ASO Survey Report

Clear 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

Survey Date: May 9, 2023
Survey # of Water Year 2023: 1
Report Delivery Date: May 11, 2023

Full basin SWE: 82 ± 5 TAF
Estimated snowline: 10000 ft

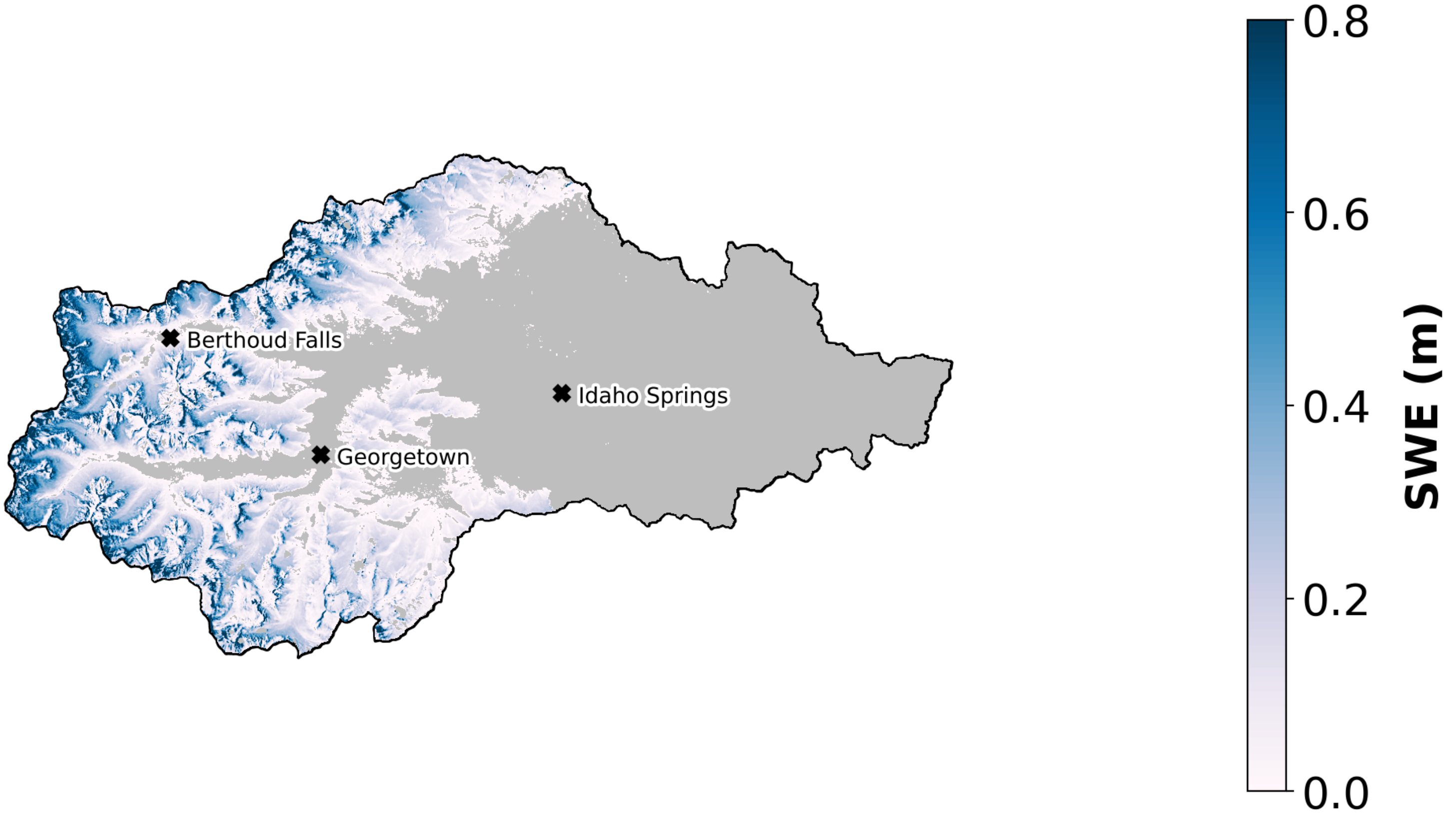
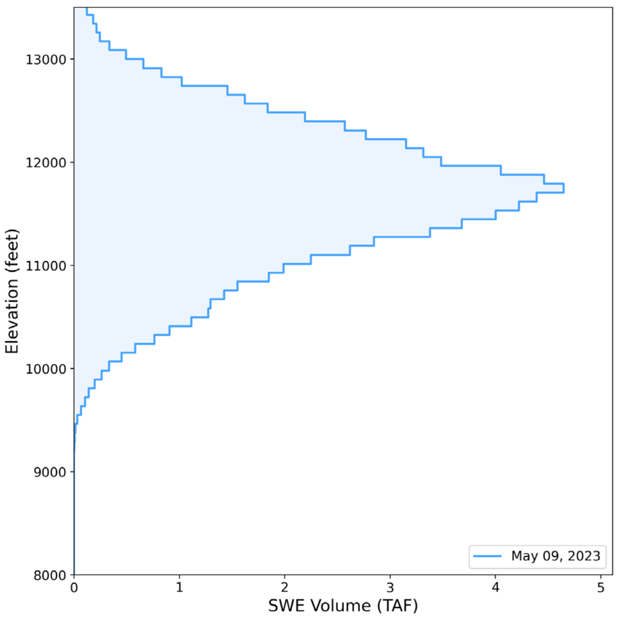


