEx2020 Experiment Plan targets snow climate gaps: Forest, Maritime, Mountain, and Prairie, as the Time Series Campaign includes sites in each of these snow climates (Fig. 1.2, 1.3).

Although, based on the Sturm and Liston (1995) snow classification, many of our Time Series sites are in snow climates classified as Taiga and Tundra, we consider these sites Mountain snow climates (not in the Sturm and Liston classification), to differentiate them from the shallow taiga and tundra snow climates that exist in Alaska and Arctic Canada; those climates will likely be the focus of a future SnowEx campaign. Due to the time series nature of this experiment, which spans accumulation and melt periods, the Wet Snow gap will also be addressed. The thermal IR campaign during the Grand Mesa IOP will address the Surface Energetics gap, through a study of the spatial distribution of snow surface temperature in different vegetation environments. Additionally, the Airborne Snow Observatory includes an imaging spectrometer, which provides data to further our understanding of snow surface albedo.

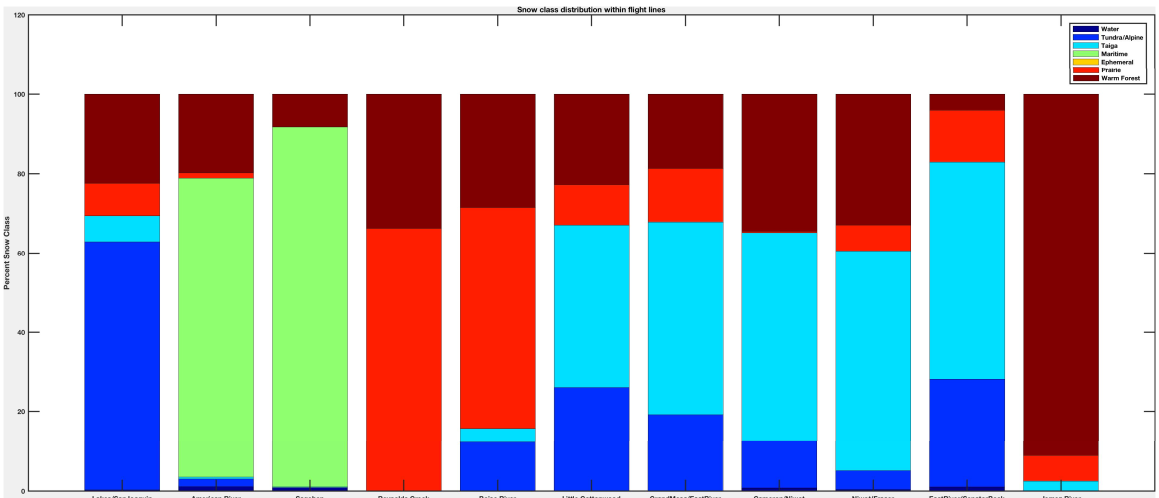



**FIGURE 1.2: PERCENTAGES OF SNOW CLIMATES IN EACH TIME SERIES INSAR FLIGHT BOX (CLASSIFICATION FROM STURM AND LISTON, 1995). NOTE THAT THREE FLIGHT BOXES CONTAIN MULTIPLE SITES, THEREFORE THERE ARE 13 FIELD SITES AND 11 INSAR FLIGHT BOXES.**

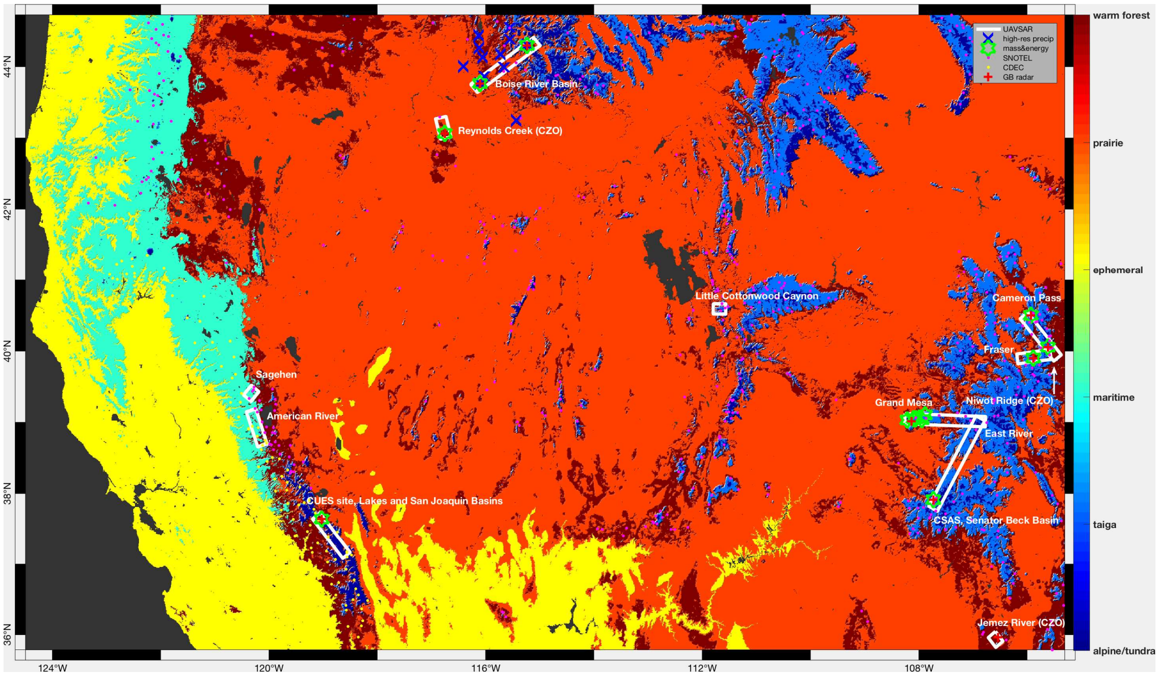



**FIGURE 1.3: INSAR FLIGHT BOXES WITH SNOW CLIMATOLOGY (STURM AND LISTON, 1995) SHOWN IN COLORS, WITH LEGEND ON THE RIGHT.**

The ***Priorities*** addressed by SnowEx2020 include all of those considered ***Mission Critical*** in the THP16 Science Plan. These include airborne experiments with: L-band InSAR (UAVSAR), X- and dual Ku-band SAR (SWESARR), and Ka-band InSAR (GLISTIN-A). These experiments will be performed coincident with airborne LiDAR, which is the most mature airborne remote sensing technique for mapping snow depth, and was stated in the Science Plan as a priority for calibration and validation of the other techniques. Modeling and data assimilation are a central part of SnowEx2020, through coordination of the SEUP efforts with the airborne and field experiments (see Section 7).

In addition, SnowEx2020 addresses all of the ***Crucial*** priorities in the THP16 Science Plan: Thermal IR (UW thermal sensor package), X-, K-, and Ka-band passive microwave (SWESARR), and hyperspectral imaging (ASO).

Both ***Important*** priorities are addressed, through optical imagery for photogrammetry / Structure from Motion (ASO, CRREL Helipod, WorldView, Planet), and synergy with a separately funded airborne FMCW campaign on Grand Mesa (University of Alabama). Through a collaboration with the National Water Center and NOHRSC, airborne gamma flights will occur coincident with some of the field and airborne experiments, and one of the time series sites includes the Fraser Experimental Forest, where there is an ongoing Signals of OPportunity (SoOP) measurements by JPL, satisfying two of the ***Beneficial*** priorities in the THP16 Science Plan.

## 1.3 SnowEx2020 Timeline of Airborne and Ground Activities

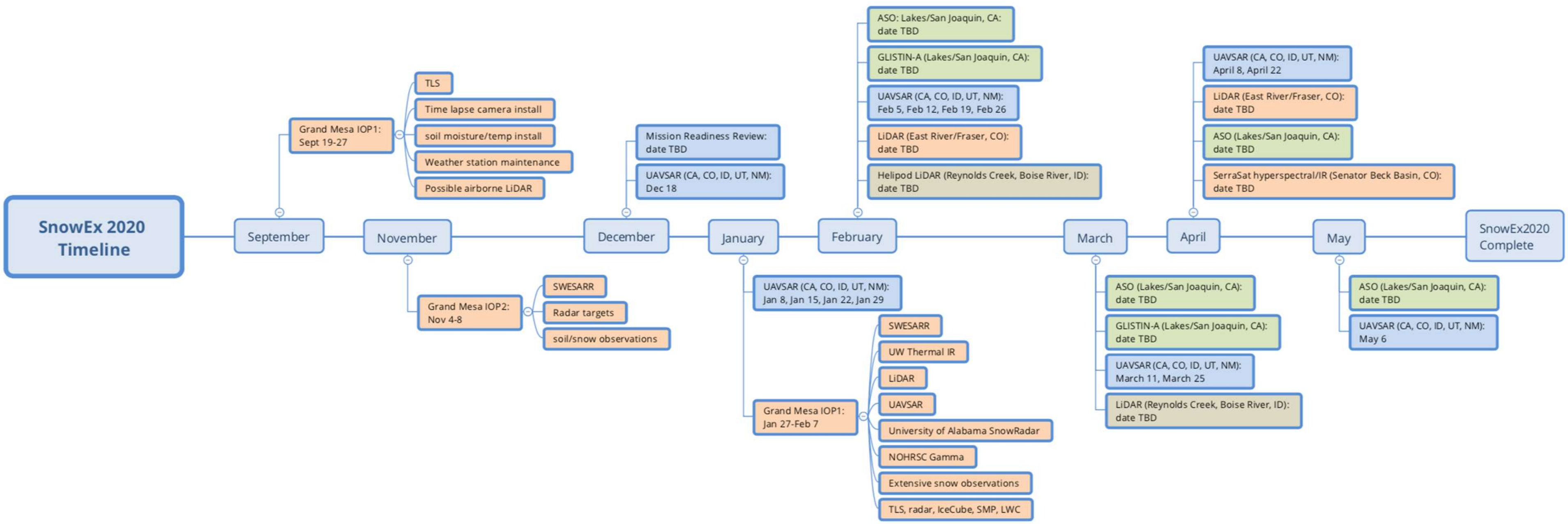
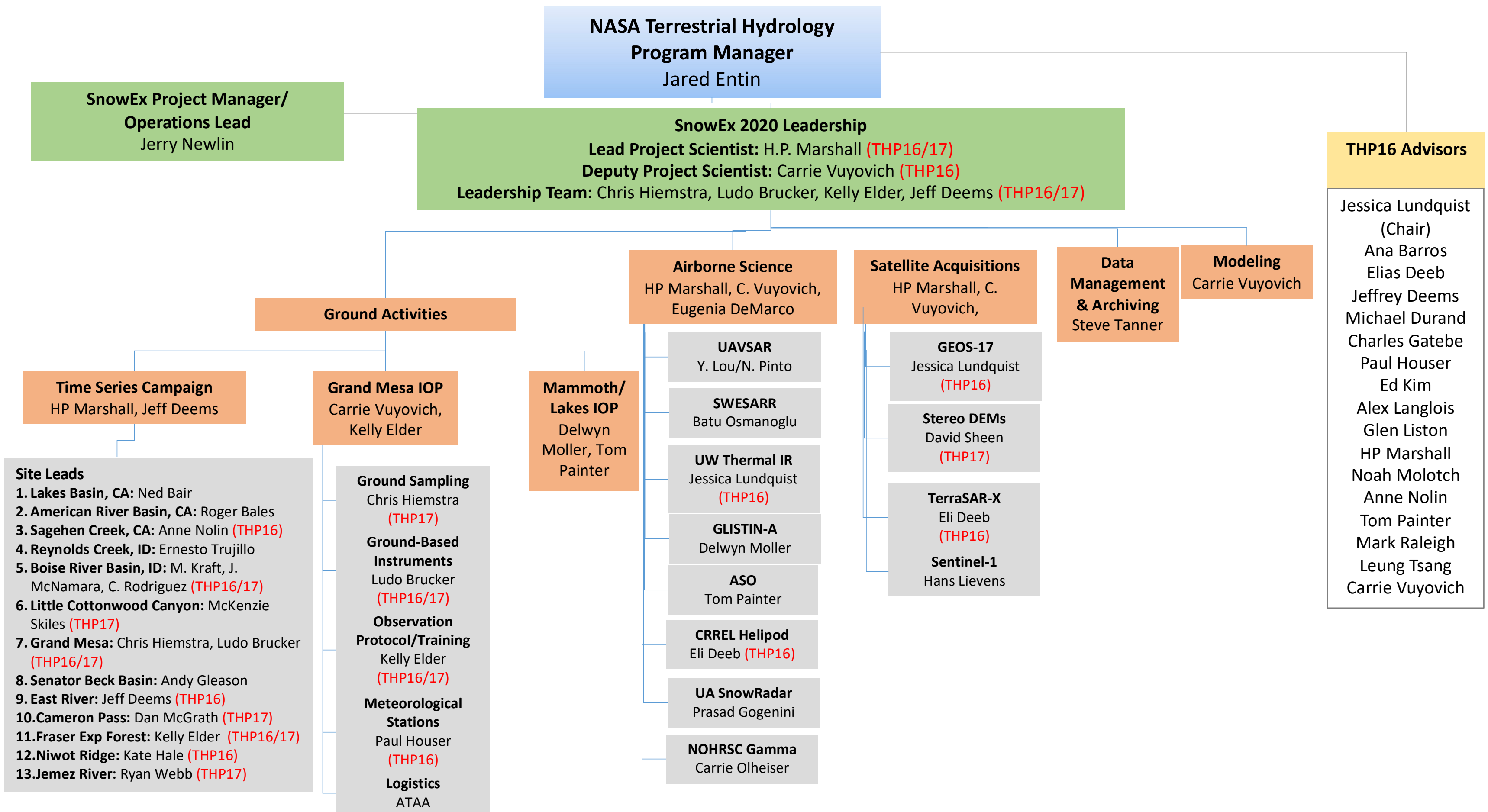



**FIGURE 1.4: SNOWEX2020 AIRCRAFT AND GROUND ACTIVITIES 12/19-5/20. TIMESERIES SHOWN IN BLUE (5 STATES). ADDITIONAL ACTIVITIES IN COLORADO IN ORANGE, CALIFORNIA IN GREEN, IDAHO IN OLIVE.**

# 2 Management

The SnowEx 2020 campaign is funded under the NASA Terrestrial Hydrology Program, directed by Dr. Jared Entin. The Project Scientist is Dr. Hans-Peter (H.P.) Marshall (Department of Geosciences, Boise State University and U.S. Army CRREL), and Deputy Project Scientist is Dr. Carrie Vuyovich (Hydrological Sciences Laboratory, NASA GSFC). Jerry Newlin (ATA Aerospace) is the Operations lead. Drs. Chris Hiemstra (CRREL), Kelly Elder (USFS), Jeff Deems (NSIDC) and Ludo Brucker (NASA GSFC and USRA) bring essential expertise to the leadership team that includes sample design, snow characterization, ground-based and airborne remote sensing, and campaign execution. Each time series site has an experienced site lead, and the THP16 Group provides overall guidance. Eugenia DeMarco (ATA Aerospace) provides expert guidance for the airborne science program.

## 2.1 SnowEx 2020 Organization Chart



## 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. 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, the airborne strategy, and a communications plan for ground and airborne activities; participant training; status reports.

There are additional responsibilities for specific roles.

Lead 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, and overall direction/schedule. Interface with community and NASA management.

Deputy Project Scientist: Support lead project scientist to ensure SnowEx project/science goals are being met, that team members have what they need, troubleshooting, team communication, reporting, and overall direction/schedule. Interface with community and NASA management.

Leadership Team: Participate in weekly planning discussions, help develop science 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 flight planning each day 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.

Time Series Site Leads: Organize and lead a team of 2-6 observers (depending on the site), to carry out consistent observations for each of the scheduled airborne overflights. Determine where to implement sampling protocol based on past experience and site access. Site leads will be responsible for "go-no go" decisions in the field, based on weather, avalanche danger, cold injury, and other possible risks, with safety as the top priority. Site Leads will participate in a briefing on aircraft status just prior to each flight day, and a short debrief two days afterwards. Site Leads will ensure that field books are photographed and data entered into online forms within 3 days of the field effort.

Project Manager/Operations Lead: Execute contracts, purchase equipment, manage shipping of equipment for field experiments, participate in weekly calls with leadership team, interface with Program Manager, manage SnowEx 2020 budget.

THP16 Advisors: Provide input on science goals of experiment plan, provide overall goals and priorities (Science Plan), and connection to long term SnowEx goals.

IOP leads: Design experiments, plan field team, and execute field campaign. Site leads will be responsible for "go-no go" decisions in the field, based on weather, avalanche danger, cold injury, and other possible risks, with safety as the top priority. Risk tolerance should be much lower than it might be for recreation – no data point is worth a significant risk to field observers.

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

## 2.3 Communication

Four levels of communication are required as part of SnowEx2020. 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 International Working Group for Remote sensing (ISWGR) snow communities will be briefed on the campaign monthly, through brief teleconferences. 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 monthly during the campaign.

# 3 Core SnowEx2020 Airborne Activities

Five separate airborne instruments, used on different aircraft and over different domains, comprise the core SnowEx2020 instruments (Fig. 1.4). UAVSAR will cover the largest expanse every two weeks. Snow-free and snow-on LiDAR acquisitions are planned for a subset of the thirteen sites. SWESARR and the UW thermal IR will fly over Grand Mesa, Colorado. GLISTIN-A will fly over the Lakes Basin site, coincident with ASO.

## 3.1 Airborne Sensor Descriptions


**FIGURE 3.1: UAVSAR INSTRUMENT AND AIRCRAFT**

### 3.1.1 UAVSAR

The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) is an L-band (1.2 GHz) repeat-pass Interferometric Synthetic Aperture Radar (InSAR), designed to observe surface deformation caused by volcanic eruptions and earthquakes, and changes in vegetation and soil moisture.  This mature NASA JPL instrument flies on a Gulfstream-III (G3) jet, with a precision autopilot which can repeat flight paths to within 10 meters.  The UAVSAR instrument has an electronically scanned array antenna, which allows repeat-pass interferometry, even in varying wind conditions.  The aircraft can survey for up to 7 hours before refueling, which allows all 13 SnowEx 2020 flight paths to be acquired in a single day, with one stop for refueling.  L-band InSAR observations of amplitude and phase are used to measure phase changes between acquisitions.  These phase changes can be related to changes in depth and SWE, and in theory when combined with LiDAR, could potentially explicitly map density in dry snow.  When snow is completely dry, the radar time of flight through snow depends only on density; if snow depth is constrained by LiDAR, phase changes with these depths could be used to estimate radar velocity, and hence density.

### 3.1.2 Airborne LiDAR

The Airborne Snow Observatory (ASO) uses a scanning lidar and an imaging spectrometer for aerial surveys over snow-covered mountains which, when combined with baseline snow-free surveys, provide accurate high-resolution snow depth retrievals and information on snowpack reflectivity. As the spatial variability of snow water equivalent (SWE) is dominated by the snow depth variation, ASO combines these basin-scale snow depth measurements with modeled snow densities and in-situ data to generate high-resolution SWE data products. The resulting SWE maps (at 50 m resolution) provide the spatial distribution of water resources in the mountain snowpack at spatial scales relevant to physically-driven processes. Calibration and validation of other snow remote sensing approaches will likely be performed with the 3-meter snow depth product.


**FIGURE 3.2: ASO AIRCRAFT**

The ASO SWE maps are being assimilated into snow models for accurate instantaneous SWE representation, provide excellent evaluation data for alternative SWE estimation techniques including satellite-based and statistical products, and continue to provide SWE information late into the snowmelt season when automatic sensor locations have melted out. The ASO SWE products can also provide estimates of storm snow accumulation when flights bracket snow storm activity.  In water year 2019, ASO provided aerial surveys and operational snow products for selected California basins, focusing on the Kaweah, Kings, Merced, San Joaquin, Lakes and Tuolumne river basins, in research partnership with the California Department of Water

Resources and the Bureau of Reclamation. ASO also worked semi-operationally with both Denver Water and the Colorado Water Conservation Board over three basins in Colorado, including Blue River, Gunnison East River and the Taylor River.

### 3.1.3 SWESARR

Figure 3.3. SWESARR Instrument

The airborne SWE Synthetic Aperture Radar and Radiometer (SWESARR) instrument was developed at NASA Goddard Space Flight Center (Fig. 4.3). 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 early November 2019. A minimal ground crew will be present to collect soil samples and move radar targets. Snow-on data collection will occur during the Grand Mesa Intensive Observation Period (IOP) in Jan/Feb 2020. SWESARR will be flown on a twin otter aircraft, from Twin Otter International (TOI), based in Grand Junction. 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 |

### 3.1.4 Thermal-IR

The Compact Airborne System for Imaging the Environment (CASIE), a suite of three thermal infrared (TIR) cameras, longwave radiometer, and visual band camera, will be flown on a Twin Otter aircraft, chartered by NASA through Twin Otter International and based out of Grand Junction CO airport. The CASIE system as flown on a Cessna 182 is shown in Fig 4.4. The system PIs are Chris Chickadel (University of Washington, Applied Phys. Lab.) and Jessica Lundquist (University of Washington, Civil and Env. Eng.). The system is moderately mature and has been used on snow temperature measurement campaigns over the northern California Sierras in

2016 and 2017, as well as several coastal oceanographic surveys from 2010-2018. During SnowEx flights, the system will record imagery and radiometry that will be post-processed to map calibrated snow, land, and tree surface temperature brightness over the study area. These maps will be used for validating snow thermal models and studying sub-pixel variability in snow temperature present in GOES16 satellite thermal imagery (2.4 km x 3.4 km pixel size). The CASIE will fly in the same aircraft as the NASA SWESARR instrument and although it will acquire data simultaneously, the two instruments will measure different locations on the ground, due to different viewing geometry. Flights will take place during the Grand Mesa IOP between 27 Jan and 7 Feb, 2020 with flight lines and target locations identified in the map in Figure 4.2.1.

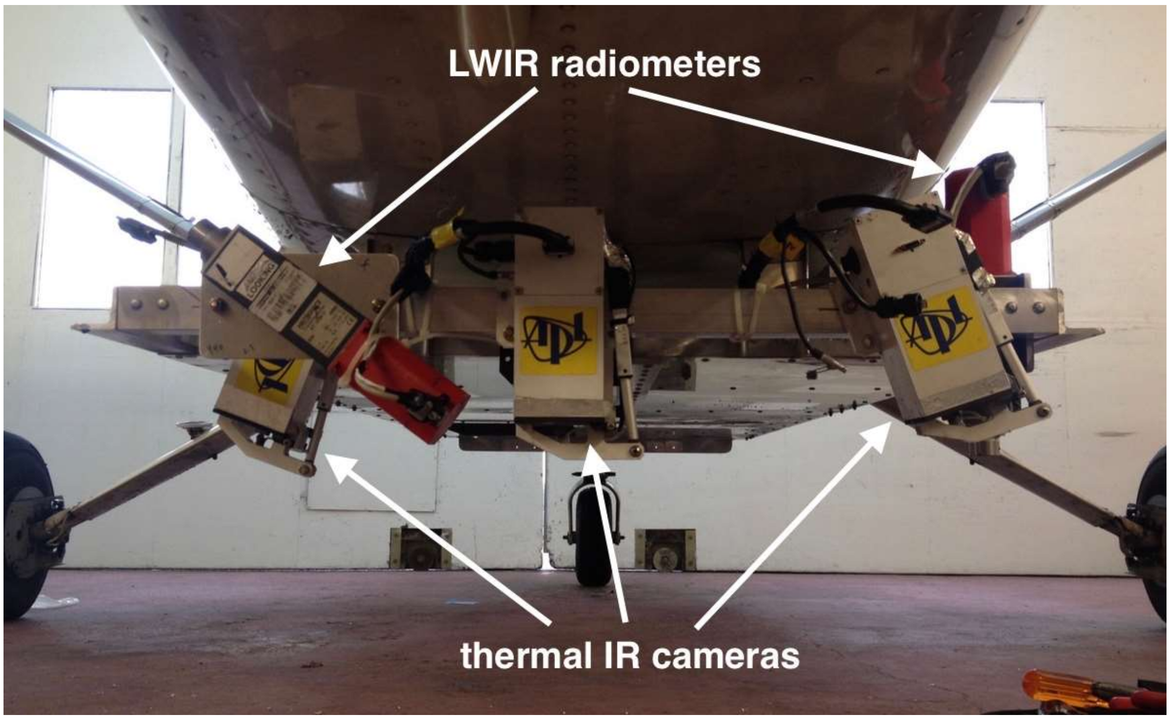



**Figure 3.4.** Thermal cameras and LWIR radiometers, the main sensors of the CASIE system, are shown mounted on the underside of a Cessna 182 aircraft. The recording system is located in the aircraft interior.

