ASO Processing Report

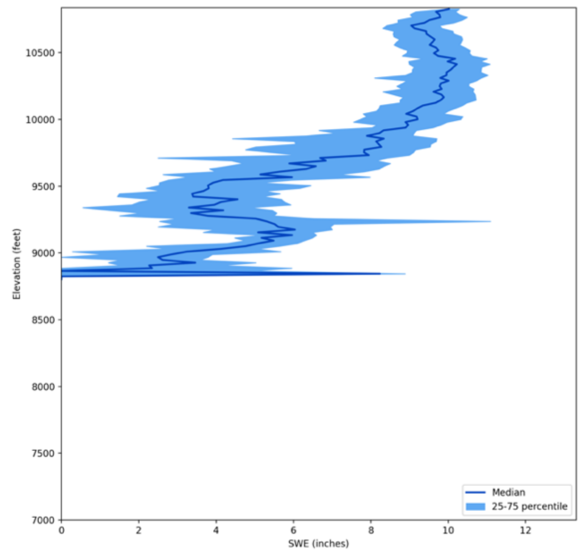
NASA SnowEx: Grand Mesa, CO

Airborne survey date: February 1-2, 2020

Data processed by: ASO Inc.
Delivery Date: May 2021

Version: 0

Data collected by: QSI
Raw data delivery date: January 2021



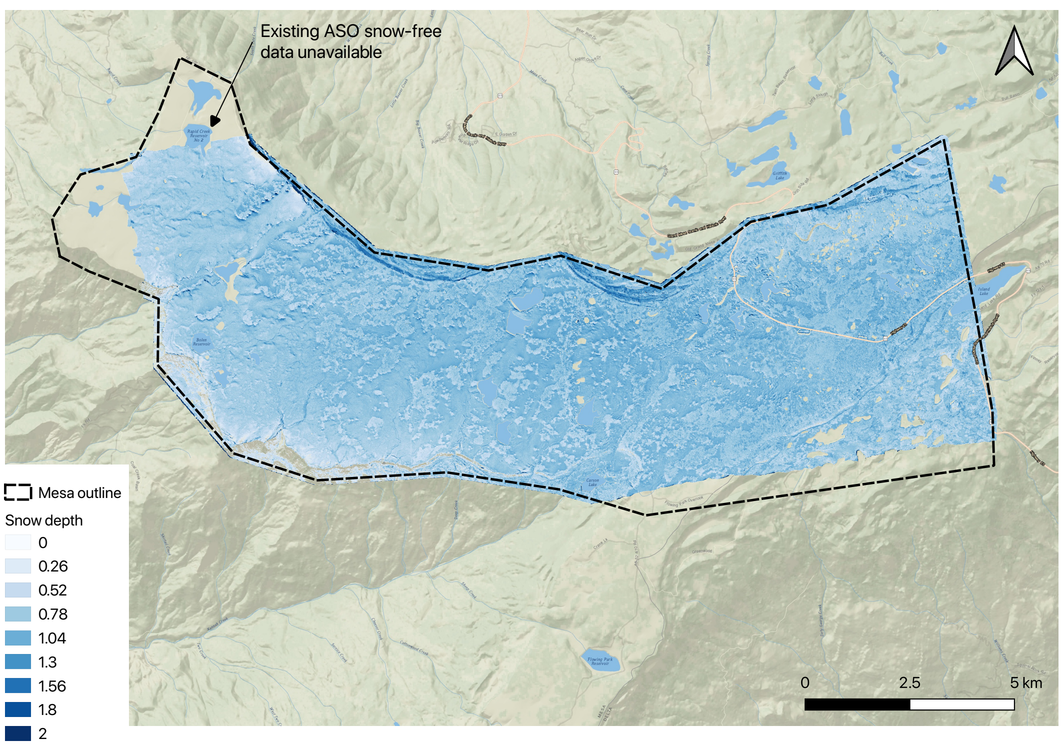


Figure 1 - February 1-2, 2020 snow depth

This document provides an overview of relevant in-situ data to support airborne survey operations for NASA SnowEx 2020 as provided by Airborne Snow Observatory Inc. (ASO). https://www.airbornesnowobservatories.com

Data acquisition, provision, and processing notes

1. The flight survey contractor provided the lidar point cloud data with the February 1 and the February 2 flights fused together into tiles, such that ASO could not implement the usual relative registration corrections on a per-flight basis. Though this procedure may be typical for more conventional topographic lidar surveys, it is unadvisable for snow surface elevation mapping due to the potential for rapid change in snow depth even on consecutive days due to melt, settlement, or wind redistribution. From examination of station data, we expect that this may introduce uncertainties into the snow depth values on the order of 2.54 cm, in the area of overlap between the two flight dates.
2. The flight line orientation of E-W was sub-optimal for snow albedo retrieval, being in the principal plane and forcing correction in forward scattering direction. This may affect broadband retrievals by several percent absolute.
3. Albedo retrieval is not possible for the Feb 1, 2020 flight due to overhead cloud (above the plane), which reduces the solar irradiance in a spatially variable and unquantifiable way (Figure A1). For this reason, we have masked our spectral products to exclude these flight data.
4. Likewise, despite Feb 2, 2020 appearing to have clear skies throughout the day, the northern-most flight lines had markedly lower radiances than physically realistic and were thus likewise masked (Figure A2)
5. The calibration of the QSI spectrometer in the wavelength ranges of 350-500 nm and 980-1050 are too problematic to allow robust retrievals of radiative forcing by impurities and of snow grain size (Figure A3)
6. The existing snow-free data, collected for SnowEx 2017, has a different footprint than the snow-on data, thus limiting snow depth retrievals from the two flanks in the northwest corner of the domain along with a linear slice in the southeastern corner (see Figure 2).