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the full Clear Creek basin for the current survey.

Basin	Estimated SWE (TAF) May 5
Full Basin	82
Uncertainty Range	*77 - 87*

2.a.



2.b.

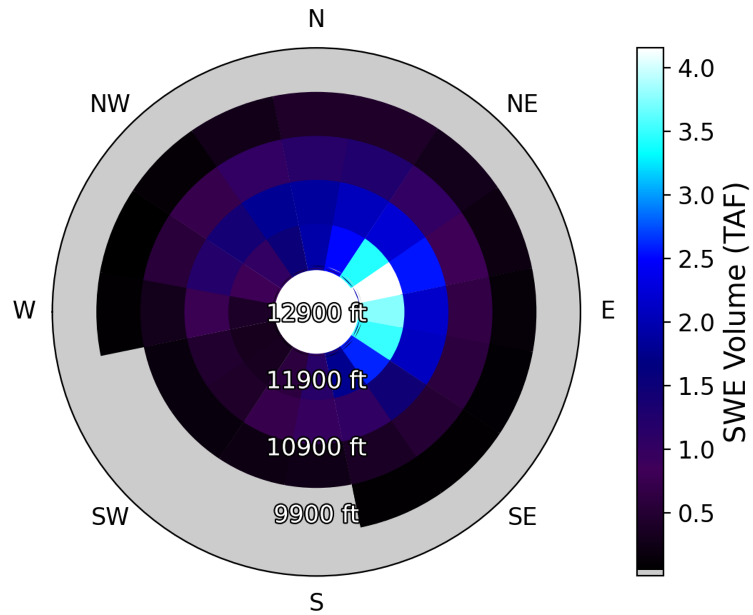


Figure 2.a. *Distribution of SWE volume (TAF) across elevations.* ***Figure 2.b.*** *Distribution of SWE volume (TAF) by aspect and elevation for the May 9 survey. See* ***Figure 8*** *and* ***Figure 9*** *for more descriptive plots.*

