ASO Survey Report

Boulder Creek Basin, CO

Survey Date: May 9, 2023

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet's precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

Dear colleagues,

Because many of you are new to the world of Airborne Snow Observatories, Inc. measurements, I want to give you a short primer on ASO, how to read the report, and how to understand the accuracy of the products provided here. The first Airborne Snow Observatory was developed by our team at the NASA Jet Propulsion Laboratory to provide the first-ever, highly accurate snow water equivalent measurements across mountain basins. The data you will see are therefore very special.

How ASO works

An Airborne Snow Observatory couples scanning lidar and imaging spectrometer on a twin turbo prop aircraft, flying mountain basins to provide complete coverage of snow depth, snow water equivalent (SWE), and snow albedo. The scanning lidar determines topography of the snow surface, including beneath the forest canopy. From that snow surface, we subtract the bare ground surface that we measured previously during summer/fall to retrieve snow depth at 3 m (~10 ft) spatial resolution in a grid across the mountain basin. While this sounds straightforward, it is a complex process covered in our exclusive software license with the California Institute of Technology and the NASA Jet Propulsion Laboratory, a software suite that we invented while at NASA JPL. The complexity comes from the analysis of GPS data for the aircraft, the inertial measurements of the attitude and changes in the attitude of the instruments, interaction of laser pulses with vegetation and the surface beneath, and interaction with complex topography. The historical validation of ASO snow depth retrievals shows that we have an unbiased measurement with an uncertainty of ~6 cm (2.4 in) at 3 m resolution. We coarsen the 3 m resolution to 50 m to be multiplied by density. At that resolution, the depth uncertainty is $(1/\sqrt{n})*6$ cm where n is the number of 3 m cells in the 50 m cell (in this case 277). Hence, the uncertainty in snow depth at the 50 m resolution is under 1 cm (0.4 in).

With the snow depth map in (virtual) hand, we incorporate it into our spatially-distributed snow density mapping with the iSnobal snowpack model developed over the last 30 years at the USDA Agricultural Research Service, and now operated by our subcontracted colleagues at M3Works (the team that wrote the vast majority of the current implementation of the model). When well-constrained by ASO snow depths and meteorological data as well as available snow density measurements, iSnobal provides accurate snow density distributions. Per grid cell, we multiply the depth and density to arrive at kg/m^3 of snow water equivalent, which can then be converted to meters of SWE by dividing by the density of water ($1000\ kg/m^3$). This spatial distribution of SWE is used to update the snowpack model and can also be aggregated to a total SWE volume for the entire basin and for any desired subbasins. Given the criticality of ASO for water management, we also convert and report out SWE in thousand acre-feet (TAF).

The imaging spectrometer is used to map snow cover and snow albedo (reflectivity). We incorporate the snow cover map to assist with the snow depth measurements and to constrain the snowpack model. We likewise will use the snow albedos to update albedos in the models.

How to read the report

The report gives you the total basin SWE, uncertainty range, subbasin SWEs, approximate snowline, the map of the distributed SWE, the elevation distribution of SWE, and a radial plot showing SWE relative to elevation and aspect. Then the report provides the background on recent weather and the snowpack development as understood from available meteorological measurements. Finally, the report details the key components in understanding the accuracy of the distributed SWE measurements – in particular, depth and density.

How to understand the ASO SWE accuracy

I will explain here how I think about ASO accuracy and how the report presents the metrics. Fundamental to ASO's accuracy is the fact that the variance in SWE across the landscape is dominated by the variance in snow depth, while snow density varies far less. So, it is critical that we first measure snow depth accurately and then constrain the density distribution well.

You'll see our validation of snow depth with (1) bias estimates between snow acquisitions and snow-free acquisitions and then (2) against available in-situ snow depth measurements (though generally there are not nearly as many as we would love to have). How does the bias estimate help? At hundreds of thousands to millions of snow-free surface pixels around the basin, we can determine how elevations from the snow-on and snow-free flights differ – they generally vary by a few cm and we are able to lock the surfaces together at those places for tight calibration (with uncertainty of about 6 cm). Every one of these points gives us a snow depth measurement (that is very close to zero!). Then the comparison with in-situ snow depth measurements is used as a sanity check just to make sure the bias is applied correctly (and that it is on average smaller than 6 cm).

Next is the validation of the snow density modeling with field measurements, snow courses, and those snow pillows that have reliable, coincident snow depth measurements. Understanding these densities then allows us to use a central density field and a range of densities according to estimated density uncertainties, typically within a few percentage points.

By constraining snow depth well and snow density well, we produce the amazing SWE map. If you have any questions, please let me know at painter@airbornesnowobservatories.com.

Best to you all,
Tom Painter
CEO, Airborne Snow Observatories, Inc.

Survey Date: May 9, 2023
Survey # of Water Year 2023: 1
Report Delivery Date: May 12, 2023