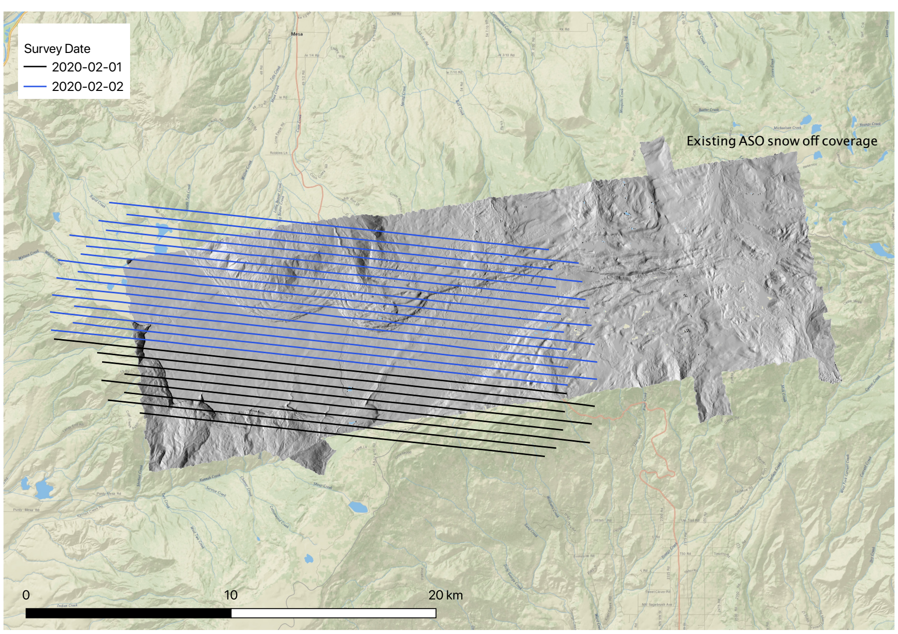
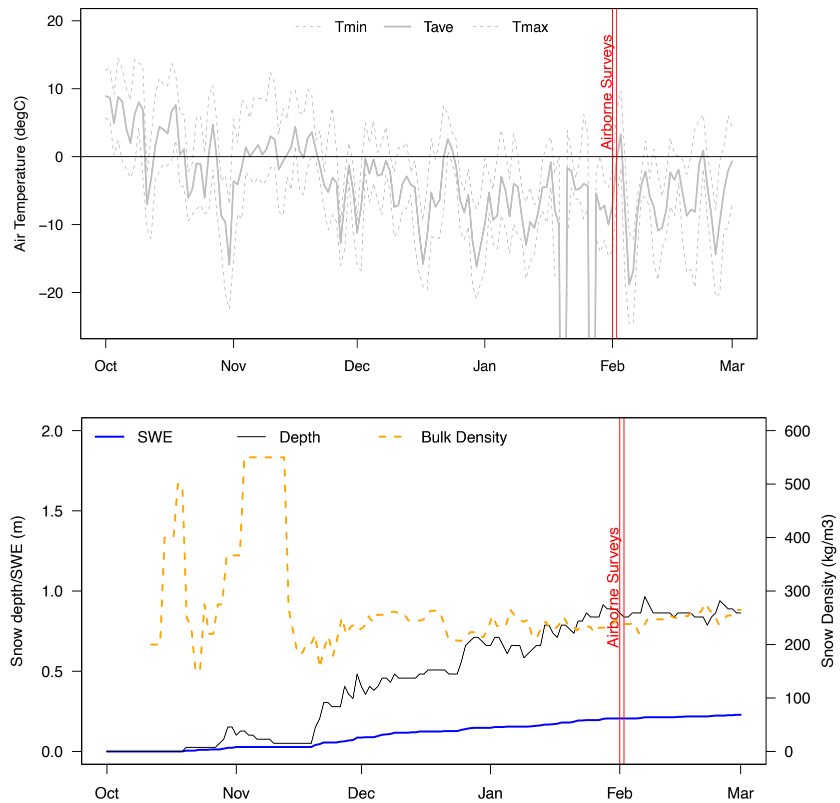


Figure 2 – Map of the existing snow-free data from SnowEx 2017 (shaded DEM) with the SnowEx 2020 flight lines overlaid

Summary of Background Conditions



The airborne surveys were conducted during a prolonged cool period, where daily surface air temperatures at the Mesa Lakes SNOTEL station (ID: 622, 10,000 ft, Figure 3) remaining largely below the melting point since late December 2019; ~ 2 months prior to the airborne survey.

The daily snow depths at Mesa Lakes had been steadily accumulating, gaining 0.86 m since mid-November 2019. The most recent snowfall event prior to the airborne survey occurred on January 27 where 3" accumulated at this location.