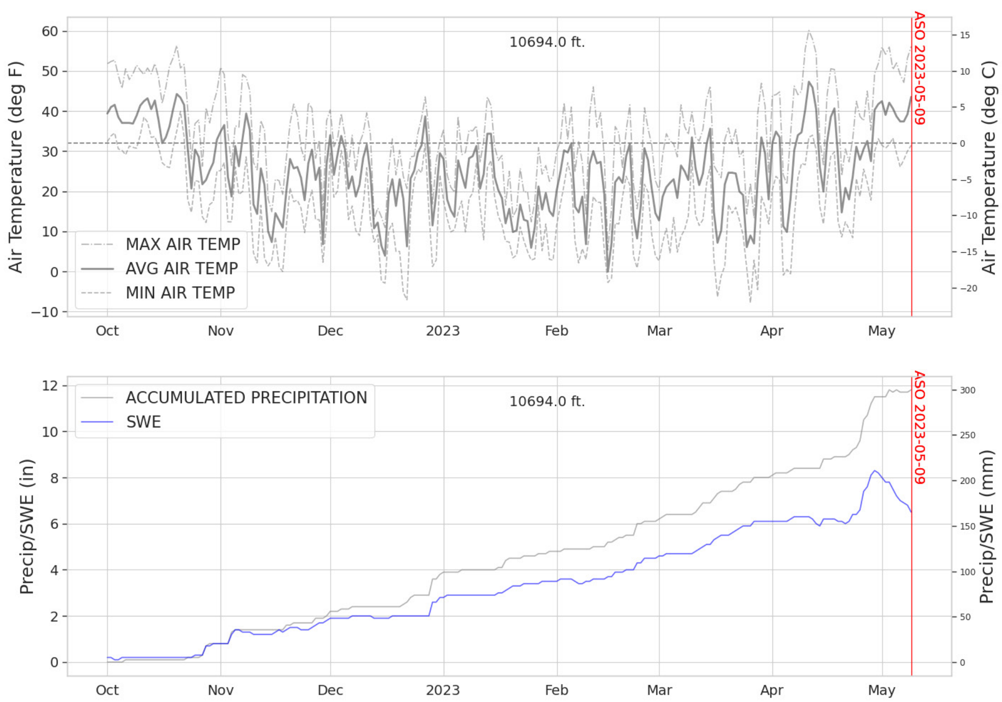


Figure 3. *Daily meteorological conditions at Echo Lake (SNTL 936) (elevation 10694 ft). This location is not used in our station comparison (see* ***Table 2****). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. 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 - while the snowpack on the stations appears to have hit its peak around the typical time (May 1st), peak values were lower than median for many front range locations.
- A strong southwesterly wind event on April 3rd deposited a substantial dust load over most of the Colorado mountains, including the Clear 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 Clear Creek Basin, the mean snow depth uncertainty was -0.5 cm (See **Table 2**)

*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 the basin. At 3 m resolution, the standard deviation of snow depth distribution was 0.01m, 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)
Echo Lake	10656	5/9/23	51	46	-5
Loveland Basin	11400	5/9/23	122	125	3
Jones Pass	10400	5/9/23	53	54	1
Berthoud Summit	11299	5/9/23	127	126	-1
				Mean	-0.5

Evaluation of snow density

Physically based model - iSnobal

- As this is the first survey of the season in the Clear 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 455 ± 34 kg/m^3.

In-situ measurements

ASO field collections

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

Sensor measurements

- In order to better evaluate the model within the Clear Creek River basin, we expanded our density analysis to include the nearby Lake Eldora and Jackwhacker Gulch SNOTEL sites
- The mean snow density reported on May 9th from six locations (**) was 354 ± 26 kg/m^3, with a range of 325-400 kg/m^3. (** Berthoud Summit, Loveland Basin, Echo Lake, Jones Pass, Jackwhacker Gulch, Lake Eldora SNOTELs.) See **Figure 4**.
- Due to an inconsistency in the reported snow density on the day of the airborne survey, the density value from May 8th was used here for Lake Eldora.

Snow course measurements

- The May snow course measurements were available from seven locations, including several in neighboring basins to the north and south, at the time of processing. These data were collected April 24th to April 27th, and the mean snow density reported from these surveys was 314 ± 33 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 3.4 kg/m³/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 seven snow courses was 356 ± 33 kg/m³.
- Due to the increased uncertainty induced by measurements taken 12-14 days prior to the survey and adjusted for densification, the snow course data were given lower weight in the model evaluation and bias correction.

Model evaluation

- The mean modeled snow density of 455 ± 34 kg/m³ is higher than the in-situ guidance of ~355 kg/m³.
- 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 (< 10000 ft).
- At lower elevations (< 10000 ft), the model is reporting a mean bulk density of 481 kg/m³ which is 20-32% higher than the in-situ mean of ~325-400 kg/m³ 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 10% at 12500 ft to a maximum of 32% reduction at 9500 ft.
- 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.