### 3.1.5 GLISTIN-A

The airborne glacier and ice surface topography interferometer (GLISTIN-A) is a single- pass interferometric SAR developed for accurate high-resolution swath mapping of land surface topography, in particular dynamic ice surfaces. GLISTIN-A's frequency of operation is 35.66 GHz, or just 8mm wavelength thereby minimizing penetration into surface cover but can operate under most weather conditions including dense cloud cover.

The use of interferometric synthetic aperture radar (InSAR) for snow topography mapping was demonstrated as a proof-of-concept over the Sierra Nevada with a promising comparison between GLISTIN-A and ASO data for the same area. GLISTIN-A is capable of measuring snow topography, and snow-free topography including in high relief and under all snow conditions to include wet snow. While this capability shows promise for the InSAR technology for snow-depth mapping in a manner similar to lidar, more extensive assessment is required over varying conditions and terrains to assess suitability for potential future missions. The GLISTIN-A sensor is mature and operational through NASA JPL.

**FIGURE 3.1: GLISTIN KA-BAND INSAR INSTRUMENT**

## 3.2 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 completely saturated wet snow conditions.

### 3.2.1 Time Series Campaign

This part of SnowEx 2020 is focused on a time series of observations, during both the accumulation and ablation periods, and covering a wide range of snow climates (Fig. 1.3,1.4). The primary instrument is the UAVSAR L-band InSAR, which will fly thirteen flight paths in five states, from December to May. These flights will be coordinated with airborne LiDAR, for calibration and validation of the L-band InSAR snow retrievals. LiDAR flights will include planned ASO flights in California and Colorado, and additional LiDAR flights in Idaho and Colorado; these may include both snow-free and snow-on flights, depending on the quality of existing snow-free LiDAR.

Because the focus of this effort is to test the capability of changes L-band InSAR phase to be used for estimating changes snow depth and SWE, a time series is required. While a dedicated multi-week effort is most efficient in terms of field personnel and aircraft time, for this type of change-detection effort, there is a high risk of observing very little change in snow conditions. Indeed, this occurred during SnowEx 2017, with 0- 5cm of SWE change, and 0-25cm of depth. For this effort, we plan a series of one-day aircraft overflights and coordinated field observations, with a temporal resolution of 1-2 weeks, from December 2019 to May 2020.

All thirteen flight paths shown in Fig.1.2 can be flown in a single day, with one stop for refueling, and half of the flight paths can be flown in both directions. Flights in both directions improve geometry of radar observations in steep terrain. The paths that will be repeated in both directions will be varied, and determined by current conditions and preliminary results.

### 3.2.2 Grand Mesa IOP

For the Grand Mesa IOP, SWESARR (Section 3.1.4) and the Thermal-IR (Section 3.1.5), mounted on the same aircraft, were identified as core airborne instruments. Twenty-five kilometers of transects can be flown with ten hours of science flight time. This includes 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. To be aligned with the SnowEx Science Plan, planned observations are composed of a mix of vegetation and snow types, which can be achieved on the western end of Grand Mesa (Figure 3.2.1). A reservoir is also included in one of the flight lines, which may or may not have ice/water (it is empty in Fig. 3.2.1). It was also desirable to have relatively easy summer/winter road/trail access to aid in ground data collections. CASIE (Section 3.1.5) is used to study sub-pixel variability in snow temperature present in lower resolution satellite thermal imagery such as GOES16 (pixel of 2.4 km x 3.4 km). This constraint was included in flight line placement planning. Four core pixels of interest (labeled GOES A-D, Figure 3.2.1) on the western end of the Mesa were identified for additional investigation. Two East-West oriented flight lines (Flightlines 1 and 2, Figure 3.2.1) were placed on the western side of the Mesa in shrubland steppe that crosses three GOES16 pixels, and have shrubland-forest transitions. One additional NW-SE oriented flight line (Flightline 3) covers another GOES16 pixel (GOES D), and additional ground within a pixel that hosts two transects already to maximize coverage (GOES B).

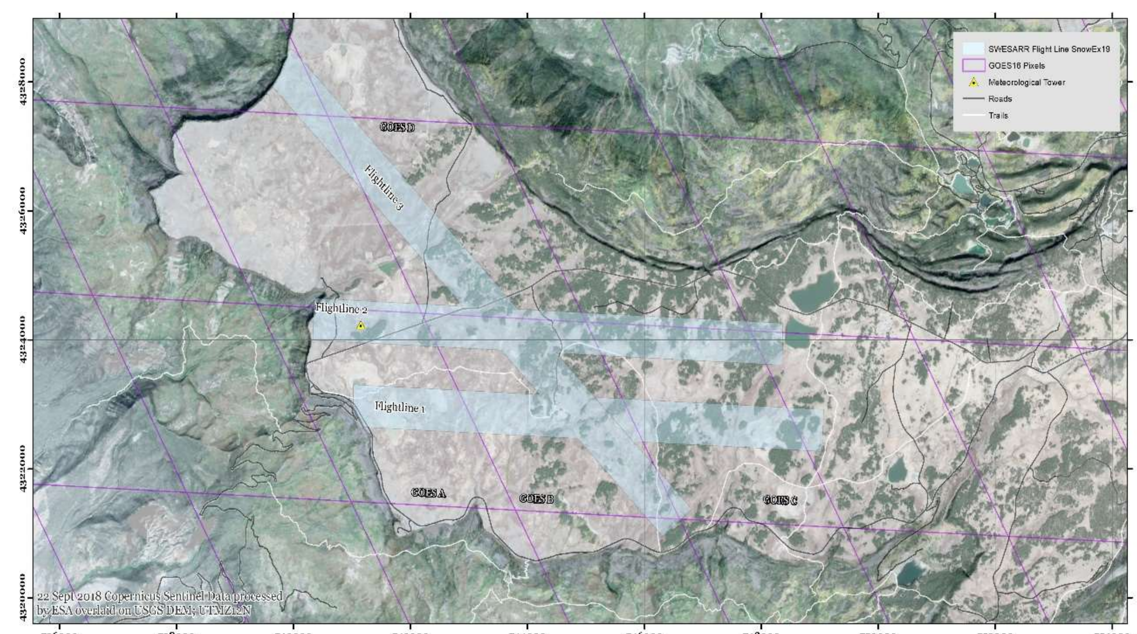



**Figure 3.2.1.** Three flight zones (blue areas) for the Grand Mesa IOP include forests and shrub-lands that span parts of four different GOES16 pixels (magenta). Coordinates are UTMZ12 N.

### 3.2.3 Mammoth/Lakes Basin Campaign

Airborne acquisitions with GLISTIN-A and ASO will be coordinated, such that the airborne LiDAR depth estimates can be used to calibrate and validate the GLISTIN-A depth retrievals. The targeted study region is the area around Mammoth Mountain, California, where previous acquisitions have occurred, where ASO is based, and is the closest SnowEx site to the GLISTIN-A base of operations. Targets include SnowEx time series study plots, the UCSB study site at Mammoth, and plowed parking lots. A field effort focused on depth observations and near surface density/microstructure will be performed during these overflights. Target dates are February and April, to capture dry and wet conditions, respectively.

# 4 Partnerships

SnowEx2020 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 SnowEx2020 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.

## 4.1 Airborne Snow Observatory

Airborne LiDAR is the most mature remote sensing approach for mapping snow depth in deep mountain snowpacks (e.g. Deems et al., 2013). Flights performed by the Airborne Snow Observatory (ASO), funded by the State of California, provide an opportunity for coarse-scale coincident observations of LiDAR with other airborne instruments. As stated in the Science Plan, airborne LiDAR is a priority, as it provides the highest resolution snow depth data for calibration and validation of other remote sensing approaches to snow monitoring. ASO includes a wide-swath REIGL LiDAR system, and a Compact Airborne Spectrographic Imager (CASI). SnowEx 2020 UAVSAR flights in the Southern Sierra Nevada will target basins flown by ASO, in particular the Lakes Basin, which is one of the time series in-situ sites. Previous ASO acquisitions over the Lakes and San Joaquin Basins, CA, Grand Mesa, East River, and Senator Beck, CO, and Reynolds Creek, ID, provide important historical context for several of our sites. Other sites, such as Niwot Ridge, CO, Jemez River, NM, and Reynolds Creek, ID, have airborne snow-free and snow-on LiDAR flown by NCALM, as part of the CZO network.

## 4.2 CRREL Helipod

The CRREL Helipod is an instrument package, co-developed by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL) and the National Center for Airborne

LiDAR Mapping (NCALM), for integration onto a R-44 helicopter. This system includes a 1550 nm LiDAR, a Hasselblad A6D hyperspectral camera, and a FLIR thermal IR imager, and has been flown on many campaigns throughout the United States. R-44 helicopters are small with low flight ceilings; therefore the instrument will not deploy to any and high elevation western U.S. sites for SnowEx2020. CRREL is currently working to modify the Helipod for use on a larger, more common R-66 helicopter. As part of a DoD-funded snow project focused on remote sensing of vehicle mobility, this instrument package will be deployed during 2020 over lower elevation portions of the Idaho SnowEx 2020 sites.

## 4.3 University of Alabama SnowRadar

The University of Alabama's Center for Remote Sensing (Director: Prasad Gogenini), with funding from NOAA National Water Center, built an ultrawideband (UWB) 2-18 GHz FMCW radar system for mapping snow and soil moisture. It is similar to the system successfully flown as part of NASA Operation IceBridge over the past decade.

A first aircraft experiment with the University of Alabama UWB radar was completed over Grand Mesa, Colorado in late-March 2019, during which a field crew from NASA and CRREL performed ground-based measurements. Preliminary results are promising, and we plan to coordinate with the University of Alabama during SnowEx 2020 for additional Grand Mesa flights during the IOP.

## 4.4 NOHRSC

NOAA's National Operational Hydrological Remote Sensing Center (NOHRSC) conducts regular airborne gamma surveys throughout the contiguous U.S. during winter to measure SWE (https://www.nohrsc.noaa.gov/snowsurvey/). These surveys have been conducted for over 20 years and include a network of over 2100 operational flight lines; SWE estimates are produced as an average over the entire flight line. Snow survey aircraft are used to make near real-time, reliable, airborne SWE measurements which are used by the NWS Hydrologic Services Program when issuing spring snow melt flood outlooks, water supply outlooks, and river and flood forecasts for the nation. NOHRSC has offered to conduct snow surveys over existing flight lines that correspond with SnowEx time series sites. In addition they will potentially add new flight lines over locations where flight lines currently do not exist, or to correspond to SnowEx planned collections.

Figure 4.1: NOHRSC Gamma Snow Survey

NOHRSC also runs the SNOw Data Assimilation System (SNODAS) which is a modeling and data assimilation system that provides estimates of SWE, snow depth and other snowpack properties in support of hydrologic modeling and analysis for the contiguous United States (including lower portions of Canada). SNODAS simulates snow cover using a physically based, spatially-distributed energy- and mass-balance snow model with downscaled output from the Numerical Weather Prediction (NWP) models as forcing data (Carroll et al. 2001). SNODAS also assimilates satellite-derived observations of snow covered area, and airborne, and ground-based observations of snow depth and SWE. Gridded model outputs include snow depth, snow melt, SWE, and snow temperature. Additional outputs, including complete energy balance components are provided at assimilation points and available near real-time on their website. NOHRSC has offered to produce output data and display observations at the time series locations throughout the winter of 2019-20. This will provide updated information to the snow community and allow comparison between the ground observations and modeled data.

## 4.5 Outreach and Education: WWA SnowSchool

SnowEx 2020 is partnering with Winter Wildlands Alliance (WWA) to engage middle and high school students to the NASA SnowEx activities, through their nationwide SnowSchool program. The WWA currently provides a unique snow science and STEM curriculum that reaches 65-site and over 35,000 participants in the western US. The primary goals of this proposed partnership with NASA's SnowEx 2020 mission are to 1) advance the SnowSchool program's mission of serving as bridge between the snow science community and K-12 students / the general public and 2) provide greater public outreach and exposure for NASA's SnowEx mission. WWA SnowSchool will also engage adults in SnowEx, through exposure and advertising for the NASA Community Snow Observations program (communitysnowobs.org), which is an online platform that allows community members to submit snow observations online.

# 5 Ground Activities

## 6.1 Time Series Campaign

### 5.1.1 Study Locations

Thirteen study sites were selected across five states to cover a range of terrain and environmental conditions (Figure 5.1). The specific locations of the field experiments were chosen based on existing ground-based infrastructure, previous remote sensing experiments, and availability of local experienced observers. Priority was given to long-term snow observation sites, which provide climatological perspective, and sites with previous LiDAR acquisitions and available data (Appendix C provides additional details for each site). Each site has a designated site lead (Table 5.1) responsible for organizing the field effort and participants at that location in coordination with the airborne activities.

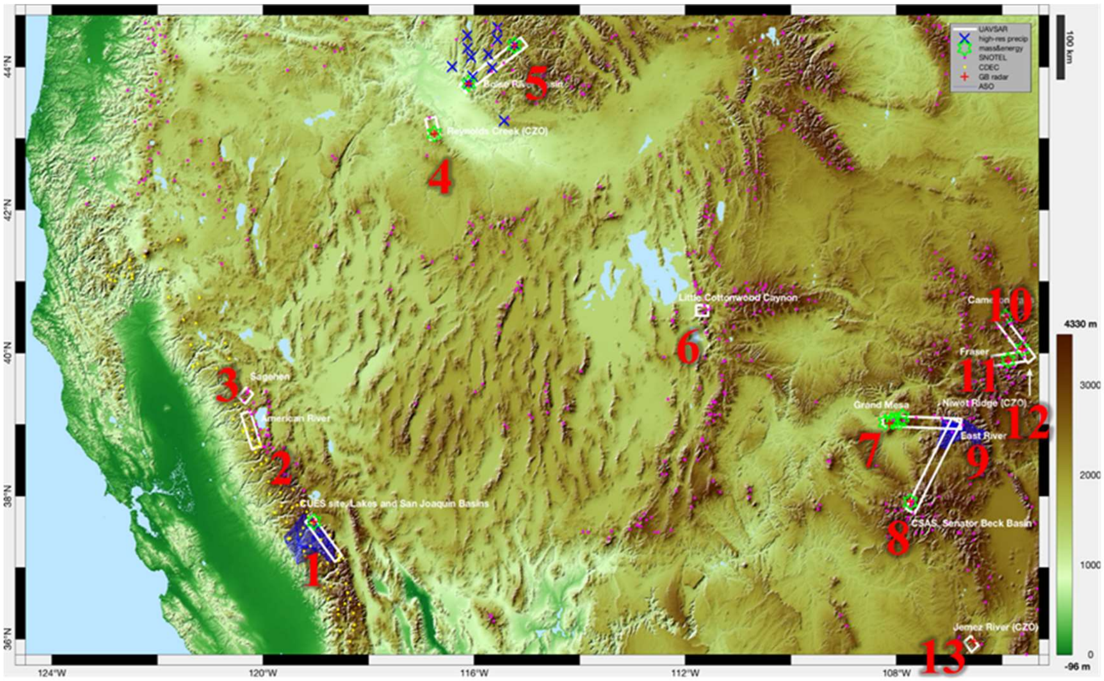


Figure 5.1: Time series site locations

Table 5.1: Time series sites and site leads

| SITE | STATE | SITE NAME | SITE LEAD |
|---|---|---|---|
| 1 | CA | Lakes Basin | Ned Bair |
| 2 | CA | American River Basin | Roger Bales |
| 3 | CA | Sagehen Creek | Anne Nolin |
| 4 | ID | Reynolds Creek | Ernesto Trujillo |
| 5 | ID | Boise River Basin | Maggie Kraft , Jim McNamara, Chago Rodriguez, |
| 6 | UT | Little Cottonwood Canyon | McKenzie Skiles |
| 7 | CO | Grand Mesa | Chris Hiemstra, Ludo Brucker |
| 8 | CO | Senator Beck Basin | Andy Gleason |
| 9 | CO | East River | Jeff Deems |
| 10 | CO | Cameron Pass | Dan McGrath |
| 11 | CO | Fraser Experimental Forest | Kelly Elder |
| 12 | CO | Niwot Ridge | Noah Molotch |
| 13 | NM | Jemez River | Ryan Webb |

## 5.2.1 Sampling Strategy

SnowEx2020 focuses on change-detection, and ground sampling primarily repeats observations at the same location during each airborne overflight. To maximize SnowEx2020 resources over such a large area and sustained campaign, field observations will be performed by a dedicated team of local observers. Each field exercise is designed to last one field day during each flyover, which occur at weekly to bi-weekly intervals from December to May. Observers are making a long-term commitment to participate, reducing training demands. This efficiency is what makes a season-long time series in five states possible, with a modest budget for an effort of this scale.

Time Series site leads determined optimal locations for regular snowpit observations and depth transects. Teams of 2-6 people, depending on the site, will measure interval board changes in snowfall, perform snowpit protocol observations, and measure depths along transects at multiple snow-study plot locations. While the spatial extent of observations at each site will not be large given time and team limitations, observations all thirteen locations (Appendix C) will capture a wide range in environmental and snowpack conditions at high temporal frequency. Observations will be focused on documenting changes in snow properties since the previous observation.

In addition to the Core Observations detailed below, many of the sites include ground-based remote sensing measurements (Appendix C). Terrestrial LiDAR Scanning (TLS) systems will operate at Grand Mesa, Niwot, East River, and Cameron Pass, CO; at Boise River Basin and Reynolds Creek, ID; and at Mammoth Mountain in the Lakes Basin, CA. Mobile ground-based radar surveys will be performed at Cameron Pass, CO; Jemez River, NM; and Boise River Basin, ID. Tower-based radar systems are installed at Mammoth Mountain in the Lakes Basin, CA; Fraser, CO; and Boise River Basin, ID. These additional observations are funded through THP16 and THP17 projects, as well as other outside funding, and these activities are part of the reason these sites were selected for the time series experiment.

### 5.2.2 Core Observations

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

- Snow depth transects (probing)
- Snow interval boards
- Snow Pits
    - Depth
    - Stratigraphy
    - Density
    - Wetness
    - Temperature
    - Grain Size

### 5.2.3 Schedule

The Time Series Campaign is focused on change-detection of depth and SWE with UAVSAR L-band InSAR observations. Flights are planed for mid December, weekly in January and February, and biweekly in March and April, with the final flight May 6 (Fig. 1.1). We will have a conflict with the Delta-X campaign at some point during the spring, which will cause a 2-week gap in observations, and they take priority because they are an Earth Venture mission. We are working with the UAVSAR team to explore options for a flight during the middle of the Delta-X campaign. It is possible there will be another conflict in January when the G3 is required to perform flights for the space program, which could cause us to miss another 1-2 flight dates.  Field teams will continue planned observations to maintain the time series record.

## 5.2 Grand Mesa IOP

The 10-day experiment will occur 27 January - 7 February 2020, after significant snow accumulation and when frozen soil and dry snow conditions prevail. Point-scale snow observations (depths, pit with microstructure, and ground-based remote sensing) will be collected on the western portion of Grand Mesa (Figure 5.1) to support SWESARR and UAVSAR airborne microwave sensors, CASIE thermal IR, and additional airborne instruments thanks to SnowEx20 partnerships (Section 3). An experimental design was developed to address SnowEx20 science objectives for a team charged with collecting a comprehensive field dataset on Grand Mesa. This area offers sufficient variability in snow accumulation and wind exposure; has variable canopy in the form of shrubs, grasslands, and forest; and features low topographic relief.

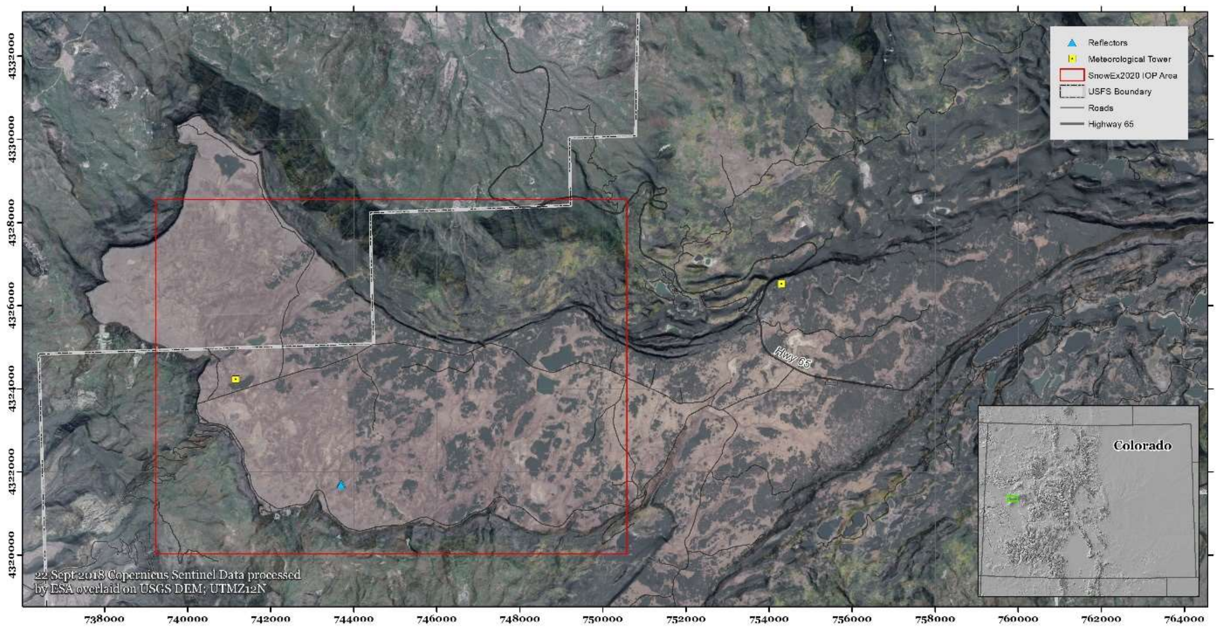



**FIGURE 5.1. SNOWEX20 IOP ACTIVITIES WILL OCCUR ON THE WESTERN PART OF GRAND MESA, WEST OF COLORADO HIGHWAY 65. THIS AREA HAS RELATIVELY EASY ACCESS VIA ROADS AND WINTER TRAILS, ABUNDANT TREE-FREE AREA, AND NUMEROUS FOREST PATCHES OF VARIABLE SIZES AND CONNECTIVITY.**

### 5.2.1 Study Location

Grand Mesa, Colorado (Figure 5.1) is a basalt-capped high-elevation plateau located in western Colorado on the western edge of Colorado's Rocky Mountains.  Ten million years ago (Chronic and Williams, 2002), basalt flowed from fissures on the eastern end of the Mesa and filled valleys to the west. Subsequent erosion created a topographic reversal where the armored basalt flows eventually became Grand Mesa's ridges.  The Mesa's elevations range from 2975 to 3900 m, with an average of 3145 m.