Full basin SWE: 73 ± 4 TAF
Estimated snowline: 9300 feet

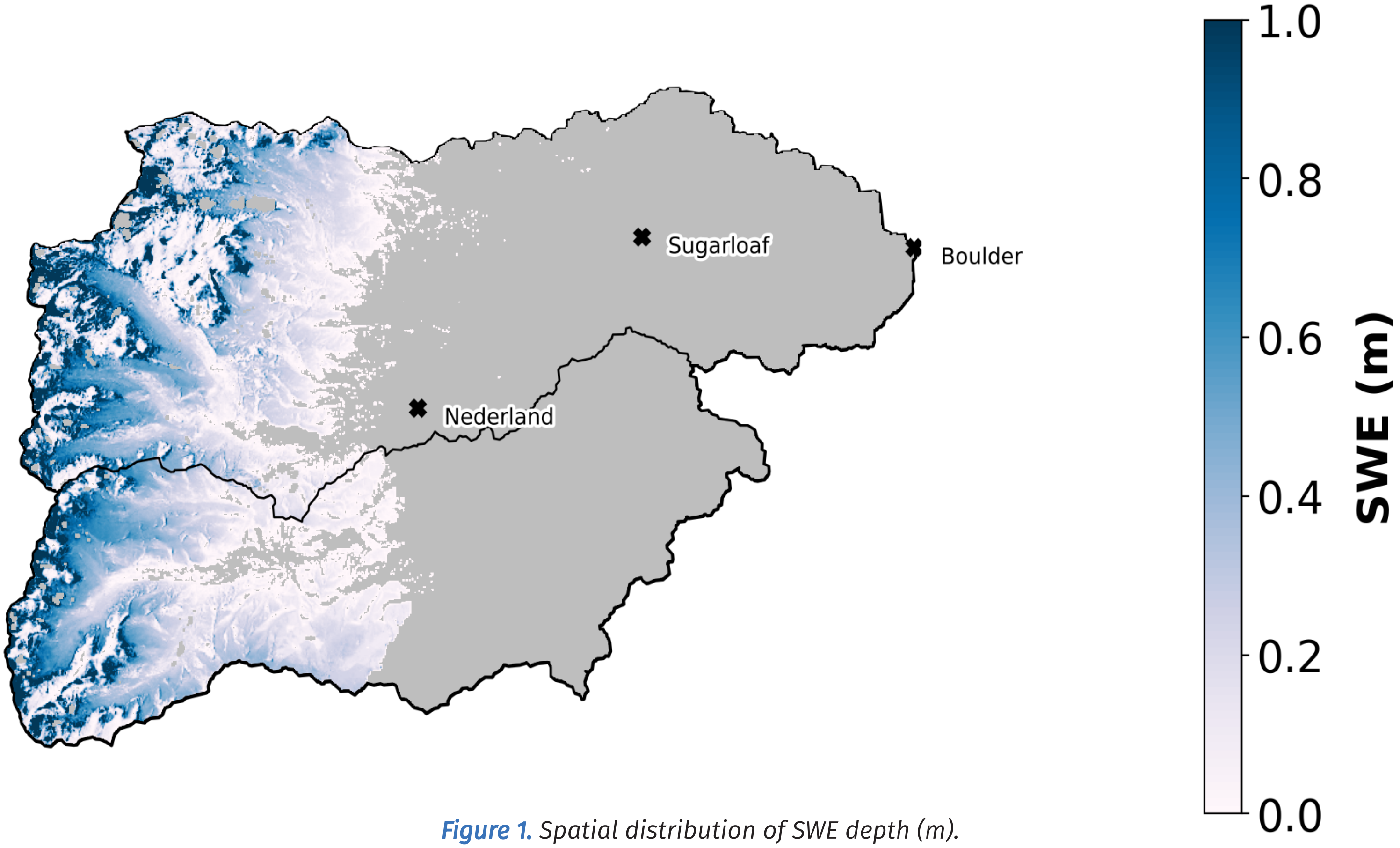


Figure 1. *Spatial distribution of SWE depth (m).*

Table 1. *Estimated SWE volume (TAF) for the full Boulder Creek basin and subbasins for the current survey.*

Basin	Estimated SWE (TAF) May 9
Boulder Creek Basin	73
Uncertainty Range	*69 - 77*
South Boulder Creek below Gross Reservoir	29