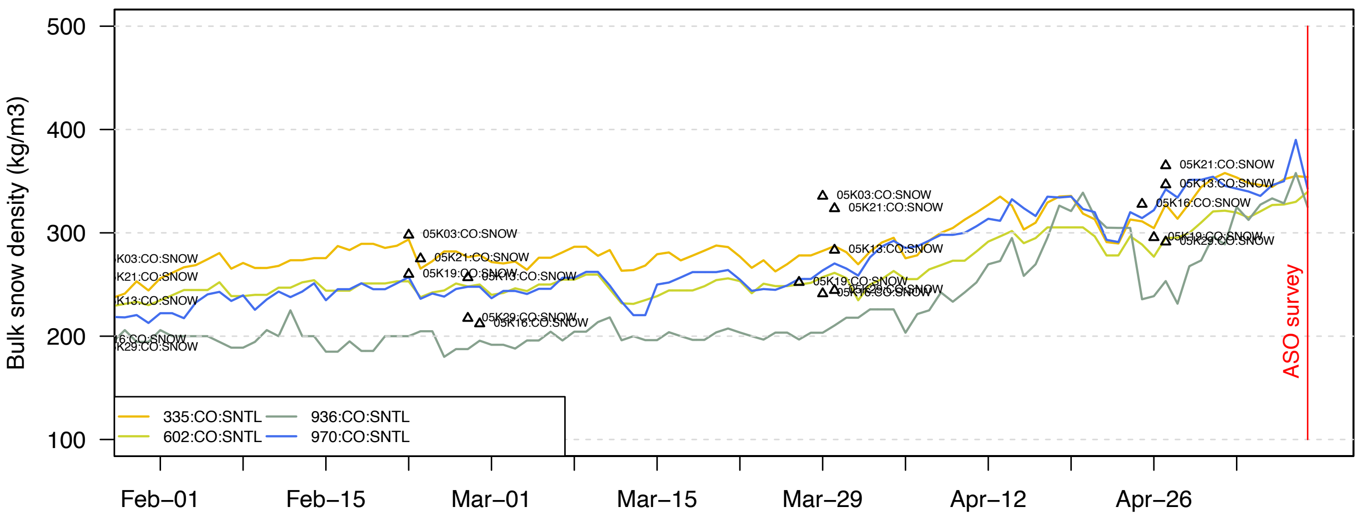


Figure 4. Daily snow density timeseries at automated sensor locations in the Clear Creek Basin. (Data source: NRCS)

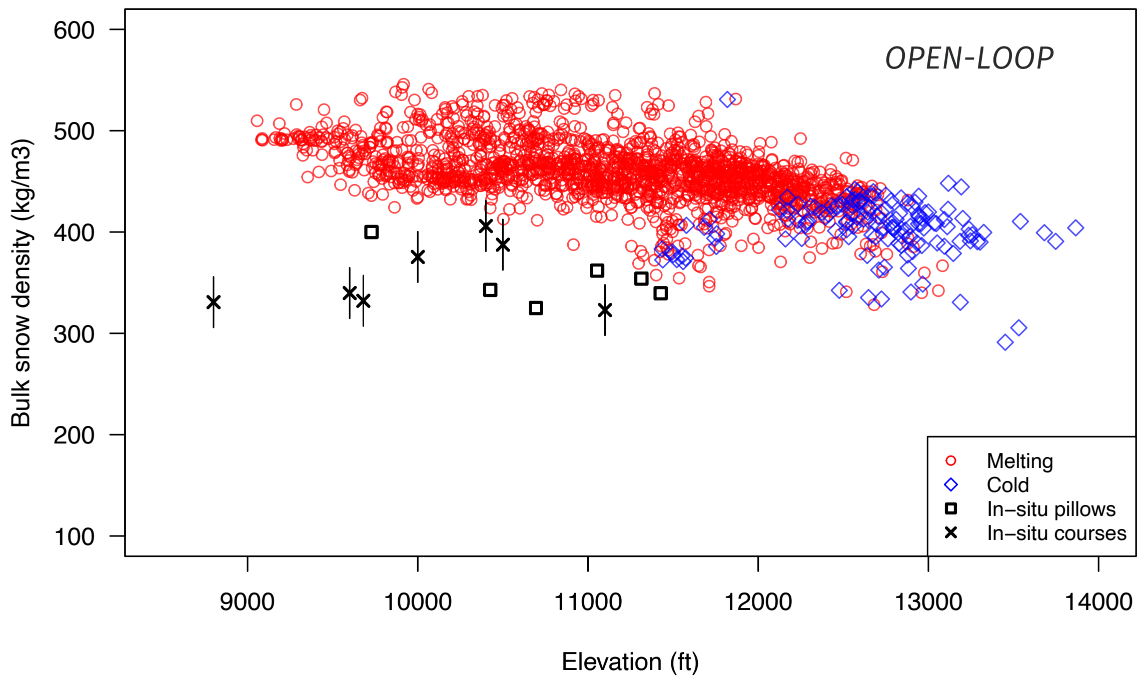
- The resulting mean-adjusted snow density across the basin was reduced to 365 ± 28 kg/m^3, and the mean in lower elevations (< 10000 ft) was reduced to 338 kg/m^3.
- After adjustment, the bias in snow density calculated using point-to-point comparisons at in-situ locations was reduced to +1 kg/m^3 from +118 kg/m^3 (model open-loop).
- Using the open-loop model density, the full basin SWE was 98 TAF and after snow density adjustments were applied, the basin SWE estimate was reduced to 82 TAF. The snow density adjustments decreased the basin SWE estimate by 17%.
- The in-situ measurements are largely unconstrained at elevations > 11500 ft, and in deeper snow (> 1.25m). To address the remaining uncertainty in bulk snow density at high elevation we have generated two snow density scenarios. In Scenario H, we adopt the non-linear reductions described above, but increase densities above 11500 ft by 4% - towards 420 kg/m^3. In Scenario L, we apply an additional 4% reduction to the non-linear reduction described above (at lower elevations) and reduce densities above 11500 by 2% - towards 390 kg/m^3.