The Mesa has a land-cover gradient from west to east. On the western end, shrub steppe is prevalent. *Artemisia tridentata* and *Dasiphora fruticosa* are shrub dominants with an assemblage of sub-canopy forbs and grasses. Canopy heights in shrub steppe are roughly 20-60 cm tall and grazing is a prevalent summer land use. Farther east, shrub steppe interleaves tree islands (Figure 5.1), which become denser and eventually almost continuous farther to the east. Tree canopy is predominantly *Picea engelmannii* (Engelmann Spruce), with small contributions of *Abies lasiocarpa* (subalpine fir) as a sub-canopy component. *Pinus contora* var. *latifolia* (lodgepole pine), and *Populus tremuloides* (aspen) are found as individuals or in limited patches (< 1 ha). Trees on the Mesa have an average height of approximately 10 meters on the western portion of the mesa (west of Highway 65, Fig. 5.2).

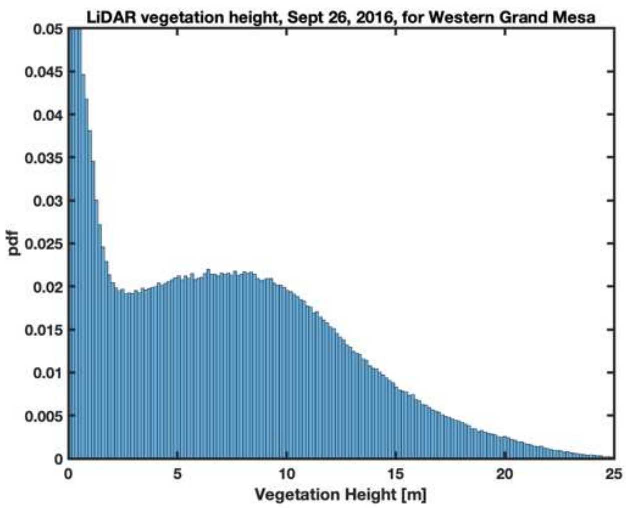



**FIGURE 5.2: VEGETATION HEIGHT FOR WESTERN GRAND MESA FROM FALL 2016 ASO SNOWEX SURVEY.**

Wind and snow conditions also vary from west to east. On the western edge of the Mesa, high winds and short canopies yield a heterogeneous snow cover with shallow snow around the Mesa's western margins and around local ridges, while deep drifts form on the lee sides of ridges and in swales. Wind speeds and spatial heterogeneity gradually decrease farther east as trees generally slow wind speeds. In the forest, trees play a larger role in forming drifts around canopies. In addition, snow depth generally increases to the east as elevations increase and wind speeds decline.

*Past Studies*. Reliable dry snow, gentle topography, excellent access, and the proximity of Grand Mesa to Grand Junction Regional Airport and Twin Otter International (TOI) are four key reasons why Grand Mesa hosts coordinated airborne snow remote-sensing and ground observation field experiments. In February 2010, a team of ten conducted a week of snow observations on Grand Mesa in support of satellite passive microwave and airborne active microwave Ku-band (POLSCAT, 13 GHz) remote sensing. Measurements were primarily collected on the western end of Grand Mesa, west of Highway 65 in forested and unforested areas.

In February 2015, a dozen people conducted another week of snow observations on Grand Mesa, this time in support of the Wideband (8-40 GHz) Instrument for Snow Measurement (WISM), an instrument with multiple passive and active frequencies that leveraged the same feed antenna to create coincident footprints. They collected ground radar observations, 23 snow pits, snow chemistry, NIR photography, SMP profiles, and snow depths. Flight lines for this effort started on

Grand Mesa west of Highway 65, within the current study area (Figure 5.1), included the County Line parking lot (that approximate area will be part of the SnowEx 2020 Time Series Grand Mesa study plots; Appendix C) and extended 10 km East of the highway. Radar corner reflectors were fabricated and deployed at the Grand Junction Airport and at a site on the far west of Grand Mesa (Figure 5.1) where they have been permitted and maintained to-date, and an array of reflectors was also temporarily installed on Island Lake. Reconnaissance was performed at the end of this campaign to determine sampling sites on the east side for future campaigns.

In March 2016, an airborne ultra-wideband (UWB) 2-18 GHz radar, developed by CReSIS for NRL, was deployed over Grand Mesa (Yan et al., 2017) as part of an instrument testing effort.

In February 2017, SnowEx17 occurred on Grand Mesa. SnowEx17's objective was to provide a synchronized and extensive, aerial and ground-based snow-remote-sensing dataset, where impacts of various forest canopy types and densities were assessed with coordinated ground, aerial, and satellite snow measurements. SnowEx17 involved nearly 40 people per week during each of three weeks, five different aircraft, ten airborne instruments, a large suite of ground-based instruments, and tasked satellites. The resultant dataset includes over 200 snowpits and 25,000 snow depths, and uniquely addressed snow-terrain interactions on Grand Mesa. Four new extensively-instrumented weather stations were installed for this effort, three of which remain on the Mesa. Data from this work is archived at the National Snow and Ice Data Center (NSIDC) at https://nsidc.org/data/snowex/data_summaries.

In December 2018, a newly designed Snow Water Equivalent SAR and Radiometer (SWESARR), using the same antenna from WISM, was installed on a Twin Otter aircraft and tested over Grand Junction and Grand Mesa. SWESARR Grand Mesa flights revisited the original WISM2015 flight lines, tested the proposed SnowEx 2020 flight lines, and were coordinated with a two-person crew on the ground that collected five snow pits and over 1500 snow depths.

From 25-29 March 2019, a ten-person crew conducted a joint field campaign (SnowRadar19 and CRREL Snow Mobility) in support of the University of Alabama's UWB radar and optical and radar satellite acquisitions. The campaign conducted 22 snow pits, over 3,700 depth observations, SMP profiles, snow casting for microCT analysis, in-situ dielectric profiles for liquid water content, and covered large areas with 4 different ground-based radar systems (dual-polarized GPR; 500 MHz, 1 GHz) and FMCW (6-18 GHz) surveys within the SnowEx20 study area (Figure 5.1). This 2019 campaign used a preliminary SnowEx20 sampling strategy described below. The existing two western Grand Mesa radar reflectors were maintained, and additional temporary reflectors were installed at the Grand Junction airport and on the Mesa.

*Existing infrastructure*. There are three SNOTEL sites, two arrays of sonic depth sensors (Jennings et al., 2018), and four weather stations. Two of the weather stations are in the region we plan to survey during 2020 (Figure 5.1). There are two corner reflectors for radar geolocation and calibration. Additional radar targets are stored at TOI for deployment near the airport, to allow airborne teams to test sensors before flying over the study site. We plan to deploy an additional six targets on Grand Mesa during the January IOP.

*Permitting*. The study area is primarily managed by the United States Forest Service, and therefore requires permitting for all permanent and semi-permanent (seasonal) installation (e.g., corner reflectors, sonic depth sensors, time lapse cameras). SnowEx 2020 is allowed to operate on Grand Mesa under permit #XXXX. The City of Grand Junction owns most of the remaining study region outside the USFS boundary.

### 5.2.2 Sampling Strategy

Representative *in situ* measurements of snow and soil 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 4.2.1) to address the SnowEx Science Plan. Ground data collection objectives include quantifying the mean, variance, and distribution of snow and soil properties on Grand Mesa during the IOP. 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 and soil 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 a three-day period centered on the overflights. Within any given three-day period, risks of significant change are not equal for different variables. First, snow surface wetness and roughness at the time of the overflight can strongly influence the remote sensing signals (microwave and infrared), and can also be very dynamic, changing on time scales of minutes to hours. Second, evolutions of internal snowpack and soil characteristics, while much less dynamic than surface characteristics (depending on conditions), also influence the microwave remote sensing signal. Next-day observations of these variables pose lesser risk. Third, recent changes in snowpack characteristics (e.g. new snow accumulation) can often be identified easily from snow pit information, but are more difficult to identify from surface and depth observations. Therefore, the ground data collection strategy takes into account safety, environmental characteristics, field crew size and experience, and also prioritizes measurements to be made on the target day for airborne data collection in the study area, and measurements to be made within $\pm 1$ day.

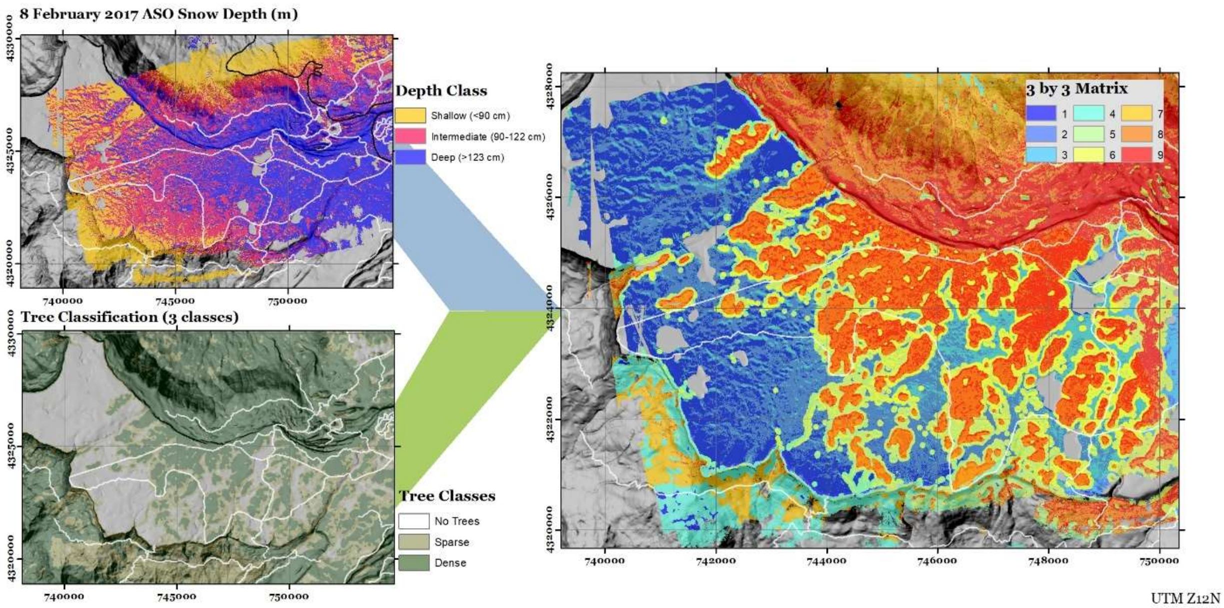



**FIGURE 5.2. TO DISTRIBUTE SAMPLE POINTS ALONG THE ENTIRE RANGE OF SNOW CONDITIONS, ASO SNOW DEPTH DISTRIBUTIONS FROM 8 FEBRUARY 2017 WERE AGGREGATED INTO THREE GROUPS AND COMBINED WITH THREE CANOPY DENSITY CLASSES TO YIELD A 3 BY 3 MATRIX OF SNOWEX 2020 STUDY AREA SNOW CONDITIONS.**

The sample design approach selected for SnowEx 2020 ground sampling used SnowEx17 data (Figure 5.2) from both airborne LiDAR and optical satellite imagery. SnowEx17's 8 February 2017 lidar-derived snow depth (at 3-m horizontal resolution) from the Airborne Snow Observatory, ASO (Painter, 2018), were binned into <90 cm, 90-122 cm, and >122 cm classes. In August 2016, a tree density map was developed by C.A. Hiemstra (Figure 5.2) using a collection of high-resolution (2 m) WorldView2 imagery from November 2010. Since the data were collected in early winter, evergreen trees were relatively easy to identify from the imagery and a simple presence/absence pixel map of "tree" vs "not-tree" was created. Using this binary raster, a neighborhood calculation was performed to measure tree pixel density within a 50 m radius, and five classes were created ranging from treeless to dense forest. The SnowEx17 tree canopy density map was binned into treeless, sparse, and dense classes. The two factors were combined to form a nine-member snow-vegetation matrix over the study area (Figure 5.2); where 1-3, 4-6, and 7-9 represent treeless, sparse, and dense tree canopies that possess three sub-categories of shallow, intermediate, and deep 8 February 2017 snow depth. Lakes and areas with no lidar data on and adjacent to the Mesa remained unclassified (in gray). Next, the domain was clipped by the chosen flight swaths (Section 4.2.1) to calculate the representativeness of each member of the snow-vegetation matrix (Figure 5.3; Table 5.1) and to determine where to sample.

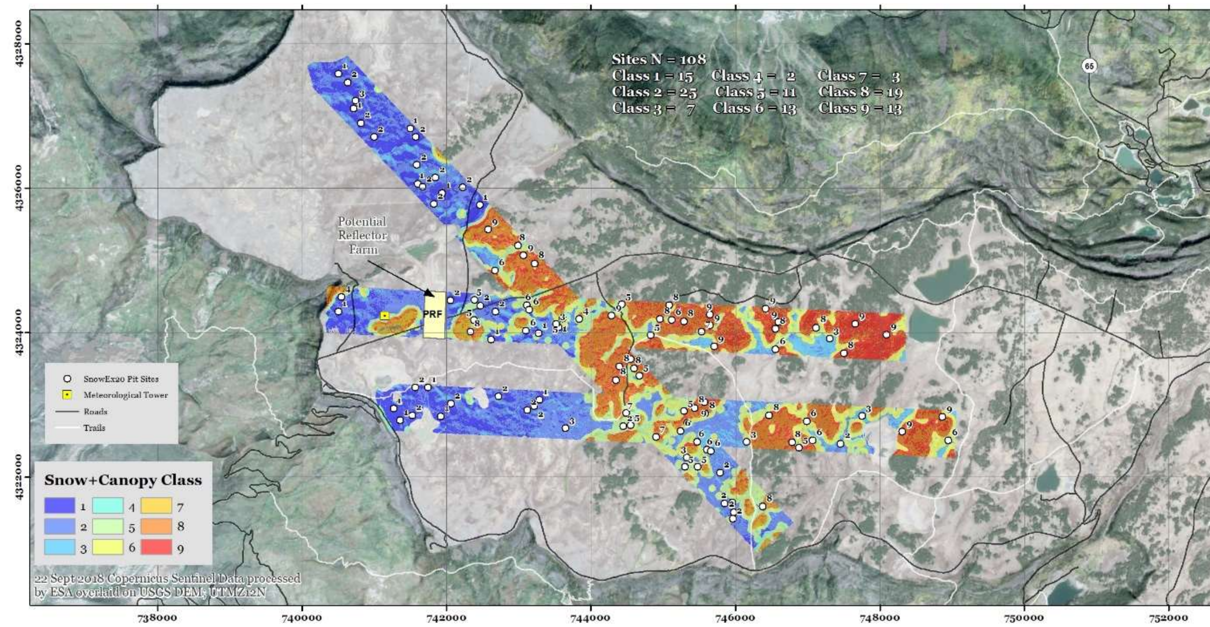



**FIGURE 5.3. SNOWEX 2020 IOP SNOW PIT LOCATIONS WITHIN THE THREE FLIGHT AREAS. THE BACKGROUND SHOWS THE 9-MEMBER SNOW-VEGETATION MATRIX (COLOR SIMILAR AS IN FIG. 5.2). PROPORTIONAL SNOW-TREE MATRIX CLASSES WITHIN THE FLIGHT LINES WERE USED TO ALLOCATE (TABLE 5.1) AND RANDOMLY DISTRIBUTE 107 SNOW PIT LOCATIONS.**

We estimated that a nine-day mid-winter campaign with three dedicated, experienced snow-pit teams would be able to sample four snow pits/day, for an expected maximum of 108 snow pits during the IOP under ideal conditions. Distribution of these 108 snow pits would be proportional to the areal composition of the nine-member matrix within our flight lines (Figure 5.3; Table 5.1). Random points were scattered throughout the nine classes and 108 potential pit locations were identified (Figure 5.3). We have planned three four-person teams, which will include two people for standard snowpit observations (density, temperature, stratigraphy) and liquid water content (LWC) profiles, one person for snow depth transects around the pit, and one person performing profiles of specific surface area (SSA).

Table 5.1. Area, in hectares, and percentage of the total area of the nine snow-tree classes within the SWESARR flight lines (Figure 5.3).

| Matrix Classes | Treeless | Sparse | Dense |
|---|---|---|---|
| Shallow | Class 1: 198 ha (14%) | Class 4: 27 ha (2%) | Class 7: 45 ha (3%) |
| Intermediate | Class 2: 339 ha (23%) | Class 5: 154 ha (11%) | Class 8: 250 ha (17%) |
| Deep | Class 3: 101 ha (7%) | Class 6: 176 ha (12%) | Class 9: 173 ha (12%) |

All ground personnel will work in teams of three to five persons each. An assessment of the likely maximum number of field personnel (~20) available for the experiment, divided into teams of three to five, provided the human resources framework to develop the data collection strategy. Given additional resources and personnel, the plan could be easily expanded to include additional data collection. During the IOP, team location management will be done nightly in coordination with air science crews. Teams will normally be located in close proximity (<4 km) for safety, easier communications, and efficiency. Teams may be distributed farther to sample a larger area among flight lines in the event snow conditions change with mid-campaign storms and weather. The locations of the 108 pits make all of this possible.

### 5.2.3 Ground Sample Design Assessment

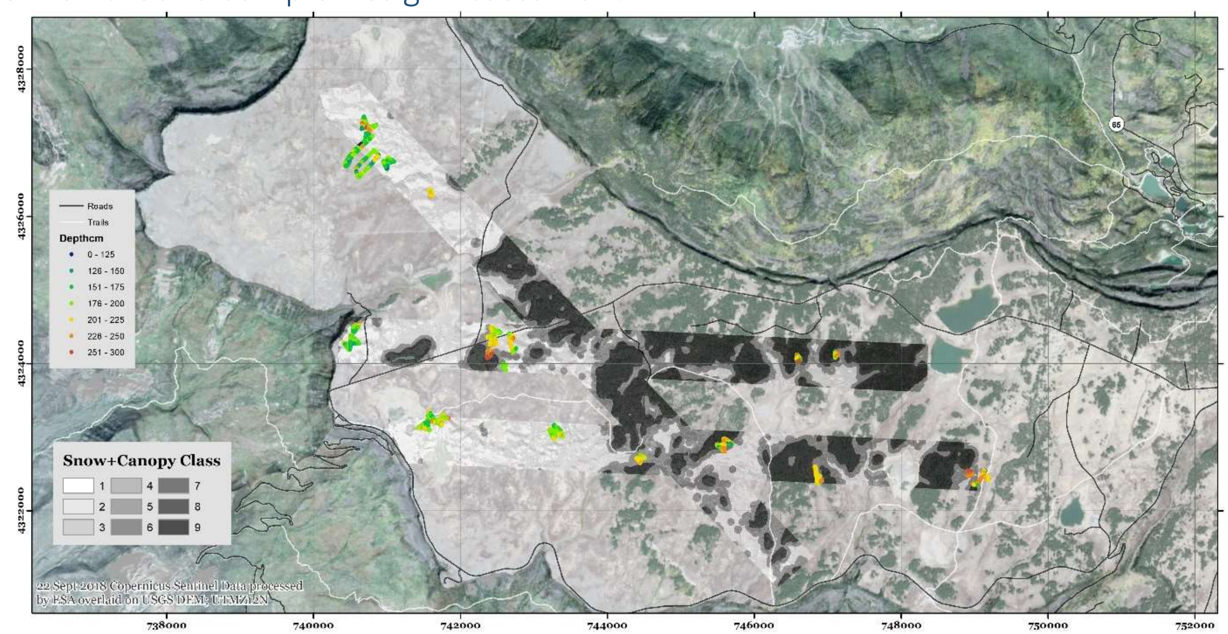



**FIGURE 5.4. OVER 3700 SNOW DEPTHS WERE MEASURED IN MARCH 2019'S DEEP SNOWPACK USING A SUBSET OF THE MAIN EXPERIMENTAL DESIGN (FIGURE 5.3).**

A five-day SnowRadar19 and CRREL Snow Mobility campaign sampled 23 snow pits and 3700 snow depths on Grand Mesa within the flight lines (Figure 5.4). University of Alabama's UWB FMCW radar flew the area with a Twin Otter, and ground sampling included a host of other snow instruments to support calibration and validation (see *Previous Studies* above). Most of the snow pit locations were intentionally in "treeless" areas (Classes 1-3), as this was one of the first airborne FMCW campaigns coincident with a ground effort in mountainous terrain, and focus was on testing the instrument in open areas, with limited testing in forested areas. Examination of measured snow depths and their sample classifications illuminate that all of the classes appear to be distinct from each other (Figure 5.5), even in different years, and they retain, on average, the same average order from 2017 to 2019. The sample design is not balanced in terms of sample size (Table 5.2), however, it is proportionally representative, and most of the classes have more than 100 observations giving some confidence that the sample design presented represents a range of Grand Mesa snow conditions.

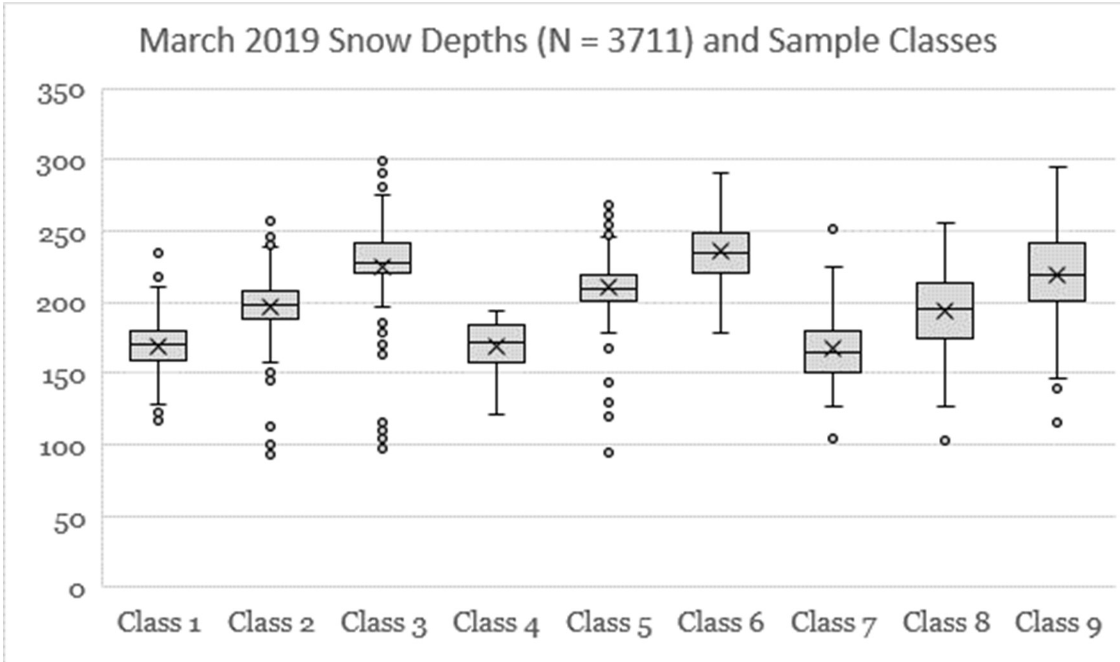



**FIGURE 5.5. MATRIX CLASSES REPRESENT GRAND MESA'S TREELESS (CLASSES 1-3), SPARSE (CLASSES 4-6), AND DENSE (CLASSES 7-9) AREAS. AALL CLASSES APPEAR TO BE DISTINCT. THE CLASSES FOLLOW FEBRUARY 2017 DEPTHS.**

Table 5.2. Distribution of depths within sampled matrix classes during the SnowRadar19 and CRREL Snow Mobility campaign

| Matrix Classes | Treeless | Sparse | Dense |
|---|---|---|---|
| Shallow | Class 1: 1048 | Class 4: 18 | Class 7: 25 |
| Intermediate | Class 2: 1294 | Class 5: 391 | Class 8: 211 |
| Deep | Class 3: 251 | Class 6: 332 | Class 9: 140 |

### 5.2.4 Core Observations

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

1. Snow depth transects (probing)
2. Snow surface roughness
3. Snow Pits
    a. Depth
    b. Stratigraphy
    c. Density
    d. Wetness
    e. Temperature
    f. Grain Size
    g. Soil Characteristics

### 5.2.5 Meteorological Stations

One of the three stations deployed as part of SnowEx17 is within the area of the IOP. This station is designed to provide fundamental micrometeorological observations that will be used to support analysis and modeling investigations activities. It measures every 10 s:

1. Incoming and outgoing shortwave radiation (Kipp and Zonen CM-21)
2. Incoming longwave radiation (Kipp and Zonen CG-4)
3. Wind speed and direction (1-level) (RM Young Wind Monitor)
4. Air temperature (1-level) (Vaisala HMP45C)
5. Relative humidity (1-level) (Vaisala (HMP45C)
6. Snow Depth (Judd Communications)
7. Snow-soil temperature profile (thermistor string)
8. Barometric pressure (Vaisala PTB101B)

### 5.2.6 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.

#### 5.2.6.1 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 ASSSAP (Arnaud et al., 2011)); 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.