Figure 3 - Daily meteorological conditions at Mesa Lakes (SNOTEL 622)

Snow density constraint

SnowEx field collections

There were extensive field measurements collected at Grand Mesa as a part of the SnowEx 2020 community effort. Of notable relevance to the Airborne Snow Observatory processing are the following datasets:

- SNEX20_GM_SP: SnowEx20 Grand Mesa Intensive Observation Period Snow Pit Measurements, Version 1
- SNEX20_SD: SnowEx20 Community Snow Depth Probe Measurements, Version 1

For the purposes of the NASA + ASO Contract for SnowEx 2020 these data were used to:

- Constrain the spatial distribution of snow density for standard ASO snow depth to SWE conversion
- Provide guidance on relative registration of ASO snow depths

A brief summary of these data is provided in Appendix A.

The mean bulk snow density observed in the snow pits on February 1 (n=14 locations) was **272 ± 19 kg/m^3** with a range of values between 230-295 kg/m^3 (Figure A1). There were no observations in the SNEX20_GM_SP dataset that were collected on February 2.

Snow course measurements
The USDA-NRCS Snow Course monthly data were collected within a few days of the SnowEx airborne surveys. There is only one snow course located in the Grand Mesa region, Mesa Lakes snow course (08K04, at 10,000 ft). On January 27, a mean bulk snow density of 259 kg/m^3 was recorded.

After adjustment for densification that occurred between January 27 – February 1 (based on observed densification rates from the Mesa Lakes SNOTEL, Figure A2) the estimated bulk snow density at this location for February 1 is **265 kg/m^3.** This value is consistent with the SnowEx field measurement range.

Sensor measurements
From the 3 SNOTEL sensors near the Grand Mesa, the mean bulk snow density from the snow sensor network is **260 – 263 kg/m^3.** These values are consistent with the adjusted snow course estimate.

		February 1, 2020			February 2, 2020		
Site	Elev.(ft)	Density (kg/m^3)	Depth (m)	SWE (m)	Density (kg/m^3)	Depth (m)	SWE (m)
622 Mesa Lakes	10,000	240	0.86	0.206	245	0.84	0.206
682 Park Reservoir	9,960	270	1.24	0.335	270	1.24	0.335
675 Overland Res.	9,840	284	0.61	0.173	265	0.66	0.175
	Mean	265	0.90	0.238	260	0.91	0.239

These values consistent with both the snow course estimate and the SnowEx field measurement range.

Note: the airborne survey did not cover any of the SNOTEL locations directly and so these data cannot be used to evaluate snow depths from the airborne data.

Snow density refinement
The mean density from the M3 Works iSnobal model was 222 kg/m^3, which is 20-25% lower than the values reported by the in-situ networks. As such, the modeled densities have been scaled to remove the bias whilst maintaining the small-scale density patterns estimated by the model (Figure 5).

We recognize that given the rich set of in-situ measurements the SnowEx community may prefer to specify custom snow density estimates for conversion of snow depth to SWE; we encourage this activity and recognize that the SWE estimates provided are one within a set of many possibilities.

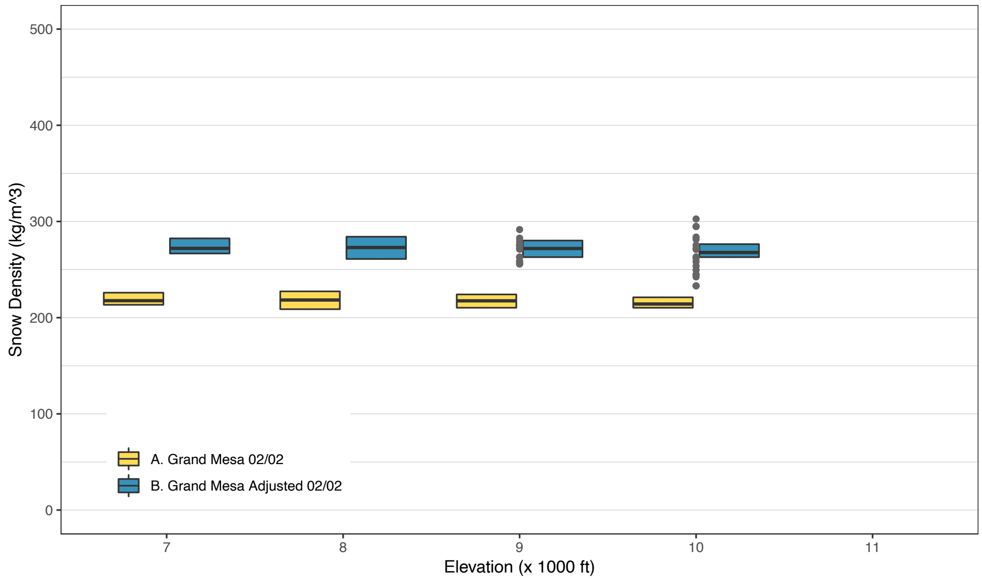


Figure 5 – Distribution of modeled (yellow) and adjusted (blue) snow densities with elevation. The markers shown are in-situ measurements from the SNEX20_GM_SP dataset

Evaluation of ASO snow depth measurements

At multiple robust comparison zones over known bare areas, the difference between snow-on and snow-off showed an uncertainty spread of 5.8 cm (2.3 inches). Vertical biases result from uncertainties in the atmospheric conditions and the entire lidar processing chain (GPS, aircraft attitude, etc.) for each of the snow-on and snow-off flights.