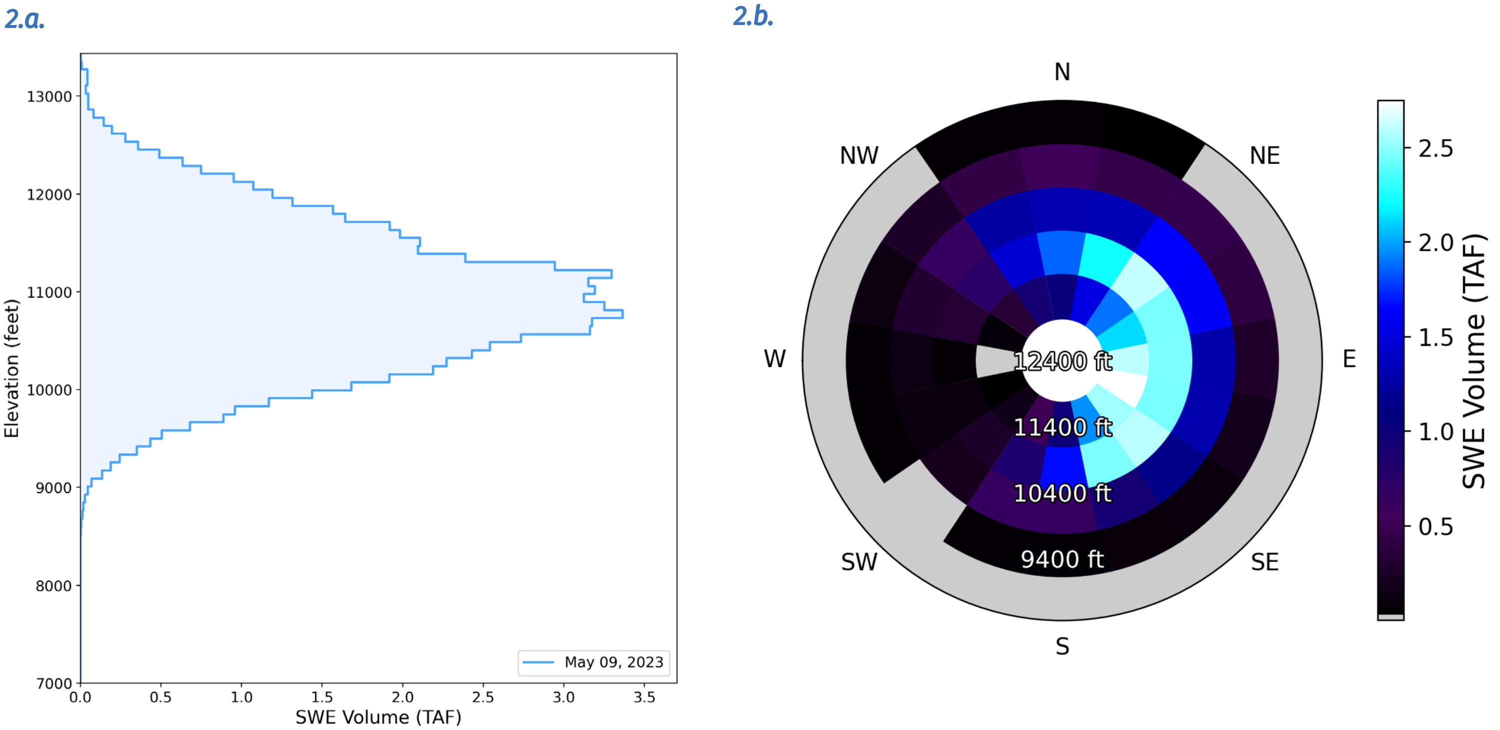


Figure 2.a. *Distribution of SWE volume (TAF) across elevations.* *Figure 2.b.* *Distribution of SWE volume (TAF) by aspect and elevation for the May 9 survey. See* *Figure 8* *and* *Figure 9* *for more descriptive plots.*

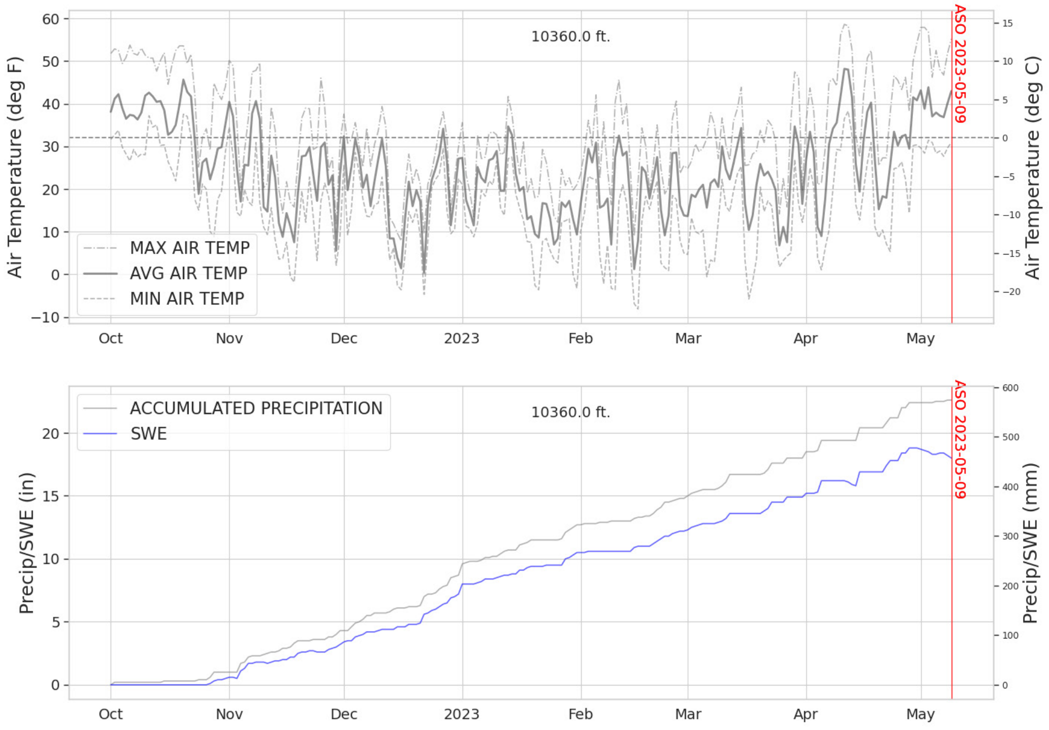


Figure 3. *Daily meteorological conditions at University Camp (838) (elevation 103060 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.*

Summary of background conditions

- SNOTEL station data indicates that beginning in late November, the basin snowpack largely kept pace with the long-term median. Regular accumulations continued into February, when snowfall slackened in the southern part of the Front Range, leading to below-normal snowpacks in the south, and above-normal at northern stations.
- A strong southwesterly wind event on April 3rd deposited a substantial dust load over most of the Colorado mountains, including the Boulder Creek basin. Although covered intermittently by recent snowfall events, this dark dust layer has been enhancing snowmelt and runoff rates for the past month.

Evaluation of ASO snow depth measurements

Point-to-point comparison of in-situ snow depths with ASO 3 m resolution snow depth* is shown in **Table 2.**

These depth comparisons are at stations for which we are very confident in 1) the location, and 2) the depth data that is being reported at the time of the ASO survey. Because we are directly comparing a point to a 3 m pixel in our data, we need to be certain that the station location is accurate to within 1.5 m. For reference, GPS data is usually only accurate to within 5 m, but we are often able to hone in on locations using Google Earth and other means, thereby enabling these comparisons. For these reasons, specific sites might not be included in the comparison. Please contact the ASO team to converge on accurate and precise coordinates and/or investigate data quality issues for any sites of interest.

At these known and trusted station locations in the Boulder Creek, the mean snow depth uncertainty was -2.3 cm.

*Note: Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and enforces snow depth accuracy throughout. At 3 m resolution, the standard deviation of snow depth distribution was 0.012 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 1 cm.