#### 5.2.6.2 Snow Surface Temperature

Snow surface temperature measurements will be relevant to assess airborne CASIE observations and space-borne GEOS16 data. These data are important for surface energy balance calculations and modeling.

#### 5.2.6.3 Liquid Water Content (WISe)

SnowEx 2020 microwave observations (e.g., from UAVSAR, SWESARR, UWB) 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 2020 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 B).

*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.

#### 5.2.6.4 GPS snow-depth probes

All SnowEx2020 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.

#### 5.2.6.5 Radar

Radar systems offer the opportunity to survey depth/SWE over long distances, contributing to the assessment of depth/SWE retrievals from airborne observations. Radar 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. It is anticipated that there will be two kinds of radar systems: 1) a wideband FMCW radar; and 2) GPR.

#### 5.2.6.6 Ground-based radiometers

Observations from ground-based microwave radiometers will be relevant to assess the SWESARR passive observations. It is anticipated that radiometers operating at 19 and 37 GHz will be deployed at some pit locations.

#### 5.2.6.7 Terrestrial laser scanners (TLS)

TLS surveys give the community access to surface elevation and roughness, snow depth, and stand scale forest structure characteristics. Also, it offers an opportunity to assess snow depth data from manual measurements and radar retrievals. Two TLS teams will be conducting five site surveys during a September snow-free campaign, and repeating them during the IOP (Table 5.2). These areas encompass shrubland steppe and forested land cover types on the relatively level western part of Grand Mesa, and the sites are located within the flight lines to bolster chances of coincident airborne data collection.

#### 5.2.6.8 Radar Corner Reflectors

Corner reflectors are needed to ensure 1) accurate geolocation of the radar images, and 2) assess radar backscatter measurements. 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. We anticipate deploying a suite of 4 radar corner reflectors at the Grand Junction Regional Airport, near the Twin Otter International hanger, maintaining the two permitted reflectors on Grand Mesa that have been in place since 2015, and deploying an additional 6 targets.

**Table 5.2. Tentative ground-based instruments to be deployed during SnowEx 2020 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<br>Ohio State Univ. | SSA profiles in all snow pits | | 3 people (1p/sensor/pit team) |
| Snow Casting for MicroCT | 3-D snow structure | Zoe Courville<br>ERDC-CRREL | | | 1 person |
| Snow MicroPenetrometer | Penetration force | H.P. Marshall<br>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** | | | | | |
| | | Jessica Lundquist & Steven Pestana<br>Univ. of Washington | | | 1 person |
| **Liquid Water Content** | | | | | |
| WISe | LWC | Carrie Vuyovich<br>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<br>Boise State Univ. | Amplitude vs. time over FMCW sweep. Processed results include snow travel-time, depth, SWE, layer thickness, geolocated and time-stamped. | | 1 person |
| GPR | 1 GHz | Ryan Webb, Univ. of New Mexico | | | 1 person |

| | | | | | |
|---|---|---|---|---|---|
| | | Dan McGrath,<br>Colorado State Univ. | | | |
| **Microwave radiometer** | | | | | |
| | | Mike Durand<br>Ohio State Univ. | | | 1 person |
| **Terrestrial Laser Scanners (TLS)** | | | | | |
| Riegl VZ 1000 | 1550nm | Nancy Glen<br>Boise State Univ. | RTK Opus corrected GPS points,<br>Geo-located TLS scans | | 2 people |
| Leica ScanStation C10 | 532 nm | Chris Hiemstra<br>ERDC-CRREL | RTK Opus corrected GPS points,<br>Geo-located TLS scans | | 2 people |

**Total personnel (current estimate): 22 people**

### 5.2.7 Schedule

The Grand Mesa campaign includes a 5-day snow-off campaign September 23-27, 2019, a background campaign Nov 4-8, 2019, and a 10-day snow-on campaign Jan 27 – Feb 7, 2020. Below is a tentative schedule for the Jan/Feb snow-on campaign.

| Sunday, Jan 19 | Monday, Jan 20 | Tuesday, Jan 21 | Wednesday, Jan 22 | Thursday, Jan 23 | Friday, Jan 24 | Saturday, Jan 25 |
|---|---|---|---|---|---|---|
| | SWESARR/Thermal IR teams arrive in Grand Junction for instrument integration and test flights | | **UAVSAR** | | | - Logistics team arrival at Grand Mesa Lodge |
| **Sunday, Jan 26** | **Monday, Jan 27** | **Tuesday, Jan 28** | **Wednesday, Jan 29** | **Thursday, Jan 30** | **Friday, Jan 31** | **Saturday, Feb 1** |
| - Unpack shipment<br>- Assemble pit kits<br>- New participants arrivals at Grand Junction<br>- Transfer to Grand Mesa Lodge<br>- Met station visit (Houser + 1) | - New participants orientation and snowmobile training<br>- Participants arrival at Grand Junction<br>- Transfer to Grand Mesa Lodge<br>- Briefing | **SWESARR/Thermal IR (am)**<br>**Quantum Lidar (12pm)**<br><br>- Field day, Survey Line 1 a&b | **UAVSAR**<br>**NOHRSC Gamma**<br>- Field day, Survey Line 1 a&b | **SWESARR/Thermal IR**<br>**NOHRSC Gamma**<br><br>- Field day, Survey Line 1 a&b<br>- Relocate corner reflector | - Field day, Survey Line 2 a&b | **SWESARR/Thermal IR**<br><br>- Field day, Survey Line 2 a&b |
| **Sunday, Feb 2** | **Monday, Feb 3** | **Tuesday, Feb 4** | **Wednesday, Feb 5** | **Thursday, Feb 6** | **Friday, Feb 7** | **Saturday, Feb 8** |
| - Field day, Survey Line 2 a&b | - Field day, Survey Line 3 a&b<br>- Relocate corner reflector | **SWESARR/Thermal IR**<br><br>- Field day, Survey Line 3 a&b | **UAVSAR**<br><br>- Field day, Survey Line 3 a&b<br>- Data QC | - Check out field participants<br>- Transfer to Grand Junction<br>- Pack pit kits, and everything else<br>- Pits at met stations (central & east) | - Package field material for shipping<br>- Tape shipping labels<br>- Check out all personnel<br>- Last transfer to Grand Junction | |

**SnowEx 2020 GM IOP generic schedule**
**(safety will always be deciding factor in all operations and decisions)**

Actual schedules will vary on daily basis based on constraints that arise from:
1) Safety and health issues
2) Weather
3) Science needs and accomplishments

**Transportation day to Grand Mesa (Jan. 27)**
Field workers will arrive at Grand Junction Airport or Grand Mesa Lodge (GML) and check in
Schedules will depend on safety, weather, and arranged transportation
HHMM Vans leave Grand Junction airport to GML
1800-1900 Dinner at GML
1900 Evening orientation – ATTENDANCE MANDATORY
Welcome and introductions – Marshall
NASA overview – Vuyovich
Ground overview – Hiemstra
Safety and logistics overview – Newlin

**Transportation day to Grand Junction (Feb. 7)**
Field workers on site will check out and leave Grand Mesa Lodge
Schedules will depend on safety, weather, and arranged transportation
HHMM Vans leave GML for Grand Junction Airport

**Training day (Jan. 27) – ATTENDANCE MANDATORY for new SnowEx Grand Mesa participants**
1000-1200 Snowmobile training

**Typical Field day (Jan 28 – Feb 6)**
0630-0715 Breakfast
0715-0745 Daily safety meeting, weather update – ATTENDANCE MANDATORY
0745-0800 Equipment issued
0830 Field crews leave for destinations – begin field measurements
1200-1230 Field crew lunch, system-wide check in with assigned contacts
Status, location, plans
1230-1630 Continue field measurements
1630 Latest time to pack equipment and return to Grand Mesa Lodge
1700 Field notebook delivery and equipment turned in to quartermaster
1830-1930 Dinner
1930-2030 Daily debriefing – ATTENDANCE MANDATORY
Safety update
Weather update
Airborne update
Lessons learned
Data issues discussion
Following day's plan
2100-2200ence, Airborne and Safety Team lead meeting

# 6 Satellite Observations

## 6.1 Tasked Satellites

### 6.2.1 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 SnowEx2020, 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 time series sites centered on ground-based and aerial lidar measurements for all 13 areas will be the main priority. In addition, the Grand Mesa IOP will feature three stereo data collections and an attempt to get WorldView 3 SWIR data mid-campaign. Snow-free mid- and late-summer collections in 2019 and 2020 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.

### 6.2.1 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 SnowEx2020 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.

## 6.2 Operational Satellites

In addition to satellite acquisitions specifically tasked for SnowEx 2020, there are a number of operational, globally observing satellite sensors that are relevant to the goals of SnowEx 2020. These are briefly described below, along with their relevance for snow property estimates.

### 6.2.1 GOES-17

### 6.2.2 Sentinel 1A, 1B

### 6.2.3 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 2020 activities through the planning phase, during the campaign, and in analyzing the results.

## 7.1 Snow Ensemble Uncertainty Project

The Snow Ensemble Uncertainty Project (SEUP) is a modeling exercise aimed at characterizing sources and regions of high snow uncertainty based on the current state of modeling snow and cold season processes. The objective of this exercise is to support NASA's SnowEx by helping to inform the selection of potential field campaign locations in regions where our current estimation capabilities could be improved. This project aims to quantify snow estimation uncertainty across a range of snow classes, terrain and vegetation types, to address the following science questions: What areas and time periods have high SWE uncertainty across the ensemble? Which factors govern spatial and temporal SWE uncertainty? How does the uncertainty in the SWE estimation contribute to the uncertainty in other components of the water budget?

The ensemble of distributed SWE estimates over North America was developed using well-established land surface models (LSMs) and forcing data, selected because of their current use in various operational centers and in research. Four different land surface models (LSMs) of varying complexity were run using the NASA Land Information System (LIS): 1) Noah version 2.7.1, 2) Noah-Multi-Parameterization, 3) Catchment version 2.5, and 4) the Joint UK Land Environment Simulator. Three different forcing datasets were used to drive each of the LSMs: 1) Modern Era Retrospective Analysis for Research and Applications, version 2, 2) Global Data Assimilation System, and 3) the European Centre for Medium-Range Weather Forecasts. The 12-member ensemble was run at a 5-km spatial resolution over the time period 2000 – 2017, with the first nine years were used as model spin-up and analysis conducted over the remaining years (2009-2017). Overall results and additional details are provided in Kim et al. (in prep).

The SEUP results were assessed over the Western U.S. and over the SnowEx 2020 Time Series and IOP study sites. The Western U.S. was evaluated by snow classes (Sturm et al. 1995; and Liston and Sturm 2014, unpublished manuscript). The greatest variability in SWE estimation occurs in the tundra and taiga snow classes, which are predominately located at the highest elevations in the Rocky and Sierra Nevada Mountain ranges. Based on the SEUP results, approximately 54% of the total snow water storage (SWS) occurs in the mountainous regions (tundra, taiga, maritime and warm forest snow classes), which makes up about 21% of the total area in the Western U.S. domain, while 46% of the total SWS occurs in the non-mountainous regions (prairie and ephemeral snow classes) (Figure 7.1).

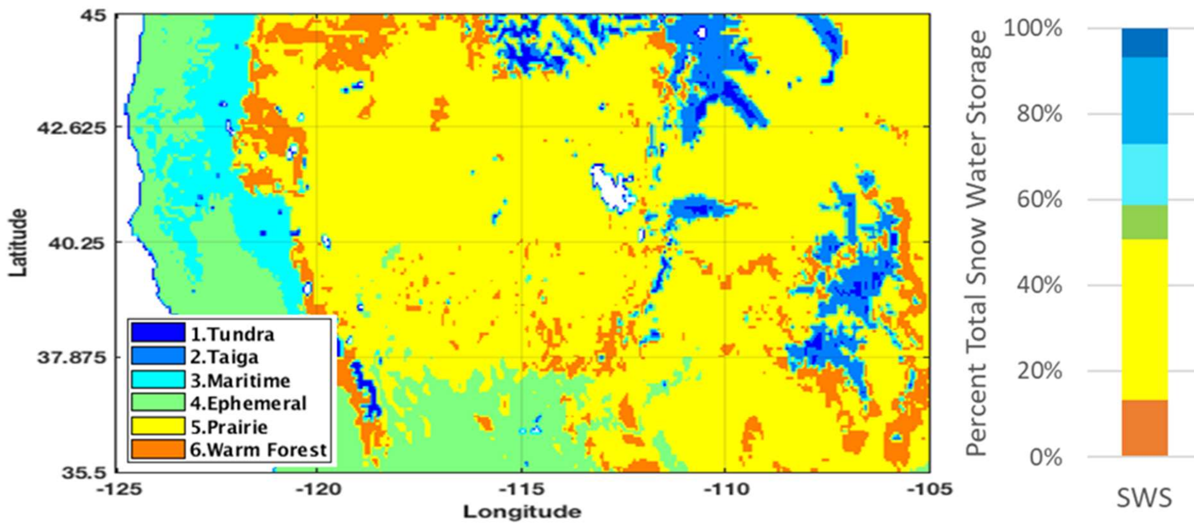



Figure 7.1. Snow classes in Western U.S. and percent total snow water storage by snow class based on mean SEUP ensemble SWE over analysis period, 2010 – 2017 (produced by R.S. Kim, NASA GSFC).

Within each of the SnowEx 2020 regional domains (Idaho, California and Colorado) and flight boxes, the mean, range and coefficient of variation from the SEUP results was assessed to identify regions of deep snow and high variability within the study areas (Figure 7.2). Surprisingly, locations with the highest variability were often found in areas with less snow and at lower elevations, with greater agreement at higher elevations with deep snow. The greatest SWE variability in deep snow was found on the windward side of the mountains. Variability between SEUP ensemble members is largely driven by model choice rather than forcing data (not shown), which is similar to what has been found over all of North America (Kim et al., in prep). However, this result varies at particular sites. For instance, there is a lot of variability between ensemble members on Grand Mesa, driven primarily by forcing data, while at Senator Beck there is much greater agreement between ensemble members and with SNOTEL data as well, with greater spread between models.

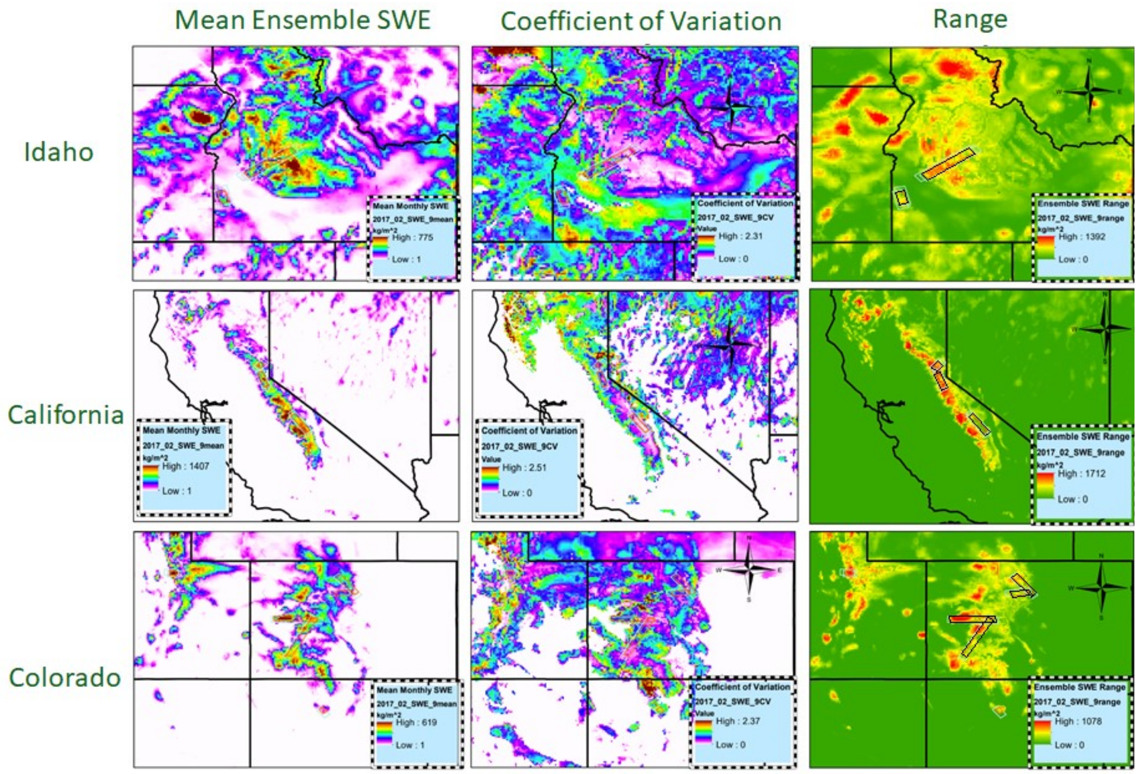



Figure 7.2. SEUP ensemble mean, coefficient of variation and range over three main SnowEx 2020 regions, Idaho, California and Colorado. (produced by J. Johnston, GMU)

## 7.2 Snow OSSE

An observing system simulation experiment (OSSE) is currently under development to assess the potential benefits of remotely sensed observations to reduce SWE variability and improve snow estimation for end-use applications. The OSSE will be conducted using the NASA Land Information System (LIS) over a Colorado domain which includes the SnowEx 2020 flight boxes (Figure 7.3). Nature run results will be validated using data from available observations and field campaigns, including the SnowEx 2017 campaign. The simulations will be run at 1 km resolution for the 2014 – 2017 winters, which include high and low snow years. Observations to be assimilated include SWE (microwave, radar), snow depth (lidar, SfM), snow covered area and albedo (visible-IR). Spatial and temporal sampling will be done at 1, 5 and 25 km and 1, 5, and 10 days, respectively, and the study will test assimilation of single and multiple variables. The OSSE will allow us to investigate the impacts of retrieval error and data resolution on the estimated snow states and ultimately on the broader terrestrial and hydrologic applications.

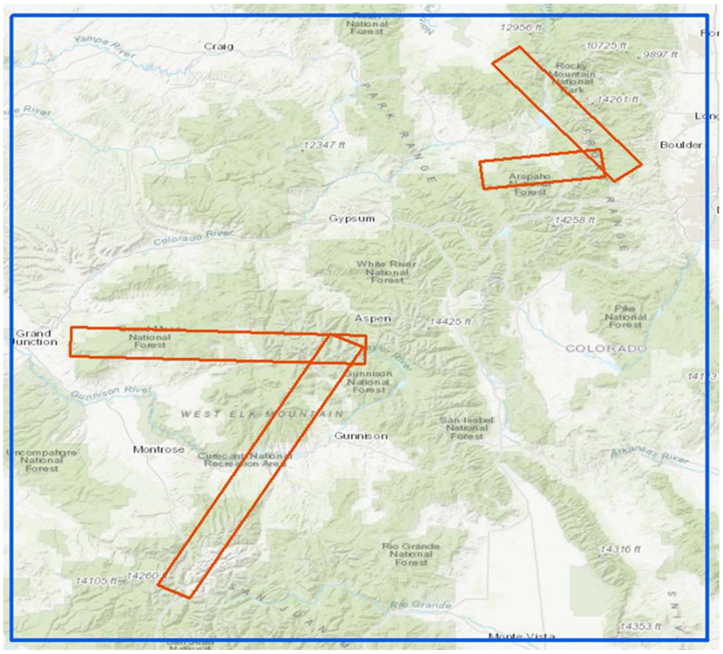



Figure 7.3. Snow OSSE domain in western Colorado. Red boxes indicates UAVSAR flight boxes.

# 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.

Data management involves support from both the PI's generating the data and staff from NSIDC to insure the data is ingested, archived and made available to the public in a timely manner.

**Western U.S. Time Series Campaign data from field books**

For the Western U.S. Time Series Campaign, data management will focus on PI entered data, submitted to NSIDC through the means of an on-line data entry tool. The plan includes the following steps:

- NSIDC will provide and maintain an on-line tool for data entry that closely mimics a PI's field notebook.
- NSIDC will provide training on data management protocols for field teams prior to time series campaign
- NSIDC will support for the teams as they use the tool for data entry.

- The PIs and their teams will enter the data from their field books within XX hour/days? for ingest into NSIDC systems
- NSIDC will then generate the required file-level metadata and handle the data through its standard ingest processes, including ingest into the NASA Common Metadata Repository (CMR)
- The PIs will support NSIDC in the generation of User Guides, metadata and other information necessary to support the distribution of the data
- The PIs are primarily responsible for the QA and QC of the data and its entry.

**Grand Mesa Intensive Observation Campaign data from field books**

For the Intensive Observation campaign, NSIDC will take a more active role in data entry. 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, etc., thus taking a more active role in the QA/QC steps as well. The data management plan includes the following steps:

- NSIDC will provide training on data management protocols for field teams during winter IOP.
- NSIDC will provide and maintain an offline data input tool to be used for data entry at Mesa lodge
    - Provide personnel to assist with data management during winter IOP. 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, including ingest into CMR
- The PIs will support NSIDC in the generation of User Guides, metadata and other information necessary to support the distribution of the data

**Campaign Data from other sources**

Data from sources other than the field books will be handled on a case-by-case basis. In general the steps are:

- PIs will submit their data to NSIDC for ingest after the campaigns are completed.

- QA/QC will be the responsibility of the PIs.
- NSIDC will work with the PI's to generate the necessary metadata, documentation, and other information necessary for data ingest and publication

**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 – Field Sampling Protocol

## B.1. Snow Depth Measurement (Probing)

Snow depth (HS), or height of snowpack, will be measured at several locations identified on the map. 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), using a collapsible, graduated snow probe.

The following steps outline the general procedure for sampling snow depth:

1. Locate initial sampling point using visual aids (marked stake), maps, photographs and GPS. (THIS WILL BE DEFINED MORE PRECISELY IN THE NEAR FUTURE).

2. Take the initial snow depth measurement close to marked stake. If there is an ablation cone or wind erosion next to the stake, locate the measurement outside of the influence of the anomaly, but as close to the stake as possible. The same is true if there is an upward cone at the stake due to post-deposition snow settlement.

3. Record sample depth in appropriate location in the field book to the nearest centimeter. Use centimeters rather than meters to avoid decimal points for field notes.