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	**375**	**82**	**Adjusted density map & ASO depths**
M3W	451	163	Modeled SWE
Open-loop	451	98	Modeled densities and ASO depths
Scenario L	401	77	Partially-adjusted snow density with non-linear +4% reduction < 11500 ft and further reduction in densities above 11500 ft by 2% + ASO depths
Scenario H	416	90	Partially-adjusted snow density with non-linear reductions < 11500 ft and an increase in densities above 11500 ft by 4% + ASO depths

- The resulting full basin SWE outcome for these scenarios were 77 TAF and 90 TAF respectively, and suggests that the basin SWE is sensitive to uncertainty in the snow density in the order of up to 5-8 TAF (or 6-10% of full basin SWE). These scenarios should be considered to span the reasonable range of snow density scenarios rather than equally possible snow density outcomes. We have factored uncertainty based on these outcomes into the values reported on the front page of this report.

5.a.



5.b.

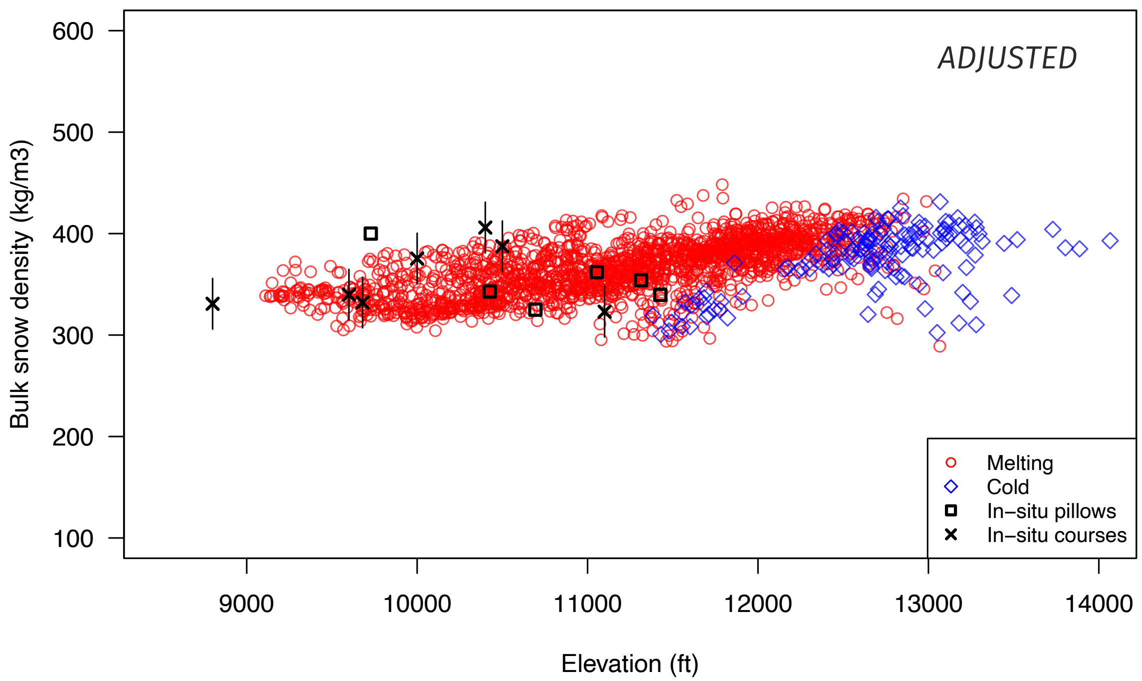
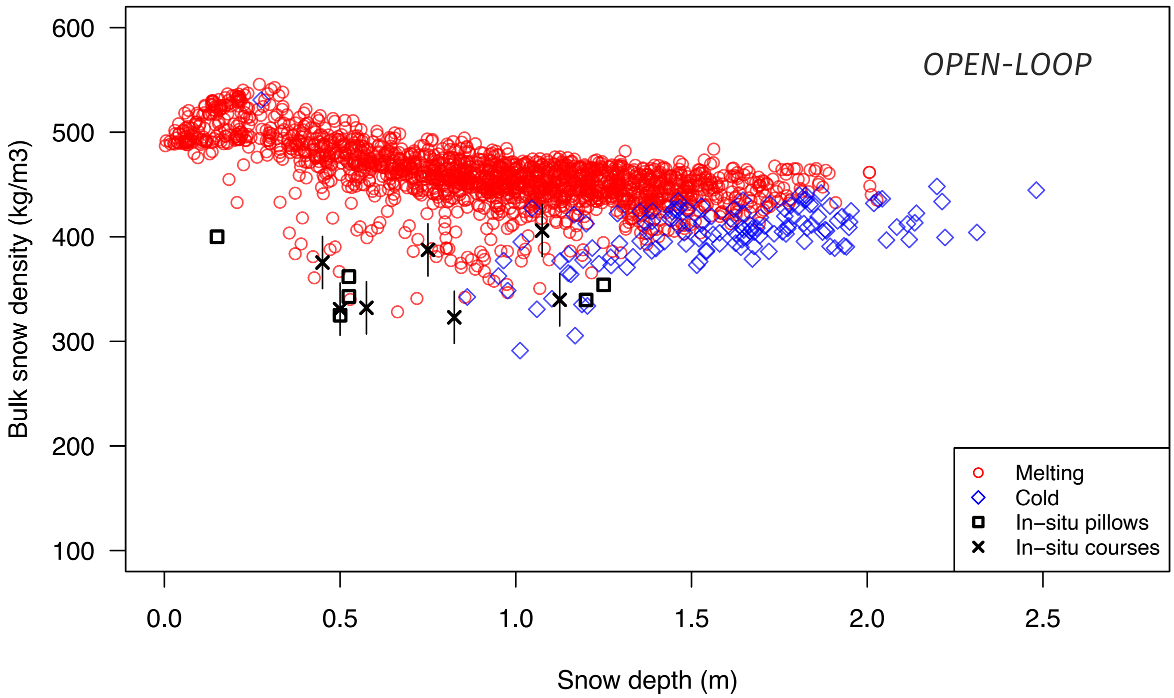