Table 2. *Comparison of ASO and snow pillow snow depths. Note: ASO long-term depth uncertainty is ± 8 cm.*

Site	Elevation (ft)	Date	Site Depth (cm)	ASO Depth (cm)	Depth Difference (cm)
University Camp	10360	5/9/23	122	117	-6
NIWOT	9910	5/9/23	56	58	2
Lake Eldora	9700	5/29/23	10	7	-3
				Mean	-2.3

Evaluation of snow density

Physically based model - iSnobal

- As this is the first survey of the season in the Boulder Creek basin, the iSnobal model is only now being updated with data from the May 9th airborne survey.
- The mean spatially distributed snow density from the open-loop model on May 9th is 460 ± 29 kg/m^3.

In-situ measurements

ASO field collections

- ASO staff did not collect any field measurements for this survey.

Sensor measurements

- The mean snow density reported on May 9th from three locations (**) was 399 ± 24 kg/m^3, with a range of 375 - 423 kg/m^3. (** Lake Eldora, Niwot, University Camp SNOTELs.) See **Figure 4**.
- Due to an inconsistency in the reported snow density on the day of the airborne survey, the Lake Eldora density value from May 8th was used for this analysis.

Snow course measurements

- The May snow course measurements were available from three locations at the time of processing. These data were collected April 27th to April 28th, and the mean snow density reported from these surveys was 334 ± 50 kg/m^3.
- The ongoing densification of the snowpack affected snow density between the collection window and the ASO survey. The densification rate has been estimated at 4.5 kg/m^3/day based on nearby in-situ sensors, and has been used to time-adjust the snow course measurements to the ASO survey.
- After adjustments, the estimated mean bulk density of the three snow courses was 385 ± 48 kg/m^3.
- Due to the increased uncertainty for measurements taken 11-12 days prior to the survey and adjusted for densification, the snow course data were given lower weight in the model evaluation and bias correction.