4. 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

5. 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.

6. 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.

## B.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.

## B.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.

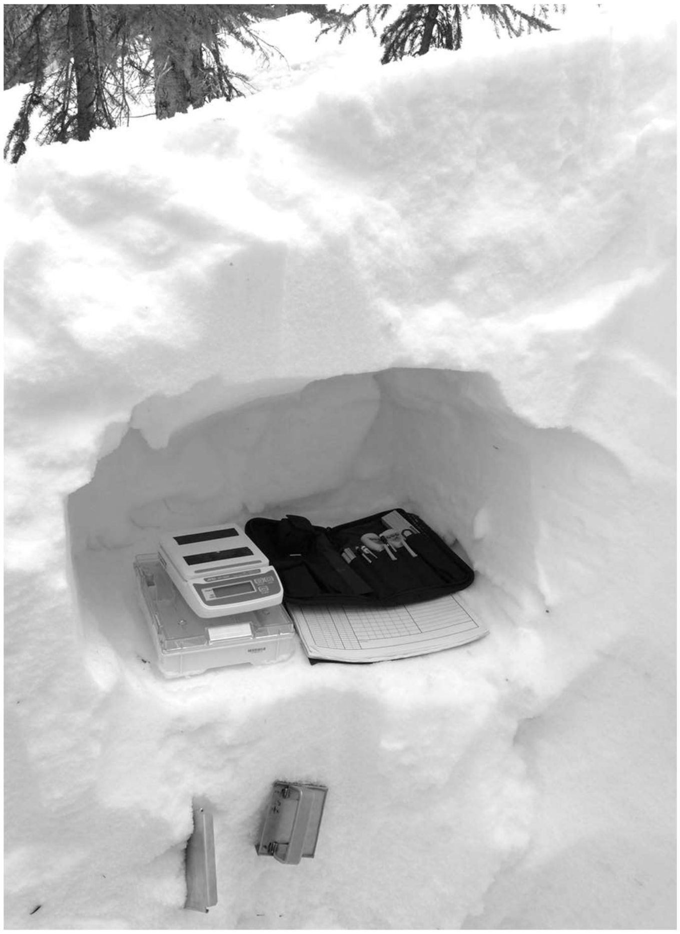


Figure B.4. Excavated hole in snowpit flank to provide a flat, protected location for the scale and fieldbook. Note that there is plenty of room to bring the density sampler in and out of the hole without knocking snow onto the scale or notebook. If the hole is too big, blowing snow will accumulate on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

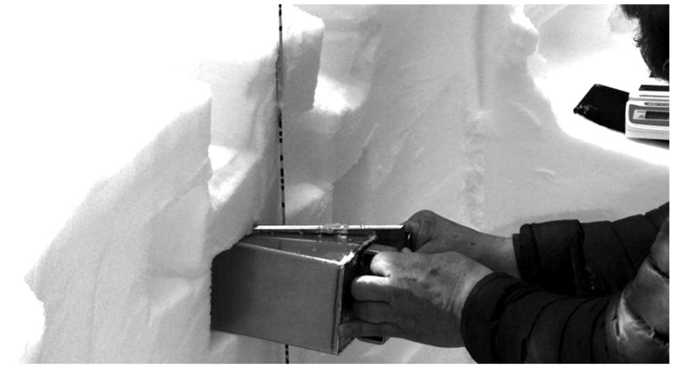


Figure B.7 Simultaneously remove both the sampler and lid to insure no snow loss from the sampler.

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.

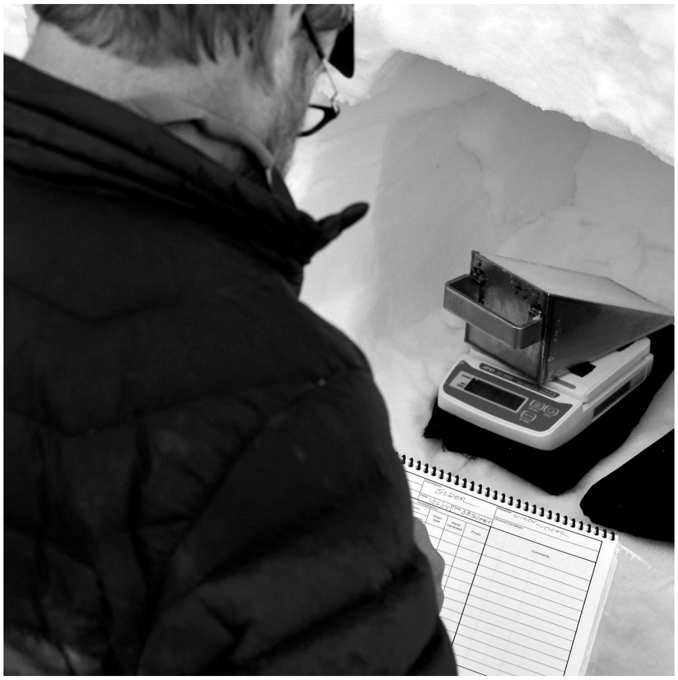


Figure B.9. Weight the clean sample and record the value in the data book.

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

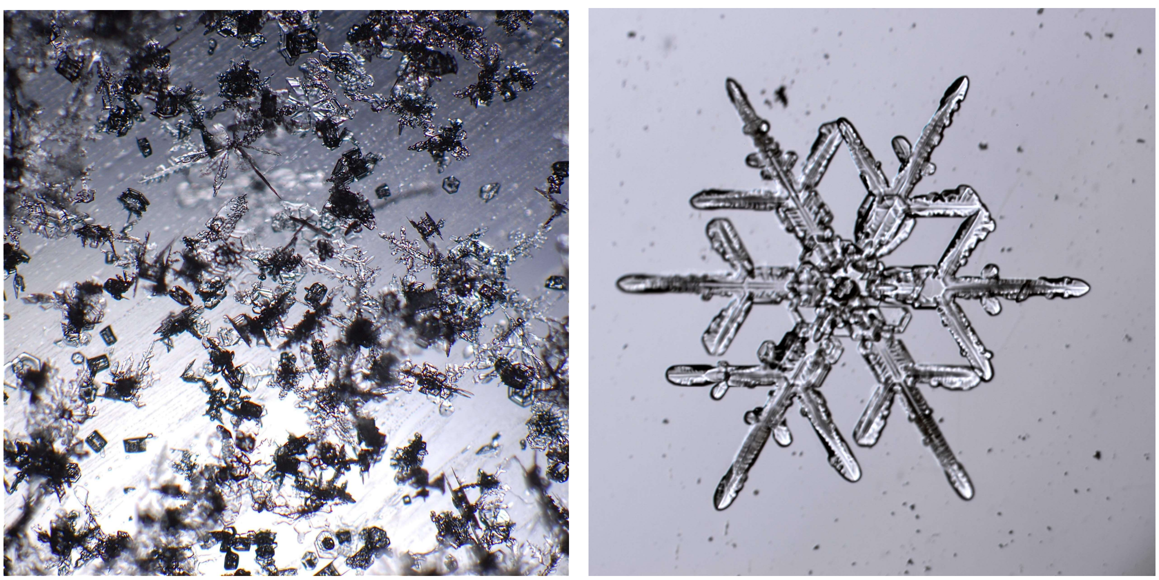
Snow grain size will be measured for each homogeneous layer in the snow profile. Use a paintbrush, dry wall brush, putty knife, hand or other instrument to determine where major grain boundaries exist in the pit profile. Mark each boundary. Collect a sample from the pit wall by gently scraping the point 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.



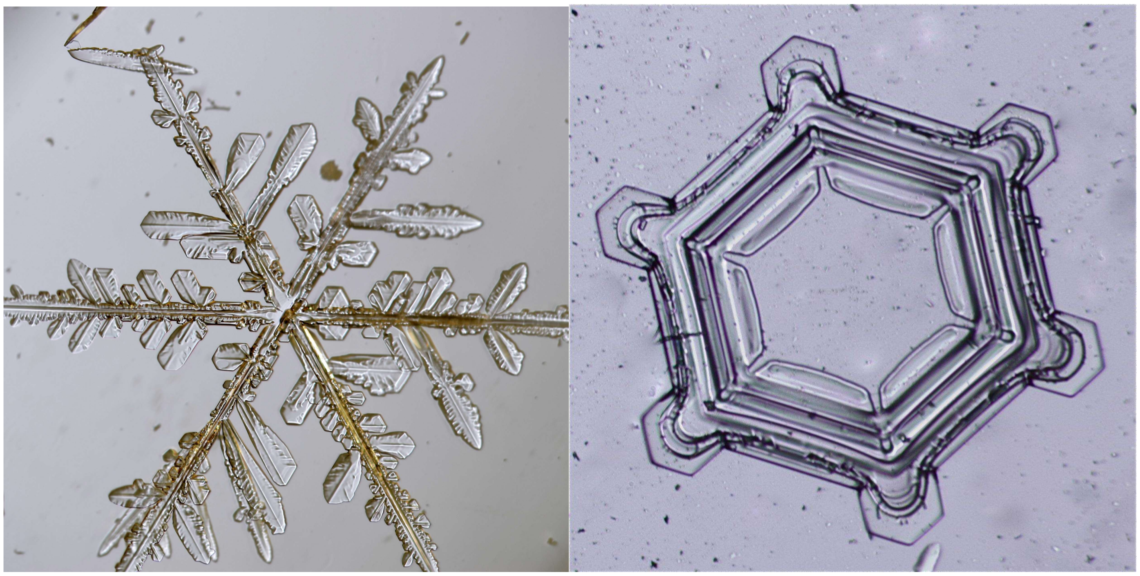
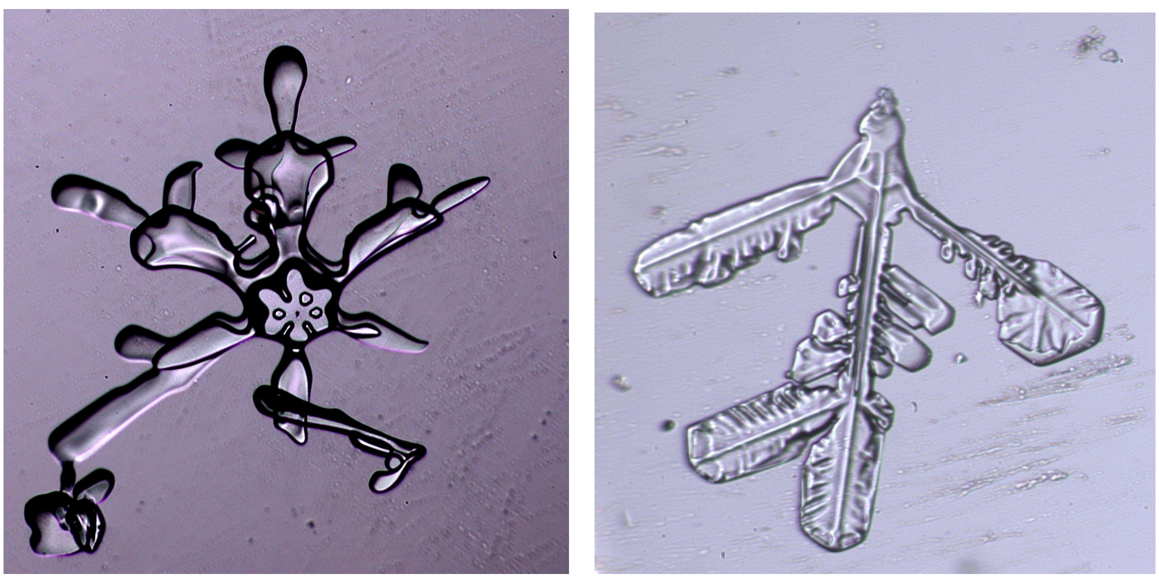


Figure B.12. New snow or precipitation particles (PP).

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.



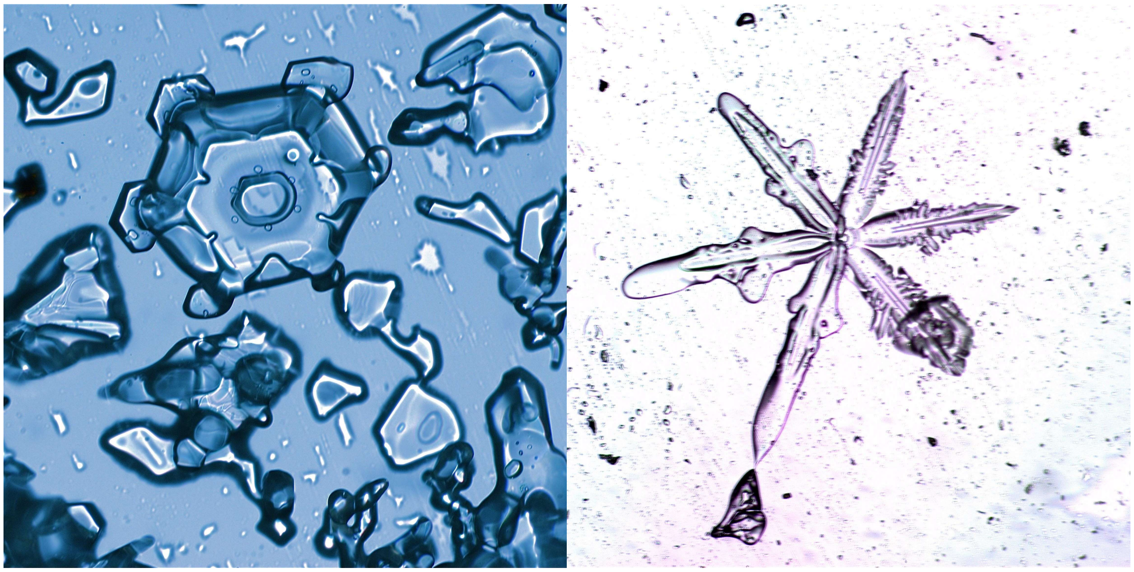


Figure B.13. Decomposing new snow or fragments (DF).

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.

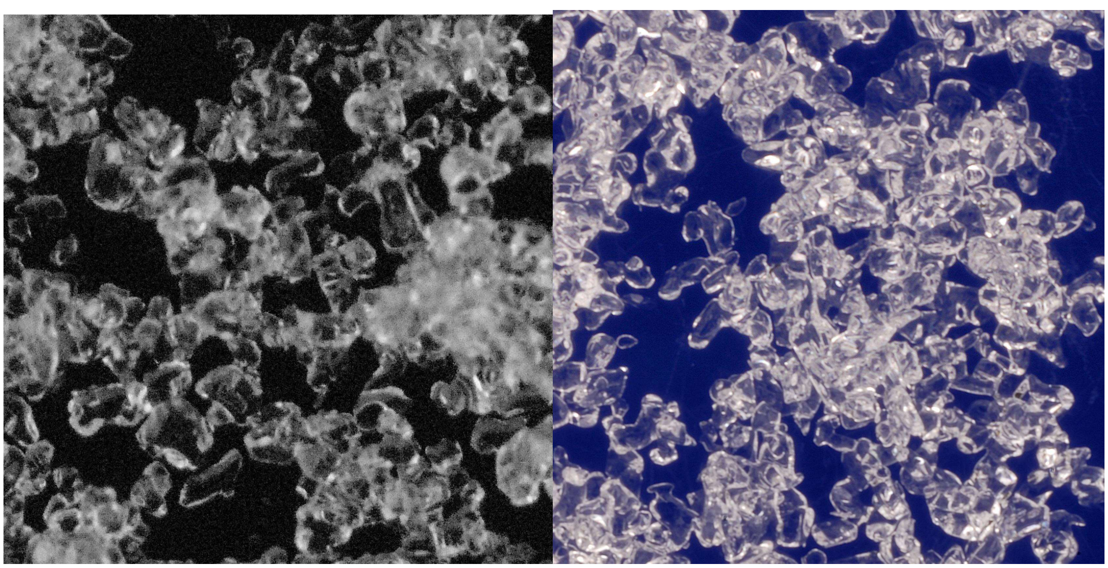
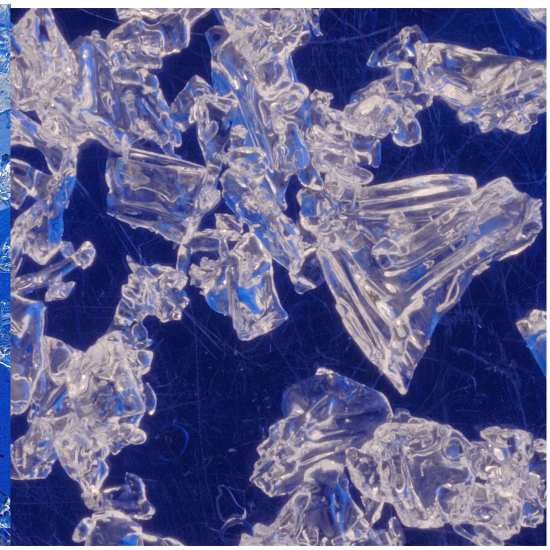
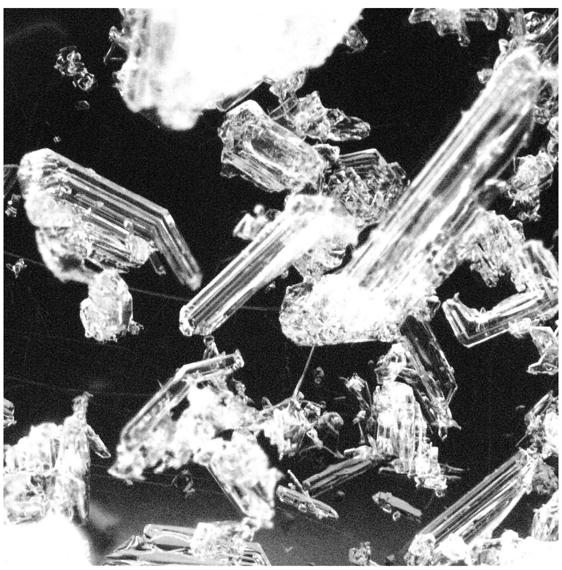


Figure B.14. Round grains (RG).

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.



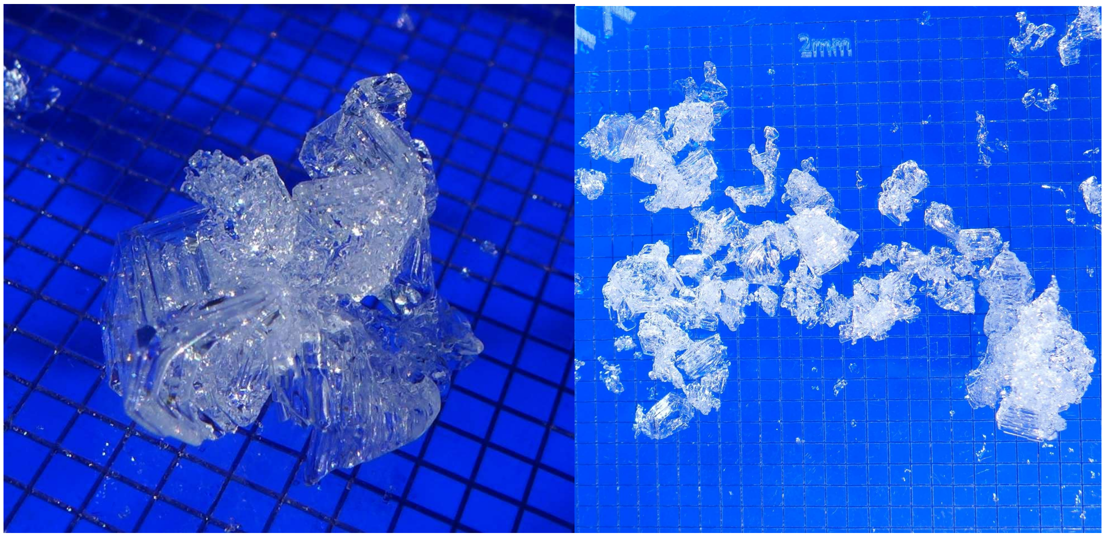
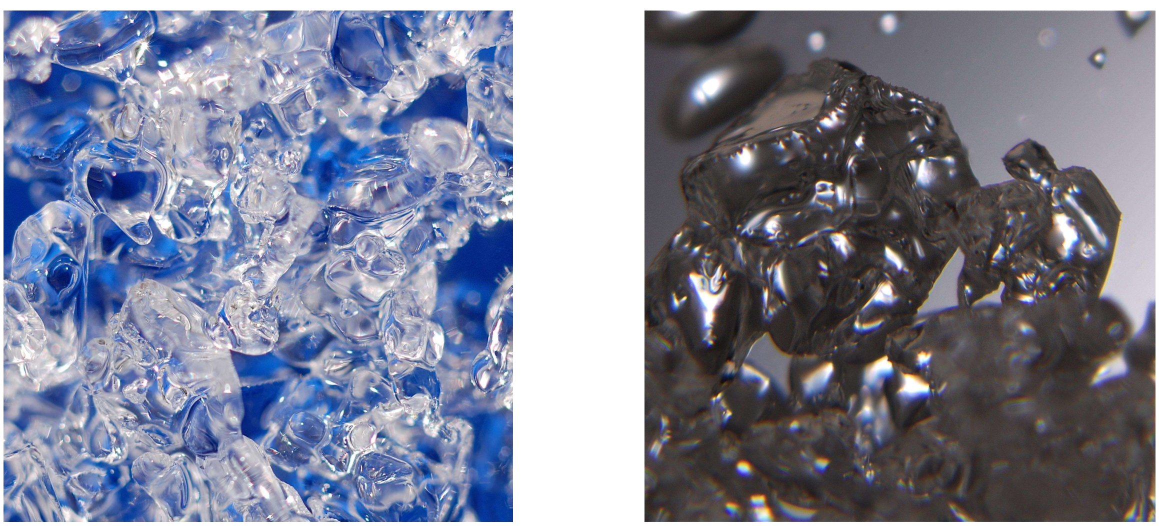




Figure B.15. Faceted crystals (FC).

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.



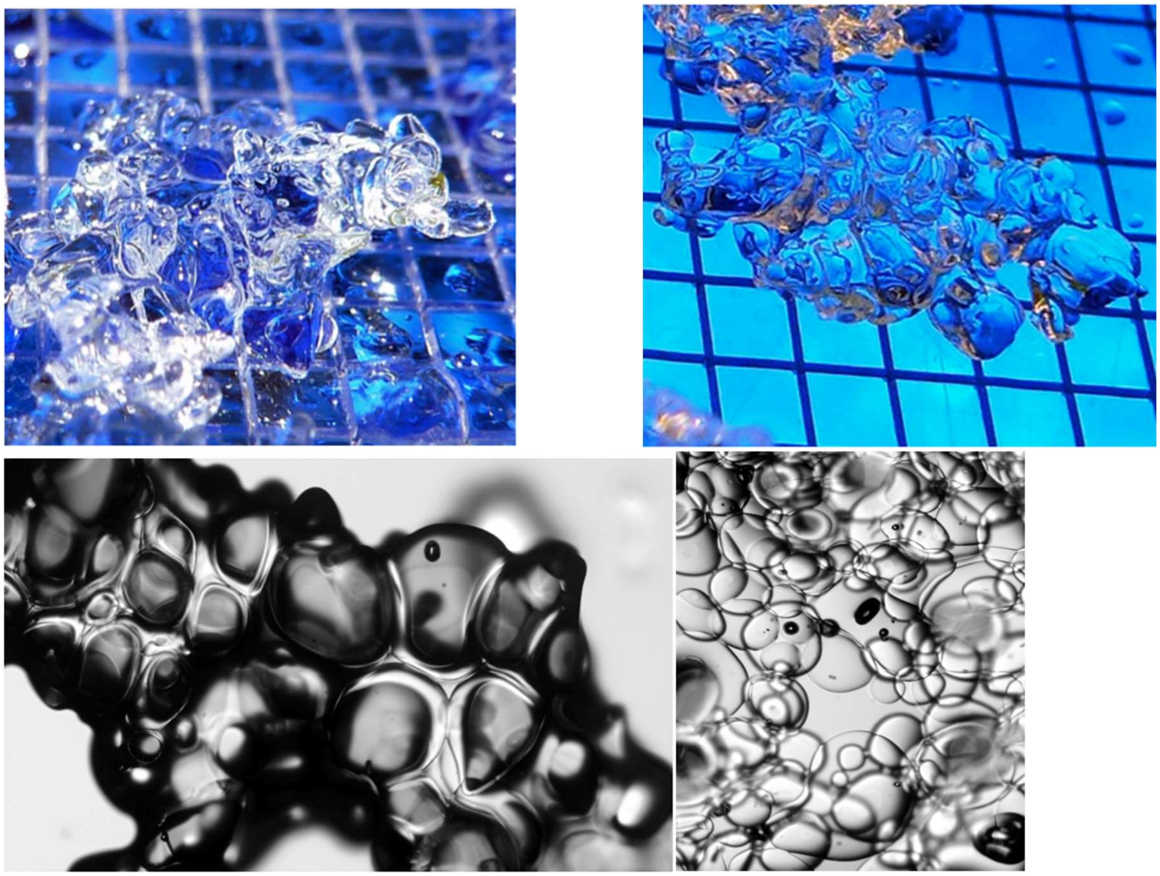


Figure B.16. melt forms (MF).