The vertical bias between the two data sets has been removed, leaving the uncertainty in snow depth equal to 9.6 cm at the point scale, 5.8 cm at the 3m spatial resolution, and < 1 cm at the 50 m spatial resolution.

The resulting snow depths compared to the SNEX20_DP in-situ measurements are shown in Figure 6.

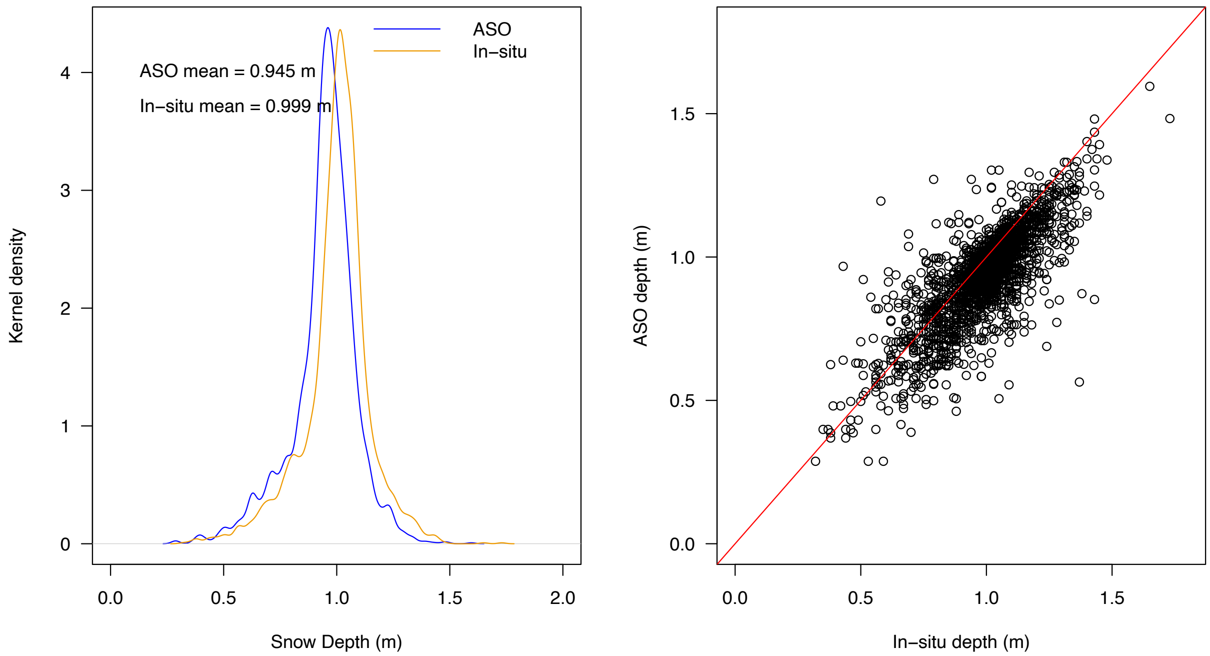


Figure 6 – ASO snow depths from the February 1 portion of the airborne survey compared to the SNEX20_DP measurements collected on February 1

The point-to-point comparisons of ASO 3m snow depths for February 1 at coincidental SNEX20_SD in-situ locations (Figures 6 and A8) were used for validation of the ASO snow depths. This comparison shows a bias of 5.4 cm (ASO depths shallower than probe depths). This bias matches our expectations, given the modes of measurement: lidar likely retrieves a slightly high-biased surface elevation in areas of low vegetation, and probe measurements will penetrate such ground cover, and often extend into a soft ground surface.

Due to the destructive nature of the snow pit measurements, we cannot use the SNEX20_GM_SP data for snow depth evaluation. Further efforts to confine a comparison to only those pits excavated after the survey aircraft overpass could provide additional ground validation data of a different nature than the probe measurements.

Albedo

Broadband albedo is the total solar reflectivity of a surface, such as snow in this case. The vast majority of solar input comes in the wavelength range 400-2500 nm, largely eliminated in the ultraviolet (< 400 nm) by ozone absorption and infrared (> 2500 nm) by water vapor absorption. However, the QSI and the ASO Inc. spectrometers are both ITRES CASI-1500h, which are silicon spectrometers that measure from 380-1050 nm. ASO selected this spectrometer because the critical variation in snow spectral albedo from grain size and radiative forcing by light absorbing particles occurs in these wavelengths and broadband albedo can be extrapolated from these measurements (Painter et al., 2016).

For this survey over Grand Mesa, February 1 was flown under cloudy skies that prevented full solar irradiance. As such, those albedo data were not useful and are masked out. The February 2 flight occurred under clear skies and gave largely useful data for albedo, except for the northern-most few lines that had an odd radiometric issue.

For those robust data, the snow albedos averaged 74.5% with a range of 70.0 to 78.0% and a standard deviation of 1.8%.