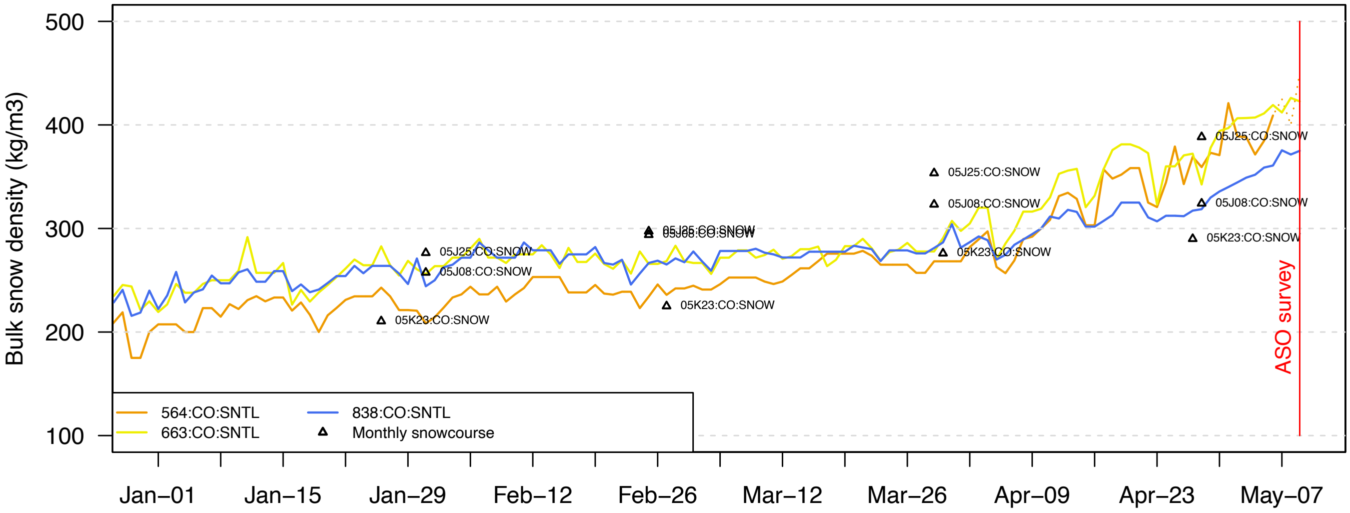


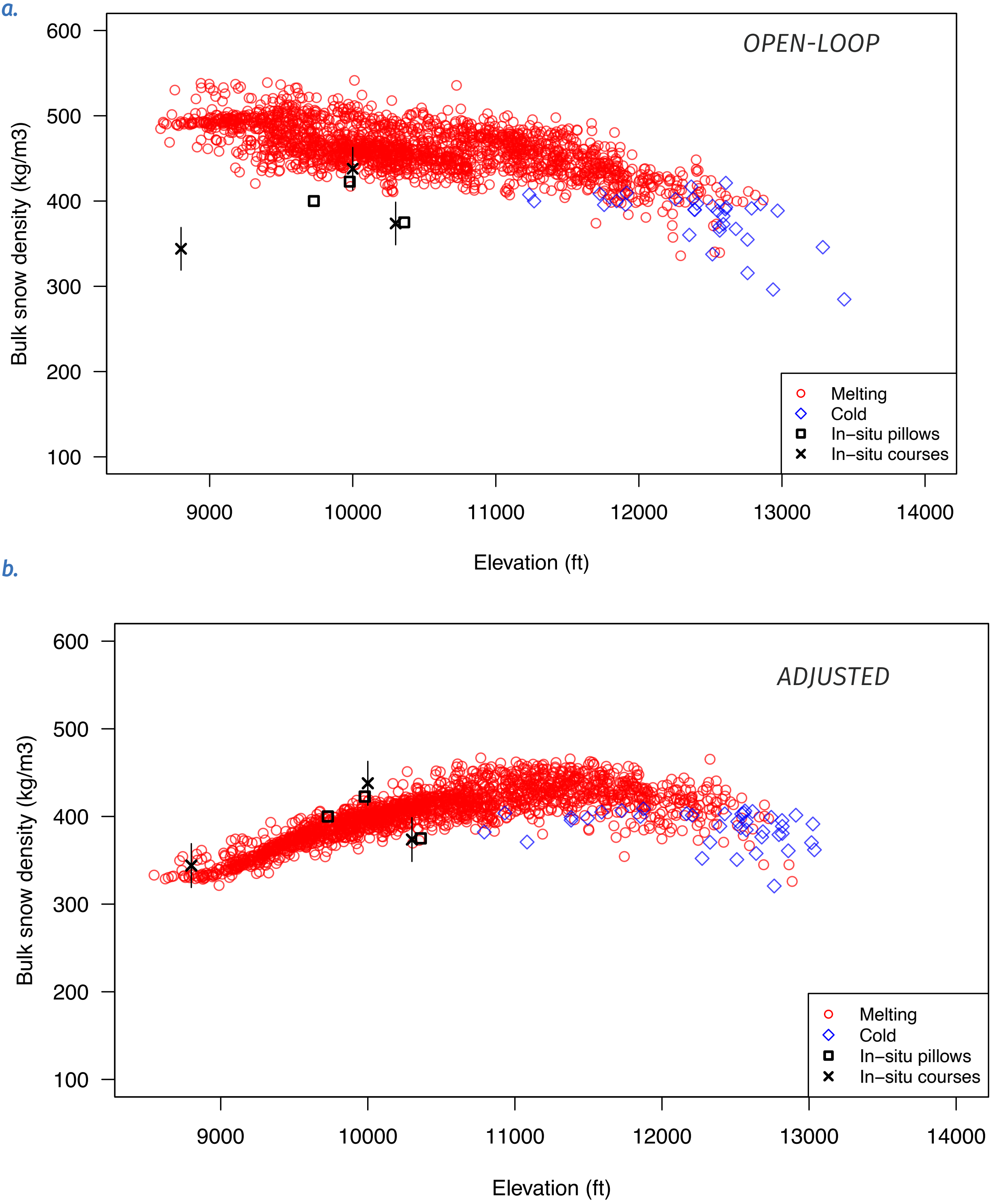
Figure 4. Daily snow density timeseries at automated sensor locations in the Boulder Creek Basin and neighboring basins. (Data source: NRCS)

Model evaluation & snow density adjustment

- The mean modeled snow density of 460 ± 29 kg/m^3 is higher than the in-situ guidance of ~390 kg/m^3.
- The distribution of modeled snow density with elevation (**Figure 5a**) suggests that the model is overestimating across all elevations, with larger overestimations at lower elevations (< 9500 ft). We observed similar model performance in Clear Creek.
- At lower elevations (< 9500 ft), the model is reporting a mean bulk density of 488 kg/m^3 which is 22% higher than the in-situ mean of ~380 kg/m^3 at the same elevations.
- To address these overestimation biases in the model, the bulk densities were reduced using a non-linear relationship (with elevation) to reduce bulk density by 1% at 11500 ft, 11% at 10500 ft, to a maximum of 25% reduction at 9000 ft. In addition, shallow snow (< 0.6 m) was further reduced by a maximum of 10%, targeting snow densities of 370 kg/m^3 in these areas.
- The rescaling resulted in a reversal of the snow density change with elevation, toward lower bulk snow densities at lower elevations - as suggested by the in-situ guidance.
- The resulting mean-adjusted snow density across the basin was reduced to 402 ± 29 kg/m^3, and the mean in lower elevations (< 9500 ft) was reduced to 354 kg/m^3.
- After adjustment, the bias in snow density calculated using point-to-point comparisons at in-situ locations was reduced to -3 kg/m^3 from +56 kg/m^3 (model open-loop).
- Using the open-loop model density, the full basin SWE was 80 TAF and after snow density adjustments were applied, the basin SWE estimate was reduced to 73 TAF. The snow density adjustments decreased the basin SWE estimate by 9% (7 TAF).
- The in-situ measurements are largely unconstrained at elevations > 10500 ft. To address the remaining uncertainty in bulk snow density at higher elevations, we have generated two snow density scenarios. In Scenario H, we adopt the non-linear reductions described above, but increase densities above 10500 ft by 3% - towards 436 kg/m^3. In Scenario L, we adopt the non-linear reduction described above (at lower elevations) and reduce densities above 10500 by 3% - towards 410 kg/m^3.
- The resulting full basin SWE outcome for these scenarios were 71 TAF and 75 TAF respectively, suggesting that the basin SWE is sensitive to uncertainty in the snow density on the order of ~ 5% of the total basin SWE. We have factored uncertainty based on these outcomes into the values reported on the front page of this report.

Table 3. Snow density scenarios and SWE volume estimates. The 'Adjusted Density' is used in calculating the reported SWE. The other density scenarios are computed to evaluate the density sensitivity and to help determine the uncertainty in the reported SWE values.