Figure 5. *Observed and modeled bulk snow density (kg/m³) by elevation (ft) for* ***a.*** *open-loop and* ***b.*** *adjusted densities. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

6.a.



6.b.

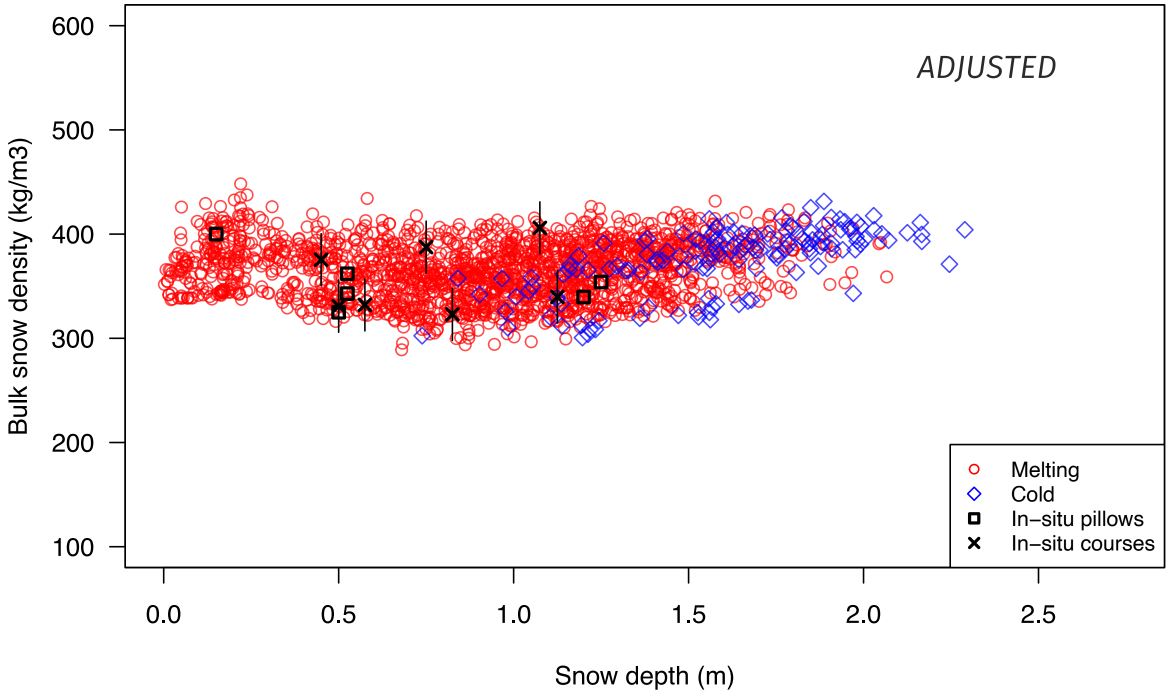
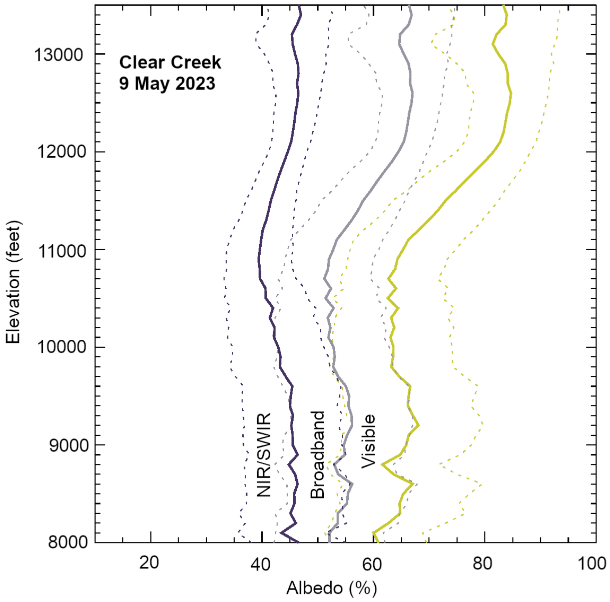