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.

NEED FIGURE HERE

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.

# Appendix C – Time Series Site Location Descriptions

## C.1. Lakes and San Joaquin Basins, California

### Site Lead: Ned Bair, University of California Santa Barbara

### Site Description

The Mammoth Mountain and Mammoth Lakes Basin area includes three long-term study plots at CRREL/UCSB Energy Site (CUES), Mammoth Mountain Ski Patrol Sesame Snow Plot, and Mammoth Pass (CDEC code MHP). Lat/Lon/Elevation*:*

- CUES (37.643◦ N, 119.029◦ W, elevation 2940 m)
- Sesame Snow Study Plot (37.650◦ N, 119.042◦ W, elevation 2743 m)
- MHP (37.612◦ N, 119.032◦ W, elevation 2835 m)

*Elevation range:* 2600 – 3400 m

*Canopy:* extends up to 3000 m consists of Whitebark Pine forest. The understory here also consists of small shrubs. Ground cover is also predominately tephra. Tree heights up to 25 m

*Snow climate:* Maritime according to Sturm et al. (1995), and predominately Maritime with Intermountain years according to Mock and Birkeland (2000)

*Ownership:* USDA Inyo National Forest

*Brief historical background:* Extensive snow hydrology research beginning in the late 1970s. See Bair et al. (2015); Bair et al. (2018).

*Synergistic Activities in 2019-20:* Field measurements accompanying planned ASO flights.

### Infrastructure

*Meteorological Sensors:* All standard met at each site. Full e-balance sensors at CUES. Available every minute at CUES and Sesame, hourly at MHP. Data available at www.snow.ucsb.edu, cdec.water.ca.gov, patrol.mammothmountain.com.

*Snow Sensors:* snow pillow at each site, 1-3 ultrasonic depth sensors at each site, operational snow course (manual measurement) near MHP, new snow weighed each morning at Sesame, snow surface temperature at CUES, lysimeters at CUES, automated lidar at CUES and Sesame. Disdrometer at Sesame (Parsivel). Data available at www.snow.ucsb.edu, cdec.water.ca.gov, patrol.mammothmountain.com.

*Soil Sensors:* soil moisture and soil temperature at CUES. Data available at www.snow.ucsb.edu.

*Time lapse cameras:* every 5 min, CUES. User-controlled, Mammoth Mountain Ski Area. *Data available at* www.snow.ucsb.edu, https://www.mammothmountain.com/cams/mccoy-cam.

*Ground-based remote sensing instrumentation:* various radars at CUES, permanent.

### Field Logistics

*Travel to site:* Five minutes from town of Mammoth Lakes to Lakes Basin.

*Site Access:* 1-3 mile ski or snowmobile ride from winter closure of Lake Mary Road to field sites.

*Avalanche/Other hazards:* No avalanche hazard at planned sampling areas. $CO_2$ hazard around Horseshoe Lake. Will avoid this area and take handheld $CO_2$ measurements at each pit to ensure group safety.

*Measurement Locations:* Time series observations will be collected at Lake Mary Campground, which can be accessed by ski, snowmobile, or walk on groomed trail. (Lat/lon/elevation: 37.607, -119.006, 2719 m)

*Number of observers for each overflight:* 4

*Training:* All observers except one graduate student have current or former WFR or EMT-B. All observers have worked or currently work as avalanche professionals (course instructors, forecasters, ski patrollers).

*Communication options:* Cell service ok. Will also use InReach.

## C.2. American River Basin, California

### Site Lead: Roger Bales, University of California Merced

### Site Description

The American River Basin site is near the Caltrans Maintenance Station at Caples Lake, off Schneider's Cow Camp Rd. (Lat/Long/Elev: *38.710834,-120.041390, 2439m)*

*Elevation range:* 2430 – 2450 m

*Canopy:* scrub, sub alpine vegetation.

*Snow climate:*

*Ownership:* US Forest Service

*Brief historical background:* The location has long term snow course measurements and a SNOTEL snow pillow. It has also been the location of a wireless sensor network since 2010.

*Synergistic Activities in 2019-20:*

### Infrastructure

*Meteorological Sensors:* Met Station associated with the SNOTEL site. Solar Radiation and Temp/RH at the wireless sensor network base station. Data available online and at request.

*Snow Sensors:* Judd sensors, hourly data. Data available at request.

*Soil Sensors:* Soil Moisture and Temperature, hourly data. Data available at request.

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* none

*Additional nearby stations:* SnoTel at the same location and elevation as our base station.

### Field Logistics

*Travel to site:* 120mi, 2 hours

*Site Access:* by foot or ski, can drive up to several hundred meters away

*Avalanche/Other hazards:* N/A. Sometimes the road is closed due to avalanches, but there is another way in.

*Measurement Locations:* Time series observations will be collected at Caples Lake, which is on public land adjacent to snow course. (Lat/lon: 38.710422,-122.042034)

*Number of observers for each overflight:* 2-3

*Training:* WFR, First Aid, avalanche AIARE Level 1 and Rescue Day

*Communication options:* Cell, InReach

## C.3. Sagehen, California

### Site Lead: Anne Nolin, University of Nevada Reno

### Site Description

*Sagehen Creek Field Station, California* https://sagehen.ucnrs.org/plan-your-visit/location/,
Lat/Lon/Elevation: 39° 25’ 54.12”N, 120° 14’ 26.98”W; station facilities located at 1,943 m.

*Elevation range:* 1800 – 1650 m

*Canopy:* temperate coniferous forest (Lodgepole, Ponderosa, Jeffrey pines). In open areas, the landscape is wet meadow with grasses. There are also shrubs including tobacco brush *(Ceanothus velutinus)*, with greenleaf manzanita *(Arctostaphylos patula)*, Squaw-carpet *(Ceanothus prostratus)*, wax currant *(Ribes cereum)*, Bloomer's goldenbush *(Ericameria bloomeri)*, dwarf serviceberry *(Amelanchier pumila)*, and woolly mule-ears *(Wyethia mollis)*. Vegetation sub-canopy includes low shrubs and grasses (see above) with heights less than 1 m.

*Snow climate:* Maritime snow climate. Mediterranean type climate with cold, wet winters and warm, dry summers. Monthly average maximum temperature ranges from 4°C in December to 26°C in July; monthly average minimum temperature ranges from -10°C in January to 2.8°C in July. Annual precipitation is about 85 cm; snowfall accounts for greater than 80 percent of the annual precipitation. The annual total snow fall is 515 cm (snow depth, not water equivalent). The University of California, Berkeley Sagehen Creek Field Station has been collecting weather data since 1953.

*Land use/land cover:* Sagehen is an Experimental Forest and field station. The entire Tahoe region was heavily logged in the Comstock mining days (late 1800s); Sagehen experienced a major fire in 1960. More recently there has been mechanical forest thinning and prescribed fire.

*Land ownership:* USDA Forest Service, Pacific Southwest Research Station

*Land management:* UC Natural Reserve System and UC Berkeley

*Brief historical background:* The field station was established in 1951, and has since accumulated a rich record of data available by going to the UC Berkeley Sagehen Creek website (http://sagehen.berkeley.edu).

*Synergistic Activities in 2019-20:* Anne Nolin's research group will be measuring SWE and snow depth along established transects in forested and open areas. We will also be measuring snow albedo using a Spectral Evolution field spectrometer. We also take snow samples along our transects to analyze for light absorbing small particles (PS-2) and large particles (filtered onto Whatman glass filters for later spectral characterization). We have measured multi-spectral reflectance and computed structure-from-motion using a drone, which was flown over our transects in the forest and open. In conjunction with Steve Drake (UNR), Nolin's group will also be measuring snow energy & mass balance at towers located in open and forested sites, including water vapor and CO2 flux (eddy flux). Adrian Harpold's research group has been intensively snow and ecohydrology at selected locations in forest including intensive tree-based radiation and sapflow, SWE. Sagehen Tower 1 (100ft) is also an Ameriflux site.

### Infrastructure

*Meteorological Sensors:*

Reported at 1-min intervals:

- air temperature, RH at 2 levels
- barometric pressure
- net radiation (SW up/down, LW up/down)
- incoming PAR
- surface "skin" temperature

Reported at 20 Hz:

- 3D wind speed
- H2O and CO2 vapor flux
- temperature

Data access: online and by request

*Snow Sensors:* snow depth (SR-50), 1-min intervals, snow depth (magnaprobe), approx.. weekly, SWE snow pillow (Tower 4 only, hourly intervals), Data access: online and by request.

*Soil Sensors:* Soil temperature and moisture at 3 depths (10cm, 20 cm, 50 cm), 1-min intervals, Data access: online and by request.

*Time-lapse cameras:* We have two hunter's cameras that we can set up where and as needed, Photos are typically acquired at 1-hour intervals, Data access: by request.

*Ground-based remote sensing instrumentation:* Field spectrometer (Spectral Evolution) snow albedo transects, approx. weekly

*Additional nearby stations:* Independence Lake SNOTEL station, (lat/long/elev: 39° 26' N/120°19' W/2541 m), https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=541

### Field Logistics

*Travel to site:* 65 km from UNR to field station. Travel time is approx. 55 min.
*Site Access:* ski/snowshoe, snowmobile

*Avalanche/Other hazards:* N/A.

*Measurement Locations:*

Station 1 (forest, maintained by Nolin/Drake)

- Lat/lon/elevation: 39° 25' 42.61"N, 120° 14' 30.98"W
- Access: snowshoes

Station 3 (meadow, maintained by Nolin/Drake)

- Lat/lon/elevation: 39° 25' 48.59"N, 120° 14' 22.35"W
- Access: snowshoes

Tower 4 (high elevation site maintained by Sagehen/UC Berkeley)

- Lat/lon/elevation: 39° 25' 20.22"N, 120° 17' 57.25"W
- Access: snowmobiles, snowshoes

*Number of observers for each overflight:* minimum of two, 2-person teams, preferably three, 3-person teams.

*Training:* Each team should have at least one member with current WFA or WFR certification

*Communication options:* InReach (we will have 1 per team), very spotty cell service, radios are a possibility

## C.4. Reynolds Creek Experimental Watershed, Idaho

### Site Lead: Ernesto Trujillo, USDA Northwest Watershed Research Center

### Site Description

Reynolds Mountain East (RME) is in the Reynolds Creek Experimental Watershed (RCEW). The headquarters of the research station are located at 20117 Upper Reynolds Creek Rd., Murphy, ID 83650. The main building at the headquarters is referred to as the Quonset within the research unit (Lat, Lon: 43.205858, -116.749681). RME (near Silver City, ID) is a small (0.38 $km^2$) snow-dominated headwater catchment located within the Reynolds Creek Experimental Watershed (RCEW) of the USDA-ARS Northwest Watershed Research Center (NWRC). (Location of cabins at RME: (Lat, Lon: 43.06552778, -116.7582222, elev, 2097 m).

*Elevation range:* 2028 – 2137 m

*Canopy:* Vegetation is patchy with fir, aspen and sagebrush. Use permits for the field activities, instrumentation and infrastructure on site are in place and on file at the NWRC-USDA-ARS office in Boise, ID

*Ownership:* USDA

*Brief historical background:* The watershed has been the focus of research for decades, and was established in 1959. Meteorological, soil and snow measurements at RME exists from 1983-present (in Digital format) (see details under Infrastructure), and snow course activities are performed during the winter at one of the instrument sites in RME, adjacent to an instrument cluster that includes a snow pillow and snow depth sensors. Details of the instrumentation can be found in Reba et al. (2011) [doi:10.1029/2010WR010030]. Two measurement sites represent the major landscape units in the catchment (see Figure below). The sheltered site is located within a clearing in an aspen/fir grove near the center of the catchment and has been used extensively for snow measurement and instrument development and validation [e.g., Marks et al., 2001a; Reba et al., 2009; Flerchinger et al., 2010]. The exposed site is located on the western catchment divide in an area dominated by mixed sagebrush. Research activities and instrumentation in RCEW have been in place since 1960, and additional data (in non-digital format) exist dating back to the establishment of the watershed.

*Synergistic Activities in 2019-20:* Winter activities are regularly performed on the experimental watershed. Winter activities at RME include bi-weekly snow courses and regular maintenance of the instrumentation located on site (described above).

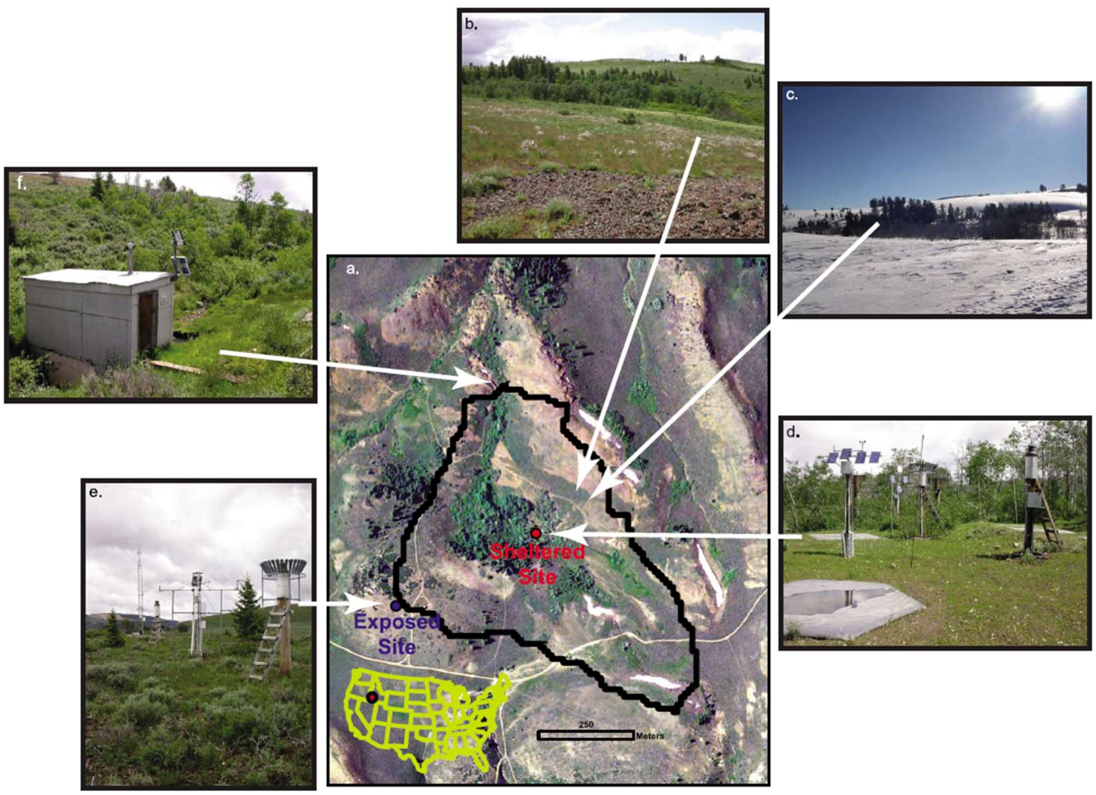



**Figure 1.** (a) Location map for the Reynolds Mountain East (RME) catchment with a shaded relief image of vegetation classes, roads, perennial streams, and locations of the outlet weir and sheltered and exposed sites, with (b) a view from the north in late spring, (c) a view from the north in winter, (d) sheltered site instrumentation and (e) exposed site instrumentation, and (f) the outlet weir.

*From: Reba et al., 2010.*

## Infrastructure

*Meteorological Sensors:* Over the period of record (October, 1983 to present), the following hourly forcing parameters have been measured at both sites:

- Precipitation
- Wind speed
- Air temperature
- Humidity
- Solar radiation

- At the exposed site, wind direction and soil temperature are also measured for the entire period of record
- Above and below canopy thermal radiation was measured at the sheltered site beginning in 2005
- Soil temperature was measured at the sheltered site beginning in 1990
- Discharge is measured hourly at the outlet

*Snow Sensors:*

- Bi-weekly snow courses at the sheltered site (SWE, snow depth and snow density)
- A snow pillow, located at the sheltered site
- Instrumentation for the continuous measurement of snow depth was added to the sheltered site in WY 1997, and to the exposed site in WY 2000.

*Soil Sensors*:

- Hourly measurements of soil moisture near the sheltered site began in late 2005.
- Hourly groundwater elevation is provided from three wells and began in late August of 2005.

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* none

*Additional nearby stations:* none

*Data Access:* At the moment no active website access exists, and direct communication is required for date inquiries.

Some of this information may be subject to change as sensors are updated, changed or modified depending on research needs. Refer to Reba et al. (2011) [doi:10.1029/2010WR010030] for more details. See Figure below for general locations within the RME watershed.

### Field Logistics

*Travel to site:* Approximately 70 miles to the site from the USDA-ARS-NWRC office in Boise, ID. The Research Station (Headquarters) of the Reynolds Creek Experimental Watershed is located 53 miles from the Boise Office, after which a combination of Chained Four-Wheel Drive and Snow cat travel is required for about 17 miles. The location of the snow cat varies depending on the snow line.

*Site Access:* Travel once the site is reached will be via Snow Cat and Skis/snowshoes.

*Avalanche/Other hazards:* Low. The Terrestrial Laser scanning (TLS) locations are in moderate terrain (no steep slopes in the vicinity) and can be reached by both skis and Snow Cat from the cabins on site. Travel around the site for collection of required snow density federal sampling, target/reflector location and retrieval can all be done within the area with low avalanche exposure.

*Measurement Locations:* Time series observations will be collected at two sites co-located with the TLS scans. *Approximate TLS locations:*

- *Scan location 1: 43°04'13.2"N 116°45'14.6"W, 2065 m*

- *Scan location 2: 43°04'06.9"N 116°44'51.0"W, 2095 m*

We performed a survey on 2019-03-19 similar to the one that would be performed during the SnowEx 2020 campaign. During the survey, we used federal samplers to obtain density estimates within RME at the locations listed below for reference of the areas that the teams would focus on during the surveys.

Table XX. Locations of Reynolds Creek snow surveys

| **[UTM Zone 11 (NAD27)]** | | **[Lat/Lon (WGS84)]** | |
|---|---|---|---|
| Easting | Northing | Latitude | Longitude |
| 520377 | 4767701 | 43.063555 | -116.7507088 |
| 520392 | 4767928 | 43.0655988 | -116.7505162 |
| 520269 | 4767921 | 43.065539 | -116.7520272 |
| 520136 | 4768030 | 43.0665241 | -116.7536567 |
| 520059 | 4768125 | 43.0673816 | -116.754599 |
| 520169 | 4768217 | 43.0682071 | -116.7532446 |
| 520083 | 4768368 | 43.0695691 | -116.7542955 |
| 520035 | 4768452 | 43.0703268 | -116.754882 |
| 519982 | 4768390 | 43.0697699 | -116.7555352 |
| 519723 | 4768004 | 43.0663007 | -116.7587301 |
| 519699 | 4768104 | 43.0672018 | -116.7590213 |
| 519837 | 4768064 | 43.0668381 | -116.7573278 |
| 519917 | 4768097 | 43.0671331 | -116.7563441 |
| 519902 | 4768216 | 43.0682051 | -116.7565241 |
| 519886 | 4768323 | 43.0691691 | -116.7567168 |
| 519940 | 4768461 | 43.0704104 | -116.7560486 |
| 519777 | 4768225 | 43.0682894 | -116.758059 |
| 519762 | 4768049 | 43.0667049 | -116.7582495 |
| 519841 | 4767964 | 43.0659375 | -116.7572822 |

*Number of observers for each overflight:* 4-5 surveyors

*Training: Most of the team members have the following training and skills:*

- *First Aid and CPR.*
- *Avalanche awareness and backcountry experience.*
- *Regular (yearly) safety trainings are performed at the NWRC due to the ongoing field activities at RCEW, with full time personnel on site at the Quonset. Field activities are maintained in the watershed throughout the year.*
- *Detailed information in the online survey filled out for the 2018-19 season by all team members.*

*Communication options:* Some limited and unreliable cell service exists around the cabins on site. Permanent radio communication with regular check-ins is maintained during the surveys between the team members, the research station (the Quonset) and the USDA-ARS-NWRC office in Boise. Teams will have SPOT devices with them during the survey.

## C.5. Boise River Basin, Idaho

### BOISE RIVER BASIN, SITE A: LOWER DEER POINT, IDAHO

#### Site Lead: Jim McNamara, Boise State University

#### Site Description

Lower Deer Point, Dry Creek Experimental Watershed. Lower Deer Point (LDP) is a meteorological station within the Dry Creek Experimental Watershed (DCEW) in the hills adjacent to Boise, Idaho. (Lat/Long/Elev: 43.737555, -116.122167, 1850 m)

*Elevation range:* 1000 – 2100 m

*Canopy:* Vegetation in the DCEW ranges from predominantly high dester grasses and shrubs in the lower elevations to Ponderosa Pine forests in the upper elevations. LDP is near the shrub-forest transition, but more forest than not.

*Snow climate:* Mean annual precipitation at LDP is approximately 700 m, 50% of which falls as snow.

*Ownership:* US Forest Service. BSU has a permit from the USFS to operate on the site. A paved, plowed road provides access to within 500 m of the meteorlogical station.

*Brief historical background:* A meteorological station has been in continuous operation at LDP since 2007. Data are freely available online (earth.boisestate.edu/drycreek/data/lower-deer-point). Other stations in DCEW have been in operation since 1999.

The DCEW has been the site of approximately 45 peer-reviewed publications, most of which focus on cold-season hydrology. (earth.boisestate.edu/drycreek/publications). LDP in particular has been featured in two publications about snow remote sensing and the spatial variability of snow in complex terrain: Homan et al. 2011; Anderson et al. 2014.

#### Infrastructure

Descriptions of the DCEW measurement network are here: Earth.boisestate.edu/drycreek/data. All data are accessible by anyone for free.

*Meteorological Sensors:* Hourly precipitation depth, air temperature, RG, 4-component radiation, snow depth (acoustic), soil moisture

*Snow Sensors:* Hourly acoustic snow depth

*Soil Sensors*: Hourly volumetric moisture content at 2 depths

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* TLS through Boise State

*Additional nearby stations:* Bogus Basin Snotel: 43 deg; 46 min, 116 deg; 6 min, elev 1932 m; DCEW Network: 7 met stations within 27 $km^2$ catchment

## Field Logistics

*Travel to site:* 15 miles from BSU, 45 mins

*Site Access:* 500 m snowshoe, ski, or snowmobile

*Avalanche/Other hazards:* minimal

*Measurement Locations:* TBD

*Number of observers for each overflight:* 2

*Training:* Both observers have had Avalanche level 1 training and basic first aid.