Appendix

Summary of conditions during the airborne survey for albedo retrieval

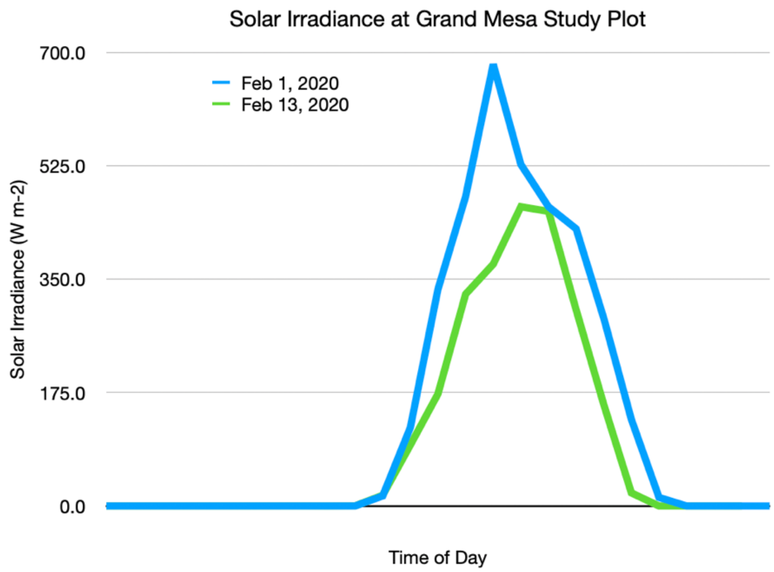


Figure A1- Measured solar irradiance at Grand Mesa Study Plot (aka Skyway) on February 1 and February 13, 2020, showing that the spectrometer measurements acquired on those days will be unreliable.

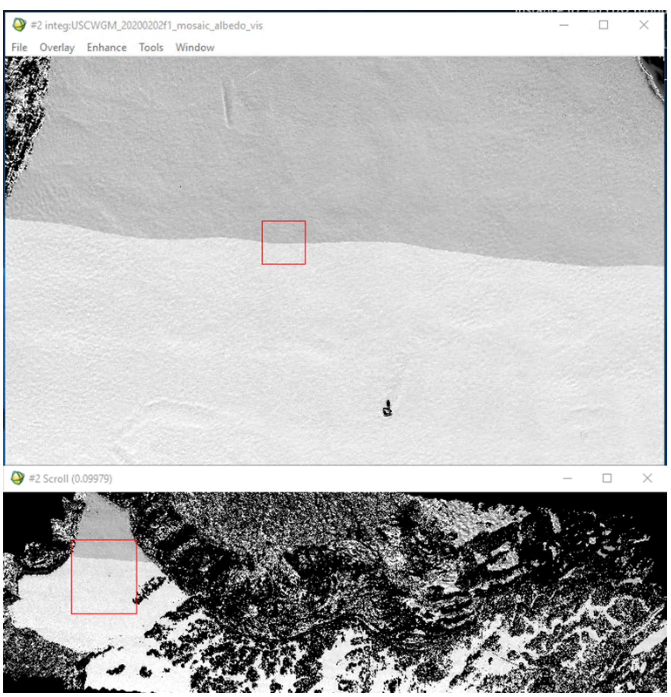


Figure A2- Broadband albedo retrieval for February 2, 2020 acquisition. The data north of this boundary are physically incorrect due to an unknown calibration issue with the QSI spectrometer. These data are masked in the final product.

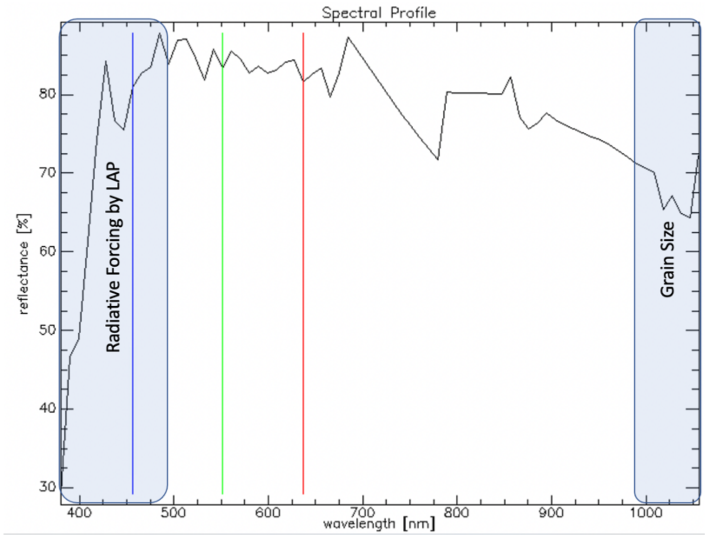


Figure A3- Spectral reflectance spectrum from February 2, 2020 acquisition by QSI over snow with wavelength ranges highlighted that are used for radiative forcing by light absorbing particles (LAP) and grain size, respectively. This figure shows the severe calibration issues in these wavelengths that inhibit reliable

Summary of SnowEx 2020 field measurements at Grand Mesa

SNEX20_GM_SP summary points:

- The snow pit data clearly show densification over the full period of observations (Jan 28-Feb 12, n=155 locations, Figure A4), although the temporal change in snow density is considered to be relatively small between the two airborne survey dates February 1-2. The linear densification rate over the airborne sampling period is estimated at 0.92 kg/m^3/day (Figure A5).
- There is no significant positive correlation between snow density with snow depth, Easting or Northing position (Figure A6).
- The map below (Figure A7) shows the locations of snow pit measurements from dates ± 4 days of the airborne survey (n=106 locations). Snow density typically changes much less with time than snow depth; as such it is less critical for snow density measurements to be temporally coincidental with the airborne survey than for snow depth measurements.
- Snow density differences between exposed snow and snow under canopy were not examined.