Figure 6. Observed and modeled bulk snow density (kg/m³) by snow depth (m) for a. open-loop and b. adjusted densities. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

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 78 ± 10%, broadband 62 ± 8%, and near IR/shortwave IR 41 ± 8% and as such the warming and melting of snowpack will be reduced in the higher elevations but accelerated primarily below 11000 ft elevation.

7.a.



7.b.

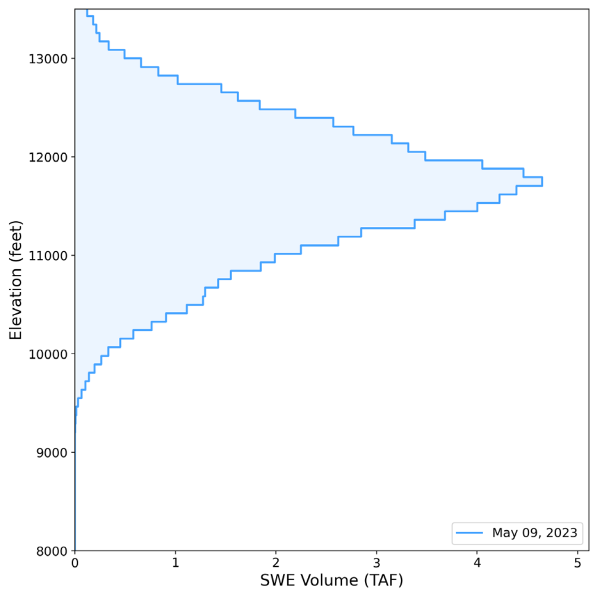


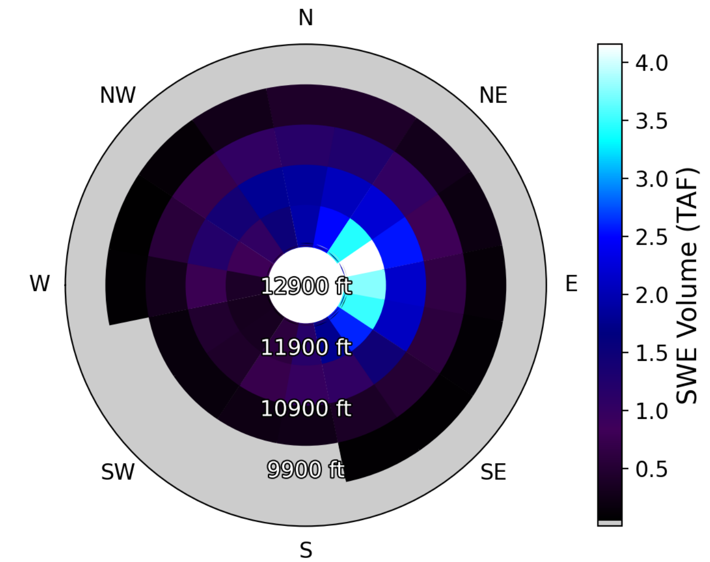
Figure 7.a. *Snow albedo (%) by elevation (ft) on May 9 with mean (solid lines) and ± 1 standard deviation (dotted lines) for near and shortwave infrared (black), broadband (light gray), and visible (gold) wavelengths.* ***7.b.*** *Distribution of SWE volume (TAF) across elevations for the May 9 survey.*

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 Clear Creek survey, we encountered several minor clouds across the basin, particularly located along the southern boundary of the domain. 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 < 3 % (< 13.8 km^2) of the snow covered area.
- 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, 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 0.2 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

8.a.



8.b.