Scenario	Spatial-mean density (kg/m³)	SWE (TAF)	Description
Adjusted density	**417**	**73**	**Adjusted density map & ASO depths**
M3W (May 9 value)	457	66	Modeled SWE
Open-loop	457	80	Modeled density map and ASO depths
Scenario L	430	71	Partially adjusted density with an additional -3% applied above 10500 ft + ASO depths
Scenario H	447	75	Partially adjusted density with an additional +3% applied above 10500 ft + ASO depths

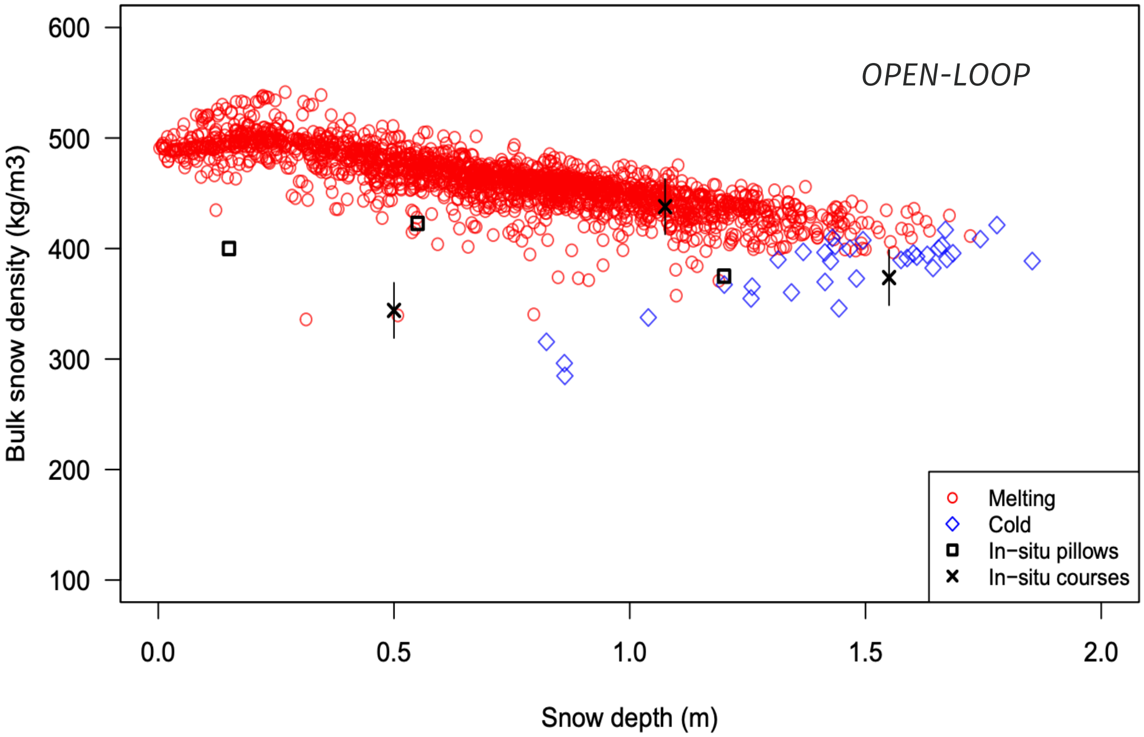


5.a.

5.b.

Figure 5. Observed and modeled bulk snow density (kg/m³) by elevation (ft) for a. open-loop and b. adjusted densities. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

6.a.



6.b.

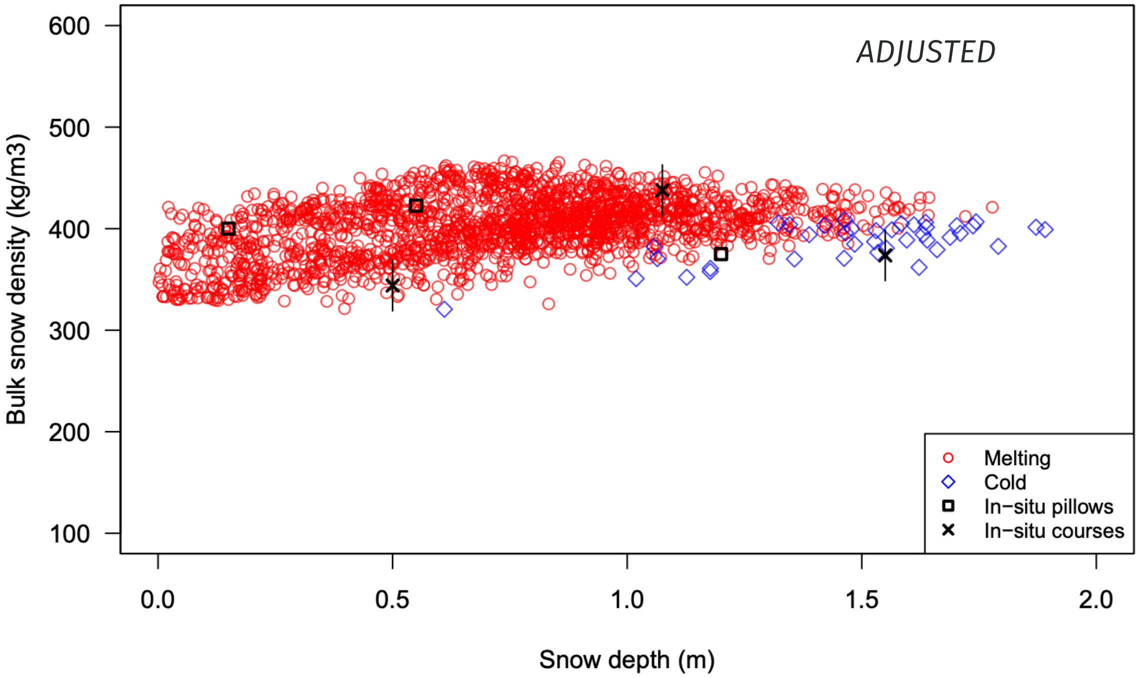


Figure 6. Observed and modeled bulk snow density (kg/m³) by snow depth (m) for a. open-loop and b. adjusted densities. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