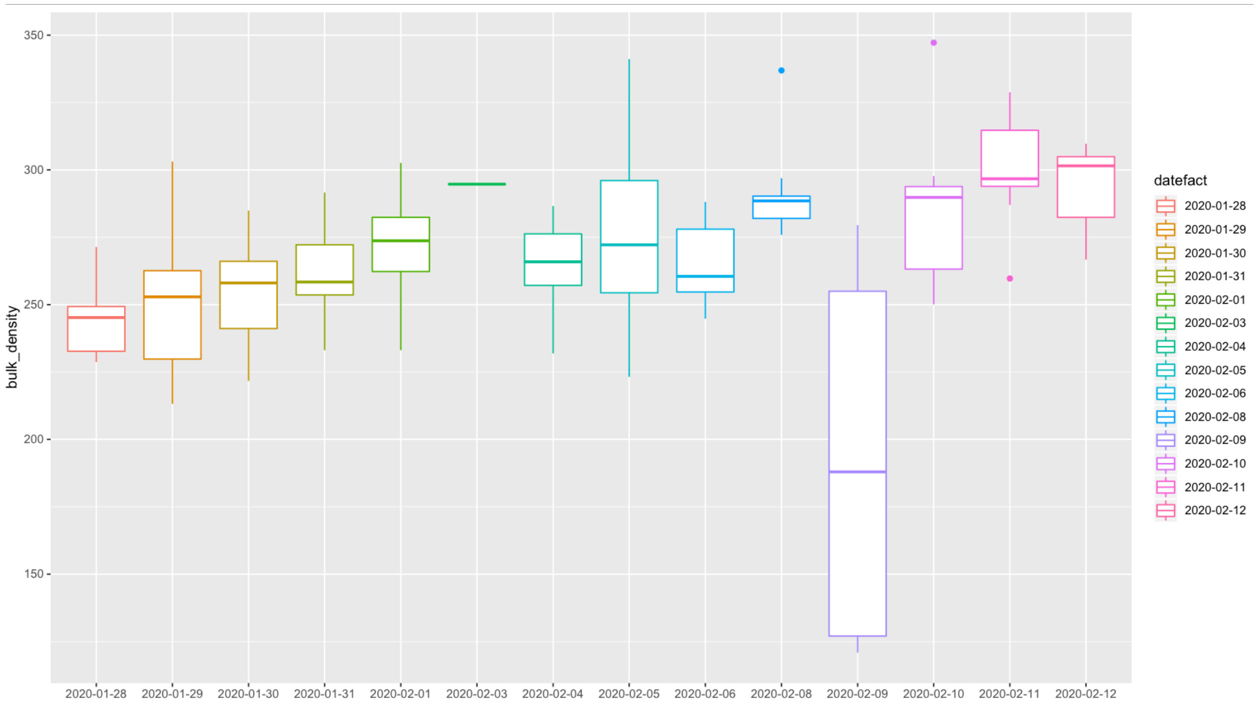


Figure A4 - Daily snow density distributions from the snow pit network (SNEX20_GM_SP)

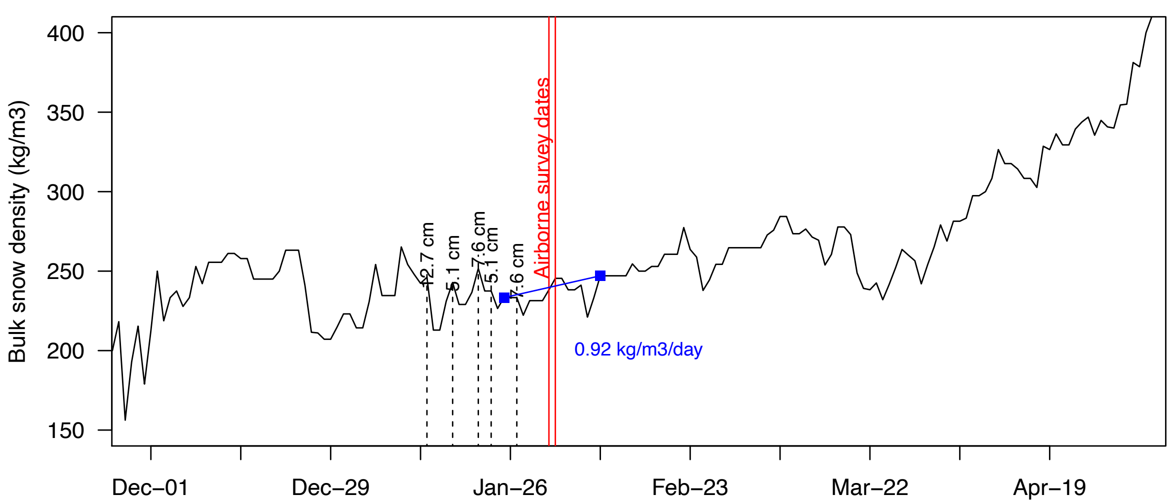
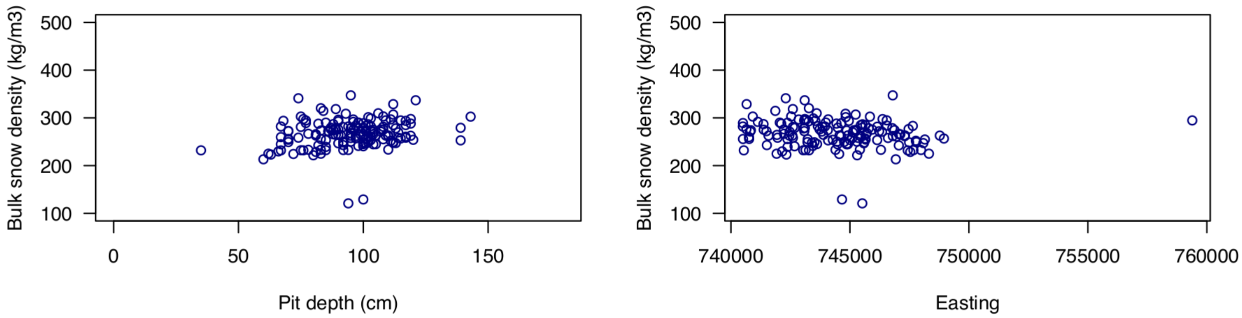