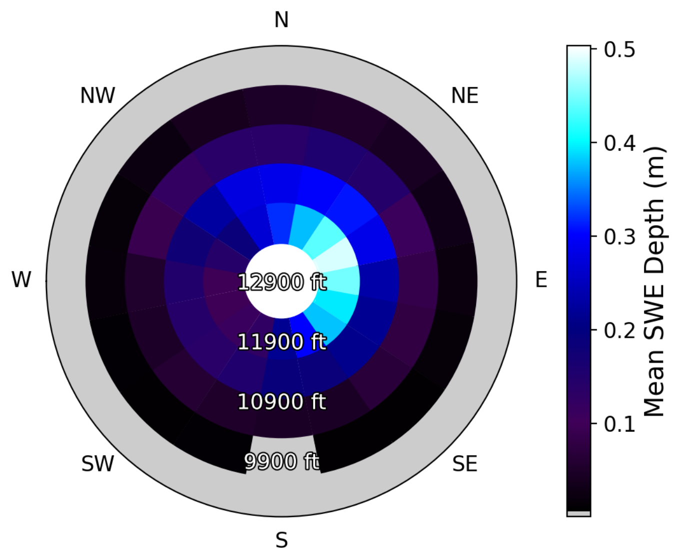
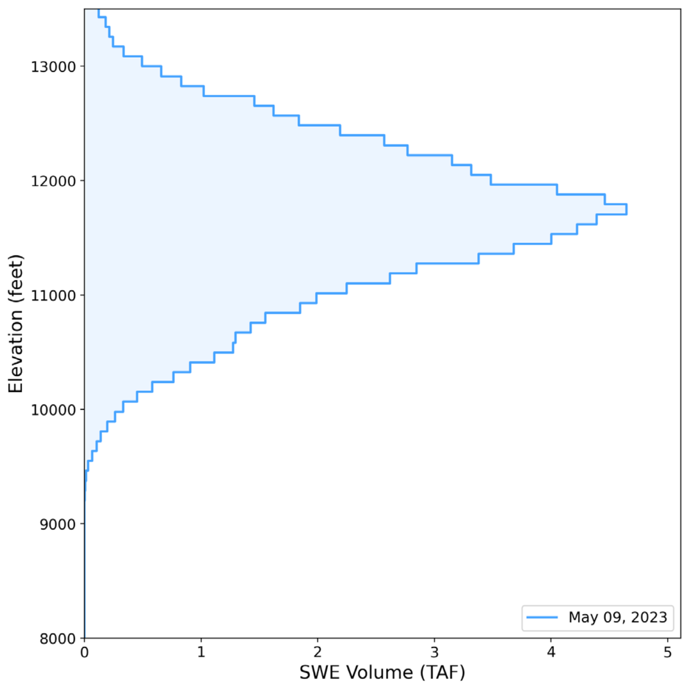


Figure 8.a. & 8.b. SWE volume (TAF) and depth (m) by aspect and elevation for the May 9 survey.

9.a.



9.b.

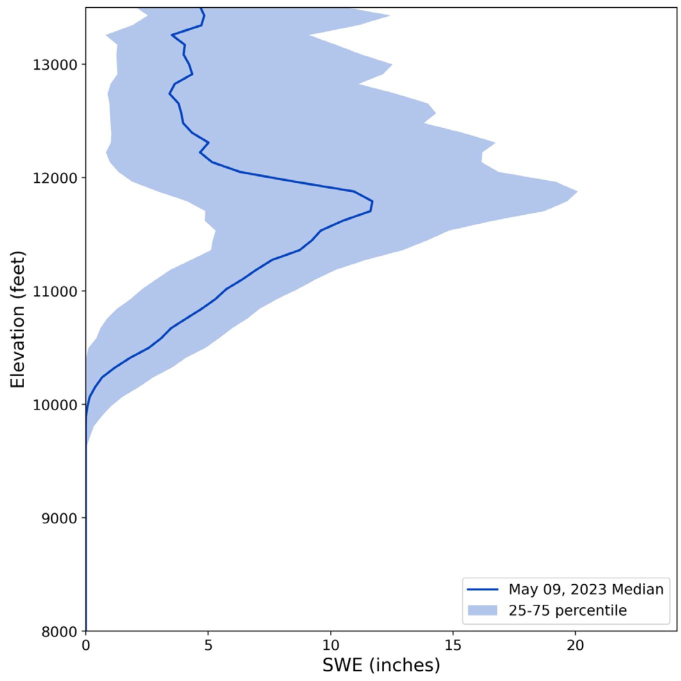


Figure 9.a. Distribution of SWE volume (TAF) across elevations for the May 9 survey. 9.b. Distribution of SWE depth (in) across elevations; solid line represents median SWE depth (in), lighter color bands represent the 25th to 75th percentile.