Snow albedo

- As described in Painter et al. (2016), in addition to the scanning lidar, ASO also carries a pair of visible to shortwave infrared imaging spectrometers from which we retrieve broadband albedo (400-2500 nm wavelength), visible albedo (400-700 nm), and near-infrared to shortwave-infrared (700-2500 nm). The latter two albedos are generated to ultimately constrain iSnobal and WRF-Hydro, as well as other physically-based models.
- Solar radiation is the primary energy source for snowmelt. The snow albedo describes the fraction of incoming solar energy that is reflected by the snow surface.
- The three wavelength bands presented in **Figure 7a** are visible, broadband, and near IR/shortwave IR, the same wavelength ranges that are used in iSnobal and WRF-Hydro Noah-MP snow albedos. These albedo traces with elevation show that the snowpack albedo decreases with decreasing elevation due to both increasing grain size and increasing impurity load. The bulk statistics for snow albedos are visible 77 ± 10%, broadband 62 ± 8%, and near IR/shortwave IR 44 ± 7% and as such the warming and melting of snowpack will be reduced in the very higher elevations but accelerated primarily below 11000 ft elevation.

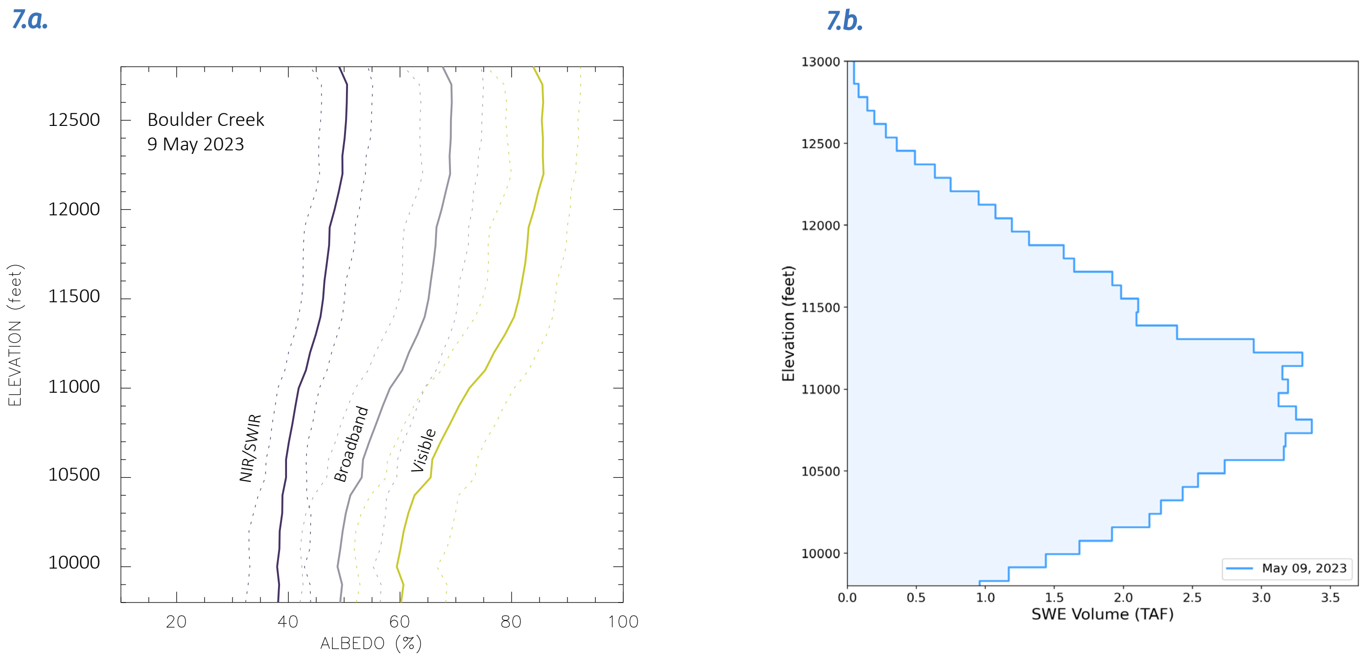


Figure 7.a. *Snow albedo (%) by elevation (ft) on May 9 with mean (solid lines) and ± 1 standard deviation (dotted lines) for near and shortwave infrared (blue), broadband (light blue), and visible (gold) wavelengths.* ***7.b.*** *Distribution of SWE volume (TAF) across elevations for the May 9 survey.*

Additional data/ remarks

- ASO survey operations target clear-sky days, however, clouds can encroach into the target area during the period of survey. The survey techniques are such that we can often get valid retrievals under clouds, but this is not always possible.
- During the window for the May 9th Boulder Creek survey, we encountered several minor clouds across the basin, particularly located along the southern and northern boundaries of the domain and covering ~ 20.3 km^2 (or 8% of the basin). Flight line overlap and penetration through clouds enabled us to retrieve a snow depth signal in many of these clouded areas. However, remaining clouds were estimated to mask < 1% (~2 km^2) of the snow covered area, though the vast majority of the clouds were over patchy snow covered areas.
- In masked areas, we backfilled depth using the median value of retrievals proximal to individually identified clouds. As some of the clouds masked partially covered snow areas, there may be some spatial artifacts associated with this backfilling procedure, though we expect this to have very little impact on total basin SWE and on the spatial distribution of SWE. For this survey, the estimated cloud-masked SWE was < 0.4 TAF. This value is included in our estimate of total basin SWE on the front page.
- Please refer to the text files included in the data package for SWE volume per elevation band and other summary statistics.