*Communication options:* All option available. Cell service, inreach, satellite phone

# BOISE RIVER BASIN, SITE B: MORES CREEK SUMMIT

## Site Lead: Chago Rodriguez, Boise State University

## Site Description

The area of study is in the Boise Mountains, in Central Idaho, USA. The survey area is located to the Northwest of Mores Creek Summit (MCS), along Idaho-21 state road. The area surveyed is known as the Lamar Ridge and contains the Summit creek watershed. We will denominate this area as MCS-Lamar area.
*Elevation range:* 5800 – 7800 m

*Canopy:* Vegetation cover ranges from sagebrush and other brush with coniferous forest at southerly aspects to a mixed forest of mostly conifers with some deciduous trees with varying canopy cover from 100% to sparse and mostly open forest.

*Snow climate:* The area to be surveyed has snow in the ground generally from December through April. The mostly forested area enjoys moderate winter temperatures that favors the development of NSF and SH surfaces from West 270 to 90 East northerly aspects. These northerly aspects preserves the snowpack cold content until late March. Southerly aspects develops rounds and melt forms crystals due to solar radiation, even during winter months. Southerly aspects snowpack become isothermal early in March. The snowpack above 7000 feet exceeds the 3 meter depth mark before the spring snowmelt. In contrast the snowpack depth below the 6500 feet do not exceeds 2 meter depth prior to the spring snowmelt.

*Ownership:*

*Brief historical background:*

*Synergistic Activities in 2019-20:* See “SnowEx 2019 – Central Idaho” writeup for more information.

## Infrastructure

*Meteorological Sensors:* Met Station associated with the MCS SNOTEL site.  Data available online.

*Snow Sensors:* SWE pillow, ultrasonic depth sensor

*Soil Sensors*: none

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* none

*Additional nearby stations:* MCS SNOTEL

### Field Logistics

*Travel to site:* The survey plan assumes 2 experienced ski tourers capable of covering 4 miles and 2500 vertical feet elevation gain as well as surveying tasks from 8 AM through 4 PM. Travel time is estimated at three hours. Surveying tasks at each snow board are estimated to 10 minutes, for a total of 4 hours for the 24 snow boards. An hour is allocated to the two study snow pits.

*Site Access:*

*Avalanche/Other hazards:* The survey track is devoid of avalanche terrain. Two surveyors will use standard AM/PM forms to asses risk during each of the outings. Each of the two surveyors will be equipped with avalanche rescue gear, first-aid kit, fire-starting kit, emergency shelter, celular phone, and radio communication gear. The party will carry an ACR PLB-375 emergency locator device. The device is registered to Santiago Rodriguez from Avalanche Science LLC.

*Measurement Locations:* Two study pits, each at 6700 and 7800 feet. Location of pit will be identified by bamboo poles. 24 Snow Boards along 4 mile transect.

*Number of observers for each overflight:* 2

*Training:*

*Communication options:* The area to be surveyed have celular coverage at some locations. There is full radio communication coverage of the surveyed are via a ham radio repeater (Pilot Peak Repeater 145.310M-, PL 100 Hz).

## BOISE RIVER BASIN, SITE C: BULL TROUT LAKE

### Site Lead: Maggi Kraft, Boise State University

### Site Description

Bull Trout Lake, Boise National Forest, Idaho. Bull Trout Lake is located in the Boise National Forest. The lake is fed by Spring Creek and empties into Warm Springs Creek and eventually the Payette River. The lake is located Northwest of Stanley Idaho. (Lat/Lon/Elev: 44.295157, -115.255281, 2119 m)

*Elevation range:* 2116 – 2615 m

*Canopy:* Vegetation in the valley bottom ranges from willow and sedge near the lake and surrounding wetlands to sagebrush meadows. Trees are dominantly sub-alpine fir and Douglas fir on south facing slopes.

*Snow climate:*

*Ownership:* The watershed is in the Boise National Forest managed by the Lowman Ranger District.

*Brief historical background:* LiDAR was collected at Bull Trout Lake watershed in August-September 2009. Previous research in Bull Trout Lake watershed focused on hydrology and nutrient concentration (Bergstrom et al. 2016; Covino et al. 2010; Kalinn et al. 2016).

*Synergistic Activities in 2019-20:*

#### Infrastructure

*Meteorological Sensors:* air temperature, snow depth (acoustic), relative humidity, wind speed, precipitation, SWE, from nearby Banner Summit SnoTEL.

*Snow Sensors:* Hourly acoustic snow depth – Currently available by request but eventually will be available online.

*Soil Sensors*: none

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* none

*Additional nearby stations:*

- Banner Snotel: 44.303333/-115.23333 /2145m
- Fox Tail Ridge Idaho, RAWS Network: 44.183056/-115.256944/1833m
- Canyon Creek, ID, RAWS Network: 44.229722/-115.246944/ 2591m

#### Field Logistics

*Travel to site:* 110 miles from BSU, 2 hours

*Site Access:* 2 mile ski or snowmobile

*Avalanche/Other hazards:* minimal

*Measurement Locations:* TBD

*Number of observers for each overflight:* TBD

*Training:*

*Communication options:* InReach, Radios

## C.6. Little Cottonwood Canyon, Utah

### Site Lead: McKenzie Skiles, University of Utah

#### Site Description

The Atwater Study Plot (ASP) is approximately 18 miles southeast of Salt Lake City, UT; near the top of Little Cottonwood Canyon Road, across the street from Alta Ski Area, adjacent to UDOT Avalanche Guard House. About ¼ acre in size, relatively flat, opening in aspen/conifer forest. (Lat/Long/Elev: 40.591206 N, -111.637685 W, 2667 m a.s.l.)

The Alta Collins Study Plot (ACP) is approximately 18 miles southeast of Salt Lake City, UT. Alpine site within Alta Ski Area boundaries, located in a relatively flat and open fetch (roped, no skier disturbance) just below the shoulder of Collins Lift, and above Glory Hole. (Lat/Long/Elev: 40.572096 N, -111.629968 W, 3132 m a.s.l.)

*Site Characteristics:* ASP is subalpine, in mixed aspen/conifer forest, with relatively low wind speeds. The snowpack is characteristically intermountain, and is also influenced by Great Salt Lake lake effect snow (typically higher snowfall than Colorado Rockies). The average elevation of the (roped/protected) ¼ acre plot is 2667 m.

ACP is above treeline, and is located in an open alpine meadow. The snow is also intermountain, but more wind effected than ASP. Due to the higher elevation, snow persists at ACP for longer than ASP.

*Ownership:* ASP is managed by my research group in collaboration with the Utah Department of Transportation. ACP is maintained by my research group with permission from Alta Ski Area.

*Brief historical background:* ASP is one of the longest continually operated snow observation sites in the Western US. It was established by Monty Atwater for avalanche research in the 1950's, and was operated by the Forest Service, and then taken over by the UDOT avalanche program. UDOT still uses the site for monthly avalanche snow pits.

ACP was established in 2009 when I was a graduate student at the University of Utah, but there are long term instrumentation and storm board records from Alta Ski resort adjacent to ACP, and on the ridgeline above ACP. Alta is supportive of our research efforts within their boundaries and I have full access to all of their historical data.

*Synergistic Activities in 2019-20:* There will be regular drone flights over ASP (monthly in winter, bimonthly in spring) for high resolution snow depth mapping using structure from motion. Snow at both sites is regularly sampled for aerosol content (dust and black carbon). iSnobal and SNOWPACK snow energy balance models are being run at ASP.

### Infrastructure

*Meteorological Sensors:* Station at ASP: temperature and RH, wind speed direction, Four component radiometer. Online access (MesoWest).

*Snow Sensors:* Snow depth and snow surface temperature. Online access (MesoWest).

*Soil Sensors*: none

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* none

*Additional nearby stations:*

Alta Guard Station (ID: AGD, NAME: ALTA - GUARD HOUSE):
https://mesowest.utah.edu/cgi-bin/droman/meso_base_dyn.cgi?stn=AGD&unit=0&timetype=GMT
(Lat/Long/Elev: 40.5905 N, -111.638 W, 8799 ft a.s.l.)

Snowbird Snotel (Site Number: 766; Site Name: Snowbird; State: Utah)
https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=766
(Lat/Long: 40.56667 N, -111.6667 W)

### Field Logistics

*Travel to site:* ASP just above Little Cottonwood Canyon road, 5 min walk/ski. For ACP, while Alta is operating, it is a 10-min lift ride up Collins lift, when Alta is not operating is a ~1hr ski tour from Alta base to the site

*Site Access:* ASP- foot, ski/snowshoe. ACP- chairlift when Alta is operating / ski, snowmobile when Alta is closed

*Avalanche/Other hazards:* Low at both sites

*Measurement Locations:* Pits/Transects- same as above (ASP/ACP). Interval board observations will be used from UDOT (Guard House, adjacent to ASP) and Alta (adjacent to ACP)

*Number of observers for each overflight:* Two, both sites can be visited in the same day

*Training:* Lead observer is Steven Clark, UDOT avalanche forecaster (all of the possible trainings), secondary observer is Matt Olson, U of U PhD Student (WFR + Avy 1), Skiles will assist as needed (expired WFR, First Aid, Avy 1,2,3)

*Communication options:* Cell service at both sites (+InReach/Radios as secondary if needed)

## C.7. Cameron Pass, Colorado

### Site Lead: Dan McGrath, Colorado State University

### Site Description

*North-central Colorado, ~1.5 hr west of Fort Collins, Colorado, year round access via CO 14 highway* (Lat/Lon/Elevation *(WGS84): 40.521° N, -105.892° W, 3135 meters).*

*Site Characteristics:* Pass elevation is 3135 m, nearby peaks reach ~3600 m, treeline is ~3400 m. Median maximum snowpack is ~180 cm (59 cm SWE) and is snow-covered from November to late May/early June and is classified as a continental snow climate. Vegetation includes lodgepole pine and mixed spruce-fir, and includes a range of forest canopy densities. Land ownership to the east of the pass is US Forest Service and to the west is predominantly State Forest State Park (operated by CO State Parks).

Historical background: Joe Wright SNOTEL has operated since 1978 (Site # 551). Ground penetrating radar (GPR) and terrestrial LiDAR surveys (TLS) were completed in March-June 2019. Dr. Steven Fassnacht (CSU) has collected a variety of probe/pit data, some continuous for last ~10 years.

Synergistic Activities in 2019-20: *GPR and TLS surveys will be continued. Potential for repeat SfM drone surveys. In situ GPS instruments will be installed.*

### Infrastructure

Meteorological Sensors: *air temperature, hourly*

Snow Sensors*: Sonic snow depth, snow pillow SWE, hourly*

Data access*:online*

Time lapse camera (*measurement interval*): *N/A; but could possibly install one in 2019-20*

Additional nearby stations: *Cameron Pass is drained by Joe Wright Creek (a tributary to the Cache la Poudre River), which is gaged prior to draining into Joe Wright Reservoir (USGS 06746095). Additional gages are located along the Cache la Poudre River.*

Ground-based remote sensing instrumentation *(measurement interval, permanent or temporary): In situ GPS instruments installed proximal to Joe Wright SNOTEL; hourly*

### Field Logistics

Travel to site *(mileage, travel time): 60 miles, 1.5 hrs each way*

Site Access *(foot, ski/snowshoe, chairlift, snowmobile)*: *ski/snowshoe*

Avalanche hazard: *Extensive in area, negligible on planned ground surveys*

Measurement Locations *(for pits/transects/interval boards, ancillary observations)*

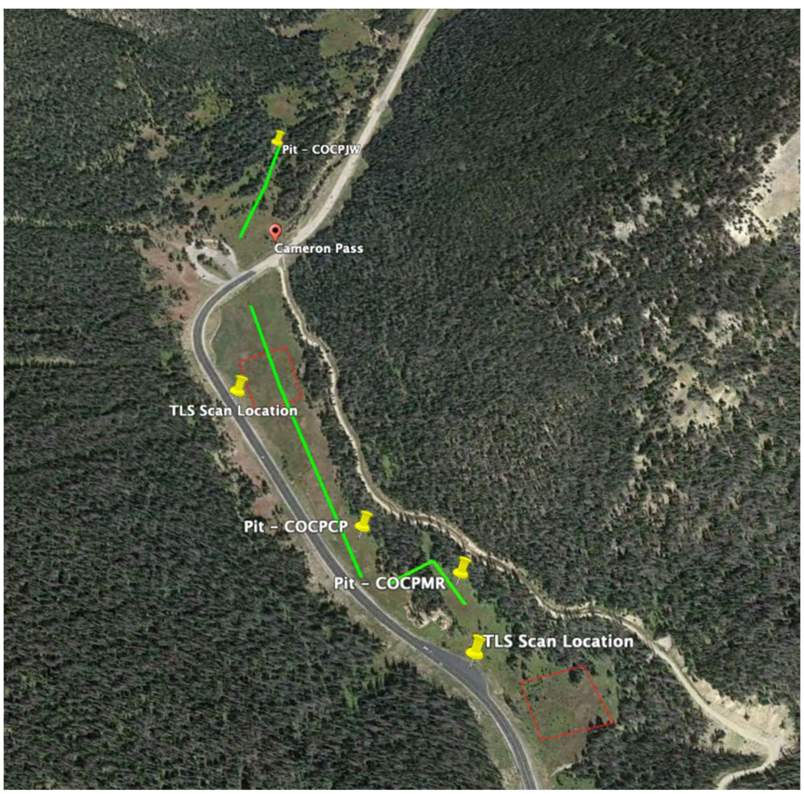
Measurement location name: *Three pit locations were used in spring 2019 (COCPJW, COCPCP, COCPMR) . It is likely that we will maintain at least two of these locations next year.*

*COCPJW: 40.522° N, -105.893° W*

*COCPCP: 40.516° N, -105.889° W*

*COCPMR: 40.516° N, -105.888° W*

*Joe Wright SNOTEL is just off the map to the north.*



Number of observers for each overflight: 2-3

Training *(WFA,WFR,First Aid, avalanche training, etc): Wilderness First Aid, expired WFR, Level 1 avy training*

Communication options *(Cell service, InReach, Radios): No cell service, InReach or radios required*

## C.8. Niwot Ridge, Colorado

### Site Lead: Noah Molotch, University of Colorado

### Site Description

Niwot Ridge, Nederland, CO, is located in the Front Range of the Rocky Mountains, 25 miles (40 km) northwest of Boulder, Colorado. The site covers 4 square miles, from the continental divide to the subalpine forest. Namesake Niwot Ridge extends east from the continental divide and Kiowa Peak. Sub-alpine forest locations below treeline and the C1 station are the "lower" elevation sites. The alpine Saddle catchment drains off the ridge into the Green Lakes Valley to the south. The Arikaree Glacier and a chain of alpine lakes feed into the Green Lakes Valley. Lat/Lon *(WGS84, decimal degrees):* 40.03209 N, -105.5357 W

*Elevation range:* 2895m (Mountain Research Station, MRS) - 3790m (Arikaree Glacier)

*Site Characteristics:*


A profile of Niwot Ridge, beyond the MRS.

- The C1 climate station is in a subalpine forest, 1 mile from the MRS, and has been collecting climate data since 1953.
- The Saddle is located along a ridge-top, in a shallow valley between the east and west knolls.
- D1 is an alpine tundra site located 2.6 km from the Continental Divide.
- There are instruments and infrastructure at each of these locations, up to the Saddle Catchment.
- The Mountain Research Station is a campus for research and additional outreach events. There is full room and board available in the form of dormitories and small cabins.
- The Tundra lab is a fully stocked/functional building adjacent to the Saddle Catchment. Minimum room and board amenities are available.
- The MRS and Niwot Ridge communities do an excellent job of providing safe yet efficient and productive research experiences within and along a very unique, sub-alpine to alpine environment. The folks providing the support and structure to this research

area have been doing so for decades and an incredible amount of work has come out of it (https://nwt.lternet.edu/)

*Brief historical background:* In general, Niwot Ridge contains a spread of long-term climate and environmental records, including meteorological and snow characteristics. More specifically, meteorological data are recorded at C1, Saddle and D1 (see figure above), dating back to 1952. Snow characteristic data are available at C1 and Saddle and include a snow pit record from 1993 to present, SNOTEL site, catchment scale sensor node grid. UAV, LiDAR, snow GPS and GPR data exist from recent years in the Saddle Catchment.

*Synergistic Activities in 2019-20:* Annual snow internship that provides opportunities for CU-Boulder Geography students to learn and use snow analysis skills at C1 and Saddle locations on Niwot Ridge. Outreach with local schools; hands-on days teaching biology, ecology, hydrology, snow science, etc. Collaboration across all environmental fields regarding research done in each catchment along Niwot Ridge.

### Infrastructure

*Meteorological Sensors:* Data access online and publicly available.

C1:

- 2000-06-24 – ongoing, hourly
- Maximum and minimum and average temperature
- Maximum and minimum and average relative humidity
- Maximum and minimum and average barometric pressure
- Maximum and minimum and average wind speed
- Maximum and minimum and average solar radiation

Saddle:

- 2009-01-01 – ongoing, hourly
- Maximum and minimum and average temperature
- Maximum and minimum and average relative humidity
- Maximum and minimum and average barometric pressure
- Maximum and minimum and average wind speed
- Maximum and minimum and average solar radiation

D1:

- 2000-07-05 – ongoing, hourly; temperature data date back to 1952
- Maximum and minimum and average temperature
- Maximum and minimum and average relative humidity
- Maximum and minimum and average barometric pressure
- Maximum and minimum and average wind speed
- Maximum and minimum and average solar radiation

*Snow Sensors:* Data access online and publicly available.

C1 (1992-02-26 – ongoing)

- Snow depth sensors
- Snow pits: snow depth, temperature, snow density and snow grain size/type at various depths throughout the snow cover profiles
- Snow density measured at 10-cm intervals using a 1000-ml cutter
- Weekly federal sampler measurements

Saddle (1992-02-26 – ongoing)

- Snow pits: snow depth, temperature, snow density and snow grain size/type at various depths throughout the snow cover profiles
- Snow density measured at 10-cm intervals using a 1000-ml cutter
- Weekly federal sampler measurements

Green Lakes Valley (2013 – ongoing)

- Annual snow surveys were conducted in the Green Lakes Valley in the City of Boulder Watershed at the estimated peak of snowpack in late spring.
    - Over a period of several days, surveying teams (1 to several people) traverse valley slopes measuring snow depth with avalanche probes.
    - Snow pits are dug at specific locations throughout the valley, measuring snow depth, density, temperature, snow grain size/type

*Soil Sensors*: Data access online and publicly available.

C1 (2000-06-24 – ongoing, hourly)

- Maximum and minimum and average soil temperature at 5cm
- Soil moisture at 5cm
- Average soil moisture profile at 10cm, 20cm, 30cm, 50cm, 70cm, 100cm, 150cm, 200cm

Saddle (2009-01-01 – ongoing, hourly)

- Maximum and minimum and average soil temperature at 5cm
- Soil moisture at 5cm

D1 (2000-07-05 – ongoing)

- Maximum and minimum and average soil temperature at 5cm
- Soil moisture at 5cm

*Time-lapse cameras:* Unknown beyond the Tundra Cam – a live camera at the Tundra Lab, near the Saddle Catchment. Data access: https://instaar.colorado.edu/tundracam/

*Ground-based remote sensing instrumentation:*

- UAV flights from summer 2017, measuring snow and soil characteristics (using RGB and infrared imagery)
- LiDAR scans (1m DEM, snow on/off scans throughout spring/summer 2019)
- Snow GPS (permanent, interval unknown)
- Weekly GPR surveys from May 2019-July 2019 with complementary snow depth survey, snow pits and federal sampler measurements

*Additional nearby stations:*

Niwot Snotel (Site Number: 663; State: CO)
Reporting since: 1979-10-01
(Lat/Long: 40.0333 N, -105.5833 W)

## Field Logistics

*Travel to site:* The Mountain Research Station (MRS) is ~90 minutes/65 miles from Denver International Airport, Denver, CO, 45 minutes/25 miles from Boulder, CO, or 15 minutes/8 miles from Nederland, CO. From the MRS, travel on foot or by snowmobile/snow cat is an additional 30 minutes-90 minutes (1-4 miles, depending on site).

*Site Access:* Foot, ski, snowshoe, snowmobiles and snow cat available

*Avalanche/Other hazards:* N/A unless entering the Green Lakes Valley, which must be done on a permit-basis with the City of Boulder.

*Measurement Locations:* Measurement location name: from C1 to D1, see figure. Lat/lon/elevation: different in location/elevation, but all along the Niwot Ridge Trail. Access: foot/snowshoe/ski/snowmobile/snow cat.

*Number of observers for each overflight:* TBD

*Training:* WFA expected, WFR recommended. Avalanche training and equipment only required if entering the Green Lakes Valley

*Communication options:* Intermittent cell service along the ridge. WiFi available at the Tundra lab (near the Saddle Catchment). InReach and radios available

## C.9. Fraser Experimental Forest, Colorado

### Site Lead: Kelly Elder, USFS

### Site Description

Fraser Experimental Forest, Fraser Colorado, Grand County (Lat/Long/Elev: 39.90587 N, -105.882814 W, 2745 m a.s.l.)

*Elevation range:* 2680 – 3900 m. Flat terrain; fluvioglacial deposits, Pinus contorta, Abies lasiocarpa, Picea, engelmannii 1-5 m high;

*Canopy:* thinned plots

*Snow climate:* continental snow climate; accumulation November through May, with snowfall events year round;

*Ownership:* US Forest Service, experimental forest.

*Brief historical background:* CLPX LSOS site.

*Synergistic Activities in 2019-20:* JPL SoOp site.  USFS RMRS long-term experimental site.

### Infrastructure

*Meteorological Sensors:* Air temperature, relative humidity, wind speed, wind direction; hourly; request.

*Snow Sensors:* Snow depth; hourly; request.

*Soil Sensors*: Soil temperature, soil moisture; hourly; request.

*Time-lapse cameras:* Three times per day – 0900, 1200, 1500 hrs

*Ground-based remote sensing instrumentation:* SoOp Radar, Boise State FMCW radar

*Additional nearby stations:* Fool Creek SnoTel; 39.868691 N, -105.867737 W, 3400 m a.s.l.

### Field Logistics

*Travel to site:* Can drive to site (with 1200 m).