Figure A5 – Snow density estimates at the Mesa Lakes SNOTEL site, with a linear model applied to estimate the densification rate at the time of the survey. The vertical dashed lines reflect snowfall events (snow depth values are included). This densification rate was used to adjust the snow course data.



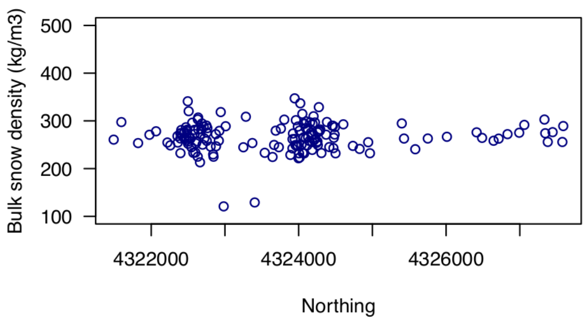


Figure A6 - Snow density vs. location and depth parameters from the snow pit network (SNEX20_GM_SP), data from all dates are shown.

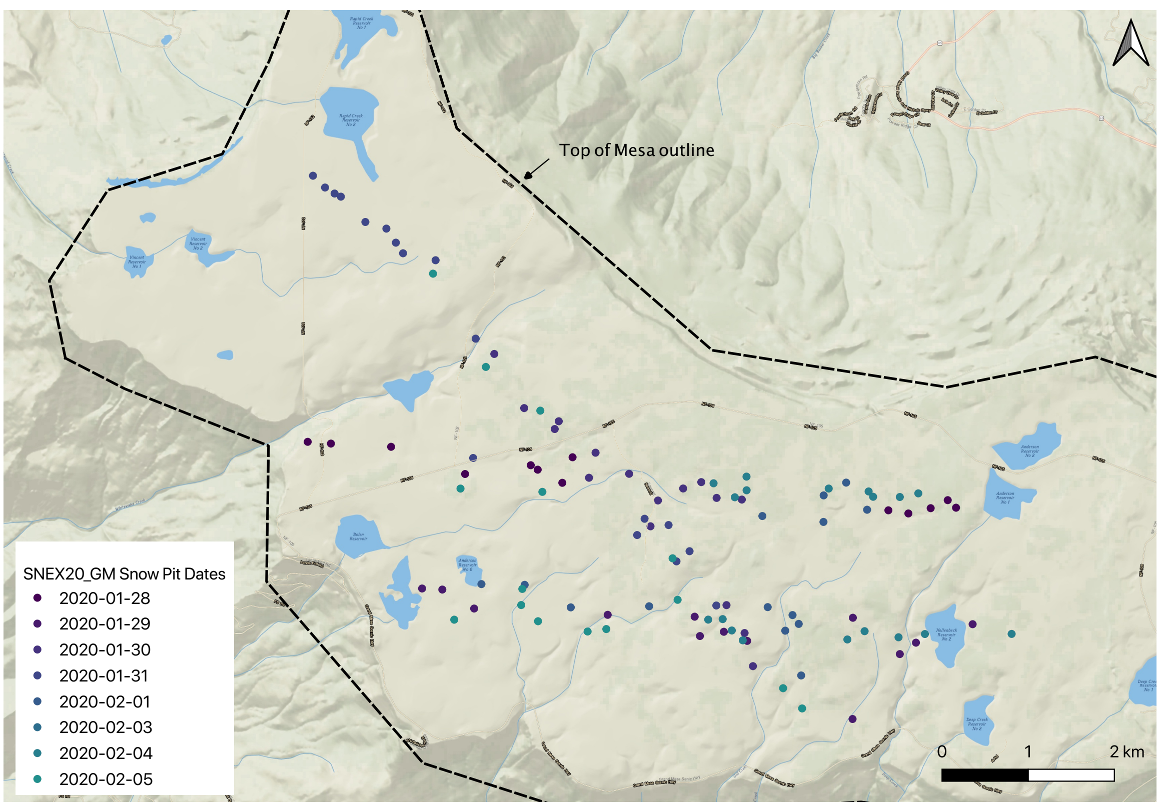


Figure A7 - Locations of snow pit measurement sites from the SNEX20_GM_SP dataset (shown are dates ±4 days of the airborne survey).