Additional data / remarks

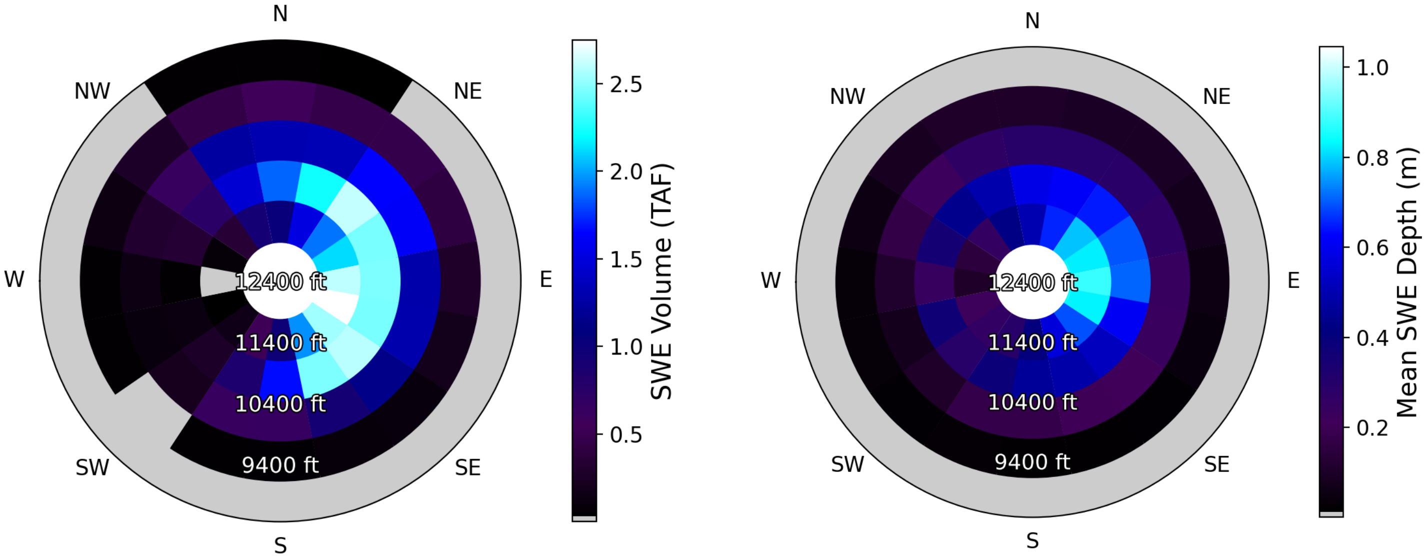


Figure 8.a. & 8.b. SWE volume (TAF) and depth (m) by aspect and elevation for May 9 survey.

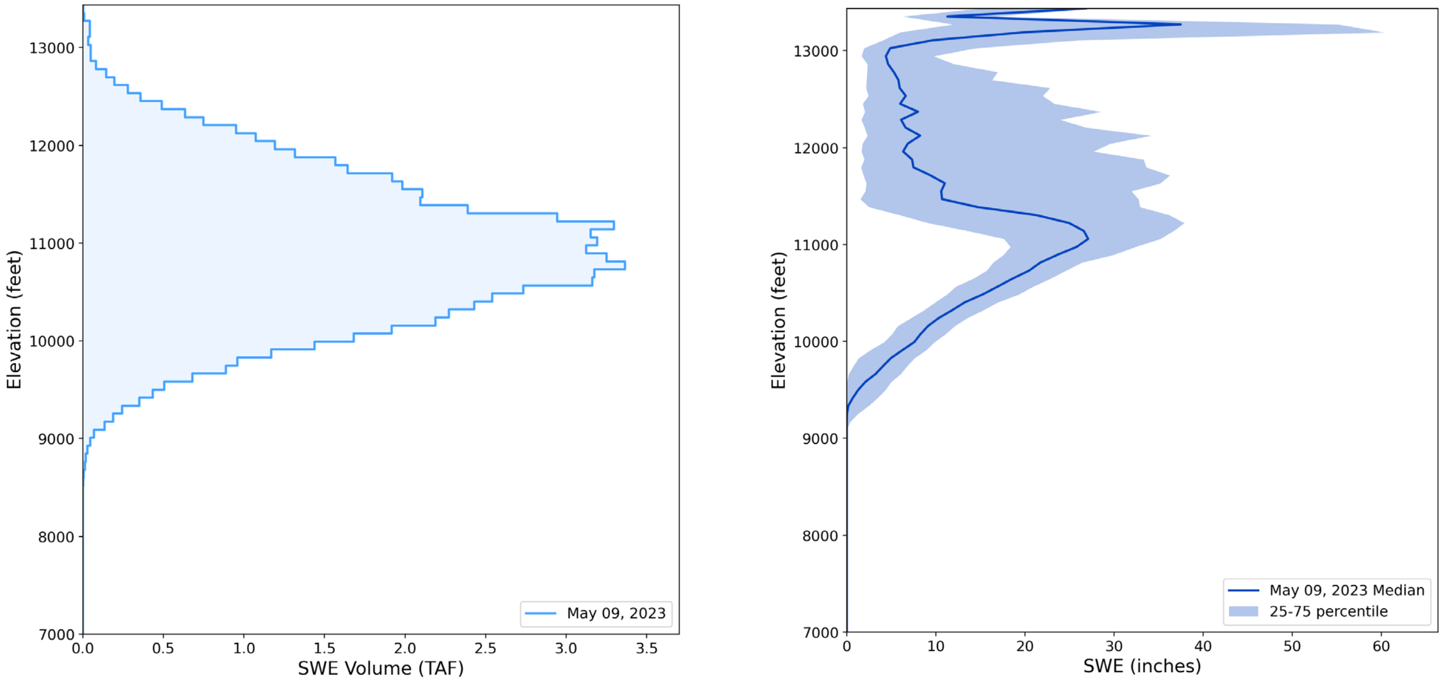


Figure 9.a. Distribution of SWE volume (TAF) across elevations for the May 9 survey. 9.b. Distribution of SWE depth (in) across elevations; solid line represents median SWE depth (in), lighter color bands represent the 25th to 75th percentile.