*Site Access:* Foot, ski, snowshoe

*Avalanche/Other hazards:* None

*Measurement Locations:* same as RMRS long-term site

*Number of observers for each overflight:* 1

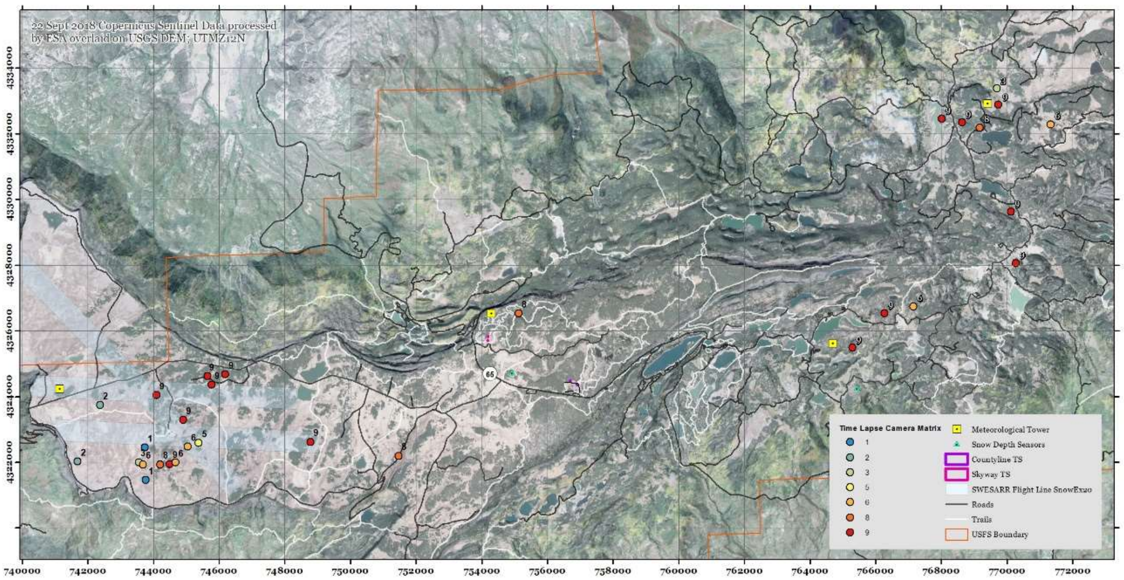
*Training:* none

*Communication options:* Limited cell – Verizon best

## C.10. Grand Mesa, Colorado

### Site Leads: Christopher A. Hiemstra, U.S. Army Cold Regions Research and Engineering Laboratory, and Ludovic Brucker, NASA Goddard Space Flight Center

### Site Description




*Grand Mesa will also host a suite of measurements useful for the time series analysis. Thirty time lapse cameras were distributed in western and eastern areas of the Mesa following a matrix developed from lidar-developed 2017 snow depths and tree cover (Section 5.1.2). Four meteorological towers, two sonic snow-depth sensor arrays, and time series pit locations are located east of Co Highway 65.*

*Elevation range:* 3,240 – 3,300 m. Flat terrain within the study plots.

*Canopy:* Tree canopy is predominantly *Picea engelmannii* (Engelmann Spruce), with small contributions of *Abies lasiocarpa* (subalpine fir) as a sub-canopy component.

*Snow climate:* Continental

*Ownership:* USFS

*Brief historical background:* See section on IOP Study Location.

*Synergistic Activities in 2019-20:* SnowEx 2020 IOP.

### Infrastructure

*Meteorological Sensors:* There are four meteorological stations, including three that were installed for SnowEx17. See section on IOP Meteorological Station for details on instrumentation.

*Snow Sensors:* None within the study plots. However, the area that will be observed with UAVSAR is large and over Grand Mesa includes: four meteorological stations, two sonic depth arrays, and five SNOTEL sites (Mesa Lakes, Park Reservoir, Overland Reservoir, North Lost Trail, and Schofield Pass). Depending on the actual UAVSAR processed swath, the area may also include two additional SNOTEL sites: Upper Taylor on the eastern part; and Butte on the southern part.

*Time-lapse cameras:* Thirty cameras will be distributed on Grand Mesa, within the UAVSAR acquisition area. They will be distributed in western and eastern areas of the Mesa following a proportional matrix developed from February 2017 ASO snow depths and three classes of tree cover (see Section 5.1.2).

*Ground-based remote sensing instrumentation:* N/A.

*Plant community:* Forest/Alpine

### Field Logistics

*Travel to site:* 50 miles from Grand Junction Regional Airport, CO

*Site Access:* All study plots are accessible by foot, ski/snowshoe in less than 10 min from parking lots. There are located within 800 m from parking lots along the main road, and no farther than 100 m away from cross country ski trails.

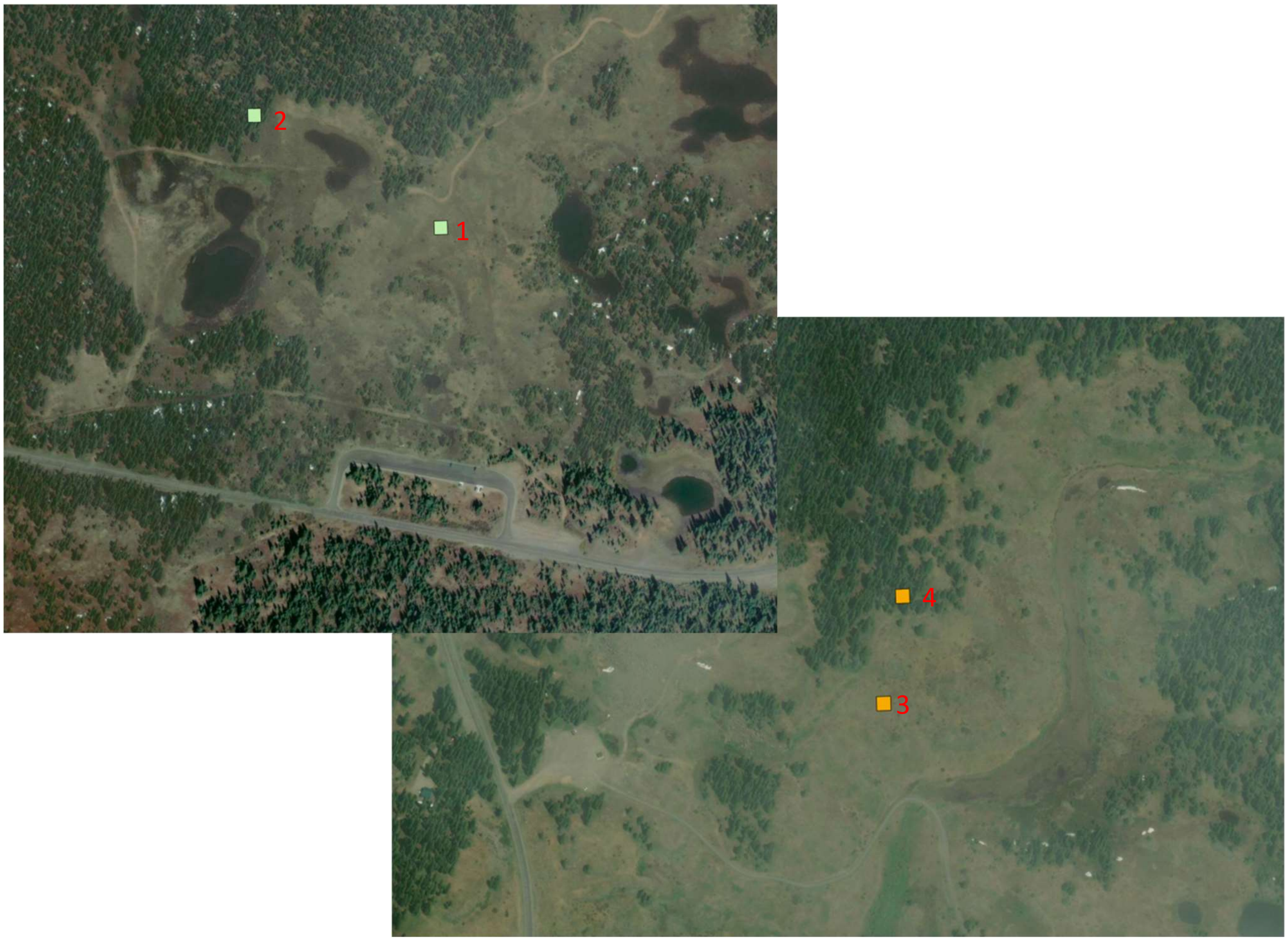
*Avalanche/Other hazards:* Study plots are not in avalanche prone terrain. The hazards are related to the road conditions and high elevation.

*Measurement Locations:*

Four study plots were identified for snow pit and depth measurements, with the following priority (and names):

1. Grand Mesa, County Line Open
2. Grand Mesa, County Line Tree
3. Grand Mesa, Skyway Open

4. Grand Mesa, Skyway Tree




*Number of observers for each overflight:* 1 out of pool of at least 6 observers

*Training:* To be updated.

*Communication options:* It is understood that communications fall under three categories:

1) regular planning teleconferences

At least one of the Grand Mesa site leads and the observer(s) of the previous and forthcoming deployment will join the regular planning teleconferences organized by SnowEx20 leadership. We see these teleconferences as an integral part of field safety as relevant information and experiences will be shared by all SnowEx20 site leads.

2) in-field primary communications

Text messages will be sent via InReach in the morning prior to the personnel leaving the vehicle. Similarly, text message will be sent once the personnel get back to the vehicle. <u>An update is required no later than 5:30pm local time.</u> Recipients of the messages sent by InReach have to be identified and ideally would include an ATAA point of contact and the two site leads.

3) emergency communications

By design, the SnowEx20 UAVSAR time series Grand Mesa study plots are located: within 800 m from parking lots along the main road, and within 100 m from well frequented cross-country ski trails. In spite of this proximity, any delay in getting back to the parking lots by 5:30pm local time requires immediate contact to ATAA and site leads to provide location, plan, and expected schedule.

In the event of help needed for a non-emergency situation, observers are can reach out to Grand Mesa Lodge – Rose & Mike: 970-856-3250.

In the event of emergency, observers should follow the following proposed emergency-response plan developed for the SnowEx17 Grand Mesa campaign.

*LEVEL 4 RESPONSE* – Emergency response - requires outside expert, professional help *911*

Life Threatening and/or Difficult Evacuation with serious Injury.

1. Activate InReach "911" device immediately.
2. Inform ATAA and one of the site lead of incident and plan. Provide the following information:
   Give GPS coordinates. Location and action plan, anticipated time out of field, additional medical and evacuation gear needed. Other needed resources. Consider air transport options.
3. Assess situation and make a plan. Formulate a patient transport plan.
4. Radio other field group members and request assistance.
5. ATAA will inform Sheriff's office, SAR of situation and help mobilize and activate resources for appropriate response.
6. ATAA will coordinate initial communications with multiple agencies for accuracy of plans and information.
7. ATAA will inform SnowEx20 leadership of incident at earliest opportunity.

Additional considerations.

- Daylight hours available?
- Patient warmth.
- Anticipate early on if patient status deteriorates and more outside help is needed with all incidents.
- Field Group Leader assigns member to ensure safety/comfort of the rest of the group.
- Other groups should stand by (once out of the field) at trailhead to assist if needed.

**EMERGENCY CONTACT PHONE NUMBERS**

Grand Mesa Lodge – Rose & Mike: 970-856-3250
Sheriff's offices
  Grand Junction - 970-244-3500
  Delta - 970-874-2015
Search and Rescue
  Grand Junction - Does not monitor phone – call 911 or 970-244-3500 (Sheriff)
  Delta - Does not monitor phone – call 911 or 970-874-2015 (Sheriff)

Hospitals. Emergent and non-emergent care facilities are available in most larger towns throughout the study area, although ground transport from remote field sites to such facilities can require several hours. Helicopter evacuation is possible from the largest medical facilities in the area. These include:

St. Mary's Hospital and Regional Medical Center – 970-298-2273
Grand Junction Community Hospital – 970-242-0920
Delta County Memorial Hospital – 970-874-7681
Flight for Life Dispatch – 800-332-3123

## C.11. Upper Gunnison River, Colorado

### Site Lead: Jeff Deems, National Snow and Ice Data Center

### Site Description

The Upper Gunnison River is a headwaters tributary of the Colorado River, and includes the town of Crested Butte. The study area includes the East River and Taylor River sub-basins, to their confluence at Almont, CO.

*Lat/Lon/Elevation* (WGS84, decimal degrees, meters):

38.66-39.06°N

106.30-107.22°W

2450-4347 MASL

*Characteristics (elevation range, vegetation canopy and sub-canopy composition and approx. heights, snow climate, land use/land cover, land ownership, land management, etc)*: Elevation ranges from 2450-4347 m above sea level. Vegetation ranges from montane sage/grass/wetlands through montane and subalpine forest to alpine tundra. Snow climate is continental.

*Brief historical background*:

ASO has been active in the Upper Gunnison since 2016. Crested Butte Mountain Resort has been in operation since the early 1960's and has long-term weather and snowfall records. The Rocky Mountain Biological Laboratory (RMBL) is in Gothic, CO, and was founded in 1928, and has long-term biological, and hydroclimatological data sets and supports a rich set of ongoing field research activities. The East River Watershed Function Scientific Focus Area (WFSFA) is a Department of Energy funded multidisciplinary study run by the Lawrence Berkeley National Laboratory, and supports a wide variety of water, energy, and nutrient cycle investigations with multiagency collaboration. The Upper Gunnison River Water Conservancy District (UGRWCD) is the primary water management partner in the area, and actively collaborates with basic and applied watershed science efforts in the basin.

*Synergistic Activities in 2019-20:*

As noted above, ongoing projects via the WFSFA and RMBL are investigating numerous systems connected with snow hydrologic interests. In particular, Drs. Deems, Raleigh, and Skiles have DoE and NSF-funded snow investigations in the study area in active partnership with the WFSFA, RMBL, and UGRWCD.

## Infrastructure

*Meteorological Sensors*: N/A

*Data access:*

*Snow Sensors*: Schofield Pass SNOTEL; Butte SNOTEL; Upper Taylor SNOTEL; Park Cone SNOTEL; possible new SNOTEL near Kebler Pass in Fall 2019; snow depth sensors on RMBL stations; snow depth and storm boards at Irwin Guides and CBMR; campaign snow depth sensors in open & forest at Raleigh sites. Crested Butte Avalanche Center weather station network.

*Data access:* online and request

*Soil Sensors:* Soil moisture/temperature at 2 depths at SNOTEL stations and RMBL stations; WFSFA investigator plot stations;

*Data access:* request

*Time lapse camera*: several phenocams in WFSFA project.

*Data access:* unknown – likely by request.

*Additional nearby stations*: CDOT RAWS station at Crested Butte;

*Ground-based remote sensing instrumentation:* TLS and drone imagery campains planned; potential for drone L-band and spectrometer surveys

## Field Logistics

*Travel to site*: site access ranges from 30min to several hours

*Site Access*: snowmobile/ski

*Avalanche hazard:* objective hazard on approach to many plots could preclude access; Snodgrass sites are safe.

*Measurement Locations*

*Measurement location name:* Irwin Barn Study Plot

*Lat/lon/elevation:* 38.888009°/ -107.107880°/3186m

*Access:* snowmobile + ski/snowshoe

*Measurement location name:* Rock Creek Study Plot

*Lat/lon/elevation:* 38.975258°/ -107.033687°/3396m

*Access:* snowmobile + ski/snowshoe

*Measurement location name:* Gothic Study Plot

*Lat/lon/elevation:* 38.959229°/ -106.990705°/2893m

*Access:* ski/snowshoe (most obs conducted by RMBL winter caretakers)

*Measurement location name:* Snodgrass Study Site

*Lat/lon/elevation:* 38.927196°/ -106.979806°/3167m

*Access:* ski/snowshoe

## C.12. Senator Beck Basin, Colorado

### Site Lead: Andy Gleason, Fort Lewis College

### Site Description

The 720 acre Senator Beck Basin is located in Southwest Colorado in the Southern Rocky Mountains (San Juan Mountains). It is accessed by Highway 550, Red Mt Pass. The closest town is Silverton, Colorado. (Lat/Long/Elev: 37.9070349, -107.7113216, 3371 m).

*Elevation range:* 3347 – 4118 m. Soil is derived from volcanic tuffs.

*Canopy:* Alpine tundra and Forest canopy. Spruce/Fir forest (Abies sp. / Picea sp.).

*Snow climate:* Continental

*Ownership:* USFS

*Brief historical background:* Alpine Senator Beck Basin (SBB) Study Area at Red Mountain Pass was established by the Center for Snow and Avalanche Studies (CSAS) in 2003 to monitor for and detect climate-driven changes in regional mountain snow systems. INSTAAR at CU had a project that included SBB, in the late 1970's to mid 1980's to measure the effects of cloud seeding on SWE.INSTAAR maintained a snow study plot on the top of Red Mt Pass from 1976-1986, plot was revived by the CAIC from 1993-2006. SnowEx17, Long historical record of ASO flights. Also Terra-SAR-X, World View

*Synergistic Activities in 2019-20:* CSAS hosts field studies at SBB and provides SBB data to academic and agency research groups focused on snow and mountain hydrology. Research teams are currently investigating new technologies for snowpack SWE monitoring (Boise State Univ., Army CRREL), improving snowmelt models (NCAR, Boise State, USFS Reynolds Creek), developing remote sensing algorithms for snowmelt forcing by dust (JPL/UCLA, Western Water Assessment), exploring long-wave radiation effects on mountain system warming (Columbia, Rutgers), and modeling snowcover distribution and atmospheric river events (NCAR, NOAA). New hydrologic and climate related research starting in summer 2013 includes a spruce beetle team from Colo. State Univ., and an SBB soils survey by NCAR's Hydrometeorological Applications Group.

### Infrastructure

*Meteorological Sensors:* precipitation, wind, air temperature, relative humidity, pressure, direct broadband solar radiation, direct near-infrared/shortwave-infrared (NIR/SWIR) solar radiation, diffuse broadband solar radiation at solar noon, downwelling thermal radiation, reflected broadband shortwave radiation, reflected NIR/SWIR radiation, and infrared snow surface temperature. Data access (online/request CSAS)

*Snow Sensors:* depth of snow cover, SWE (manual), snow temperatures, snow profiles, snow albedo, tower based L-Band Radar. Various measurement intervals. Data access (online/request)

*Soil Sensors*: heat flux, temperature, volumetric water content. Data access (online/request)

*Time-lapse cameras:* Putney Peak (measurement interval-unknown). Data access: request-Jeff Deems.

*Ground-based remote sensing instrumentation:* tower based L-Band Radar.

*Plant community:* Forest/Alpine

*Hydrology:* stream stage, discharge, water temperature, electrical conductivity

*Additional nearby stations:* Red Mountain Pass SNOTEL (SWE, Snow Height), Elevation:3413 m, 11200 ft., Latitude: 37.89, Longitude: -107.71

### Field Logistics

*Travel to site:* 62 miles from Durango, CO

*Site Access:* foot, ski/snowshoe, 10minutes to SASP, 30 min to flats 1 hour to SBSP.

*Avalanche/Other hazards:* Yes, can close access to site via HWY 550. If HWY 550 is open-no hazard to SASP or flats.

*Measurement Locations:*

Location 1. **Swamp Angel Study Plot (SASP)**

- Snow Pit 1: Snowpit (Bi-monthly), Storm Board (Bi-monthly SWE measurements).
- Equipment: Full Pit Kit, Denoth Meter or Snow Fork. SWE tube with spring scale
- Elevation: 3371 m, 11,060 Ft
- UTM Zone:13S
- Easting: 261631.00 m E
- Northing: 4198967.00 m N

Location 2. **Flats**

- Transect 1. North-South and East-West snow depth transects every 3 m for ~75 meters. Bi-monthly
- Storm Board Bi-monthly
- Equipment: Snow Depth Probes. 4m, SWE tube with spring scale
- Elevation: 3464 m, 11,364 Ft
- UTM Zone:13S
- Easting: 261108.00 m E
- Northing: 4198307.00 m N

Location 3. **Senator Beck Study Plot (SBSP)**

- Snowpit 2: Snowpit (Bi-monthly), Storm Board (Bi-monthly SWE measurements).
- Equipment: Full Pit Kit, Denoth Meter or Snow Fork. SWE tube with spring scale
- Elevation:3714 m, 12,186 Ft
- UTM Zone:13S
- Easting: 260316.00 m E
- Northing: 4199006.00 m N

*Number of observers for each overflight:* 2-3

*Training:* 2-3 student observers, Avalanche Level 1, First Aid, One has WFA, Lead Observer: Avalanche Training Level 3+, First Aid previous participation in Snow-Ex 2017.

*Communication options:* InReach, Radios

## C.13. Jemez River, Colorado

### Site Lead: Ryan Webb, University of New Mexico

### Site Description

The Jemez River Basin is located in northern New Mexico (USA), at the southern margin of the Rocky Mountains ecoregion. A central feature of the Jemez River Basin is the Valles Caldera located at the top of the watershed. The caldera is a collapsed magma chamber, 25 km in diameter that encloses several resurgent lava domes formed after the chamber collapsed ca. 1.2 Ma. The caldera interior is a single watershed unit draining through a breach in the caldera wall. The largest of the resurgent domes, Redondo Peak, is located in the center of the caldera resulting in the unique situation where headwater streams of the Jemez River originate on different aspects of the same mountain, providing the opportunity to probe contrasting microclimates on a uniform parent material with a common precipitation regime.
(Lat/Long/Elev: *35.8582 N/106.5215 W)*

*Elevation range:* 2600 – 3400 m

*Canopy:* Mixed conifer, pine, fir, aspen, alpine, grassland, post-wildfire scar areas. Large range of canopy heights. Vegetation ranges from semi-arid juniper savanna to high elevation mixed conifer forest, with soil types that are characteristic of the region, including aridisols, alfisols, mollisols and inceptisols. The geological and geomorphic history of the basin, which is underlain by rhyolitic parent material ranging in age from 1.13 Ma to 0.13 Ma, is well characterized.

*Snow climate:* warm forest – alpine

*Ownership:* nature preserve in the national parks system

*Brief historical background:* Critical Zone Observatory with long term observations and previous remote sensing studies. snow-off and snow-on airborne LiDAR, multiple current UAV plots. Instruments in place include snow depth sensor array, mass & energy flux towers, numerous stream flumes, flux towers, met station network

*Synergistic Activities in 2019-20:* Univ NM, National Parks, USFS, U. of Ariz., CZO, Ameriflux, biology/terrestrial ecology, lots of wildfire studies, USGS

### Infrastructure

*Meteorological Sensors:*

- https://criticalzone.org/index.php/catalina-jemez/data/search?collection=datasets&loose_ends=right&search_mode=all&keywords=jemez&category=64

- https://wrcc.dri.edu/vallescaldera/

*Snow Sensors:* https://criticalzone.org/index.php/catalina-jemez/data/search?collection=datasets&loose_ends=right&search_mode=all&keywords=jemez&category=64

*Soil Sensors*: https://criticalzone.org/index.php/catalina-jemez/data/search?collection=datasets&loose_ends=right&search_mode=all&keywords=jemez&category=64

*Time-lapse cameras:* none

*Ground-based remote sensing instrumentation:* GPS experiments for hourly data, temporary status. Planned ground based GPR during overflights.

*Additional nearby stations:*

- Garita Peak SNOTEL: 36 deg; 0 min N; 106 deg; 33 min W; 10160 feet; site #1173
- Quemazon SNOTEL: 35 deg; 55 min N; 106 deg; 24 min W; 9500 feet; site # 708

### Field Logistics

*Travel to site:* one-way: 80 miles, 1 hr 40 min

*Site Access:* ski/snowshoe

*Avalanche/Other hazards:* none

*Measurement Locations:*

Measurement location name: Pit,NMJRHQ
Lat/lon/elevation: 35.8582 N/106.5215 W/2650 masl
Access: Ski

Measurement location name: Pit,NMJRBA
Lat/lon/elevation: 35.8884 N/ 106.5324 W/3045 masl
Access: Ski

Measurement location name: Transect,T-1,
Lat/lon/elevation: FROM: 35.8589 N, 106.5218 W TO: 35.8565 N, 106.5235 W elev.: 2660 masl
Access: Ski

Measurement location name: Transect,T-2
Lat/lon/elevation: FROM: 35.8752 N, 106.5236 W TO: 35.8780 N, 106.5237 W elev: 2900 masl
Access: Ski

Measurement location name: Transect,T-3
Lat/lon/elevation: FROM: 35.8871 N, 106.5326 W TO: 35.8873 N, 106.5359 W elev.: 3020 masl
Access: Ski

*Number of observers for each overflight:* at least 2, likely 3 ea. time

*Training:* WFA, avalanche

*Communication options:* cell service in places, radios