SNEX20_SD summary points:

- The snow depth in-situ data collected on February 1 that coincides with the Feb 1 portion of the airborne survey finds n=2737 points (Figure A8). The full set of SNEX20_SD data was subset to these points for evaluation.
- From the 2737 points, the mean snow depth from the in-situ data was 0.999 m. At these locations the mean snow depth from the ASO data was 0.945 m.
- The map below shows the subset of coincidental measurements for February 1
- There were no snow depth measurements from the SNEX20_SD campaign collected on February 2.
- Snow depth can vary substantially with time, as such for evaluation purposes we compare only snow depth measurements temporally coincident with the airborne data.

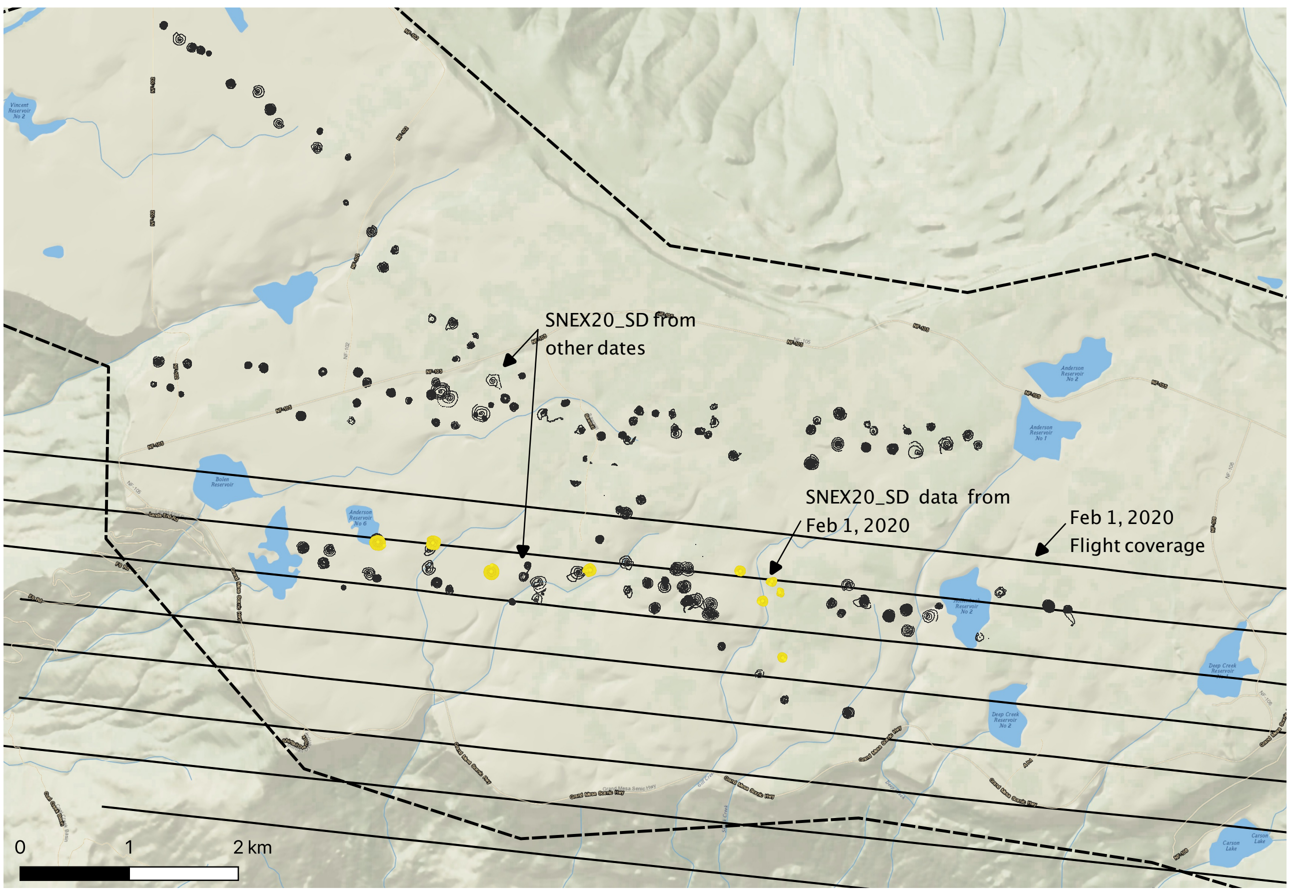


Figure A8 - Snow depth evaluation locations (SNEX20_SD) within the February 1 flight coverage (yellow). SNEX20_SD sampling locations from other dates are shown in black.

References

Painter, T. H., et al., The Airborne Snow Observatory: scanning lidar and imaging spectrometer fusion for mapping snow water equivalent and snow albedo (2016), *Remote Sensing of Environment*, 10.1016/j.rse.2016.06.018.