ASO Survey Report

St. Vrain & Lefthand Basins, CO

Survey Date: May 21, 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.

ST. VRAIN & LEFTHAND BASINS
MAY 21, 2023 SURVEY

Survey Date: May 21, 2023
Survey # of Water Year 2023: 1
Report Delivery Date: May 24, 2023

Full basin SWE: 67 ± 4 TAF
Estimated snowline: 9400 feet

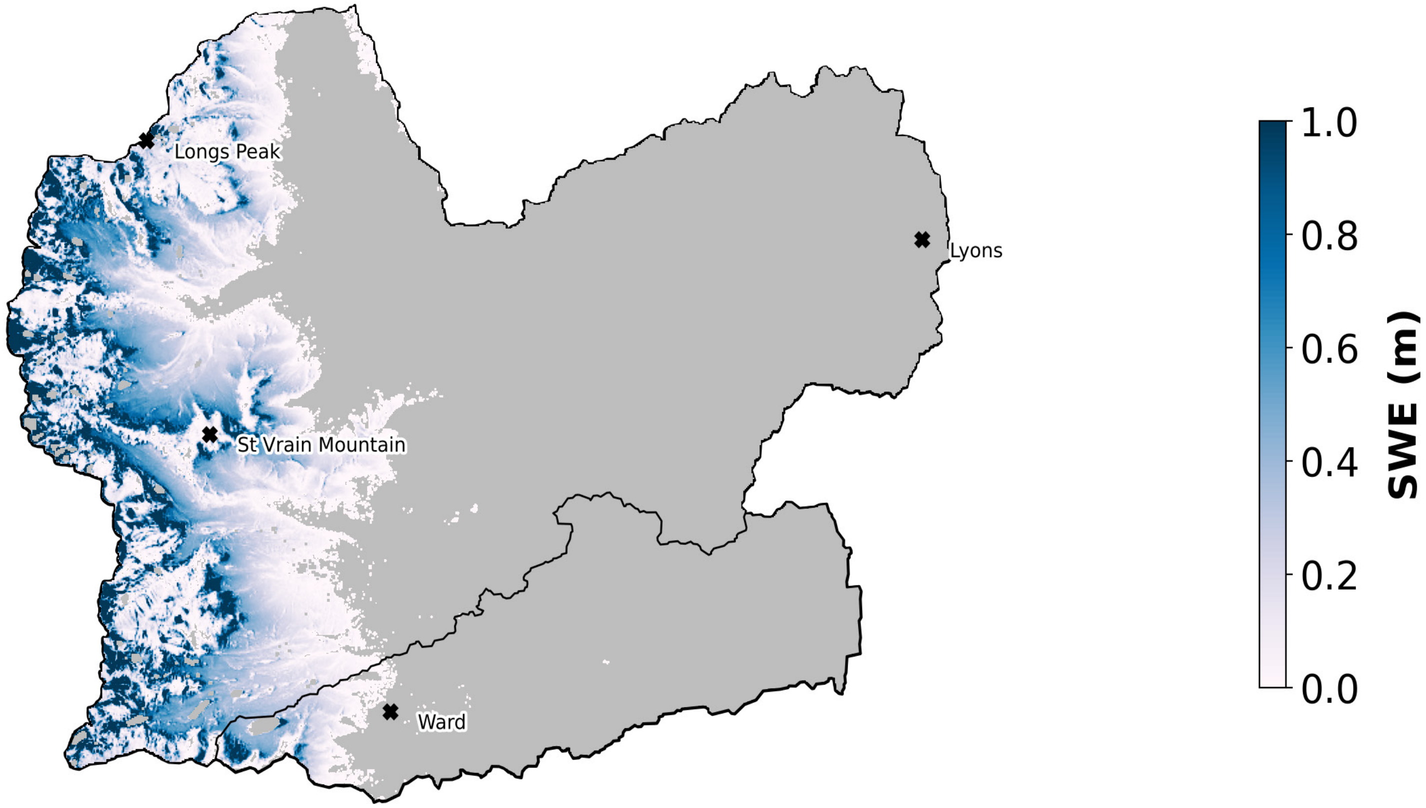


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the full St. Vrain & Lefthand basins and subbasins for the current survey.

Basin	Estimated SWE (TAF) May 21
St. Vrain & Lefthand Basins	67
Uncertainty Range	*63 - 71*
Lefthand Creek	2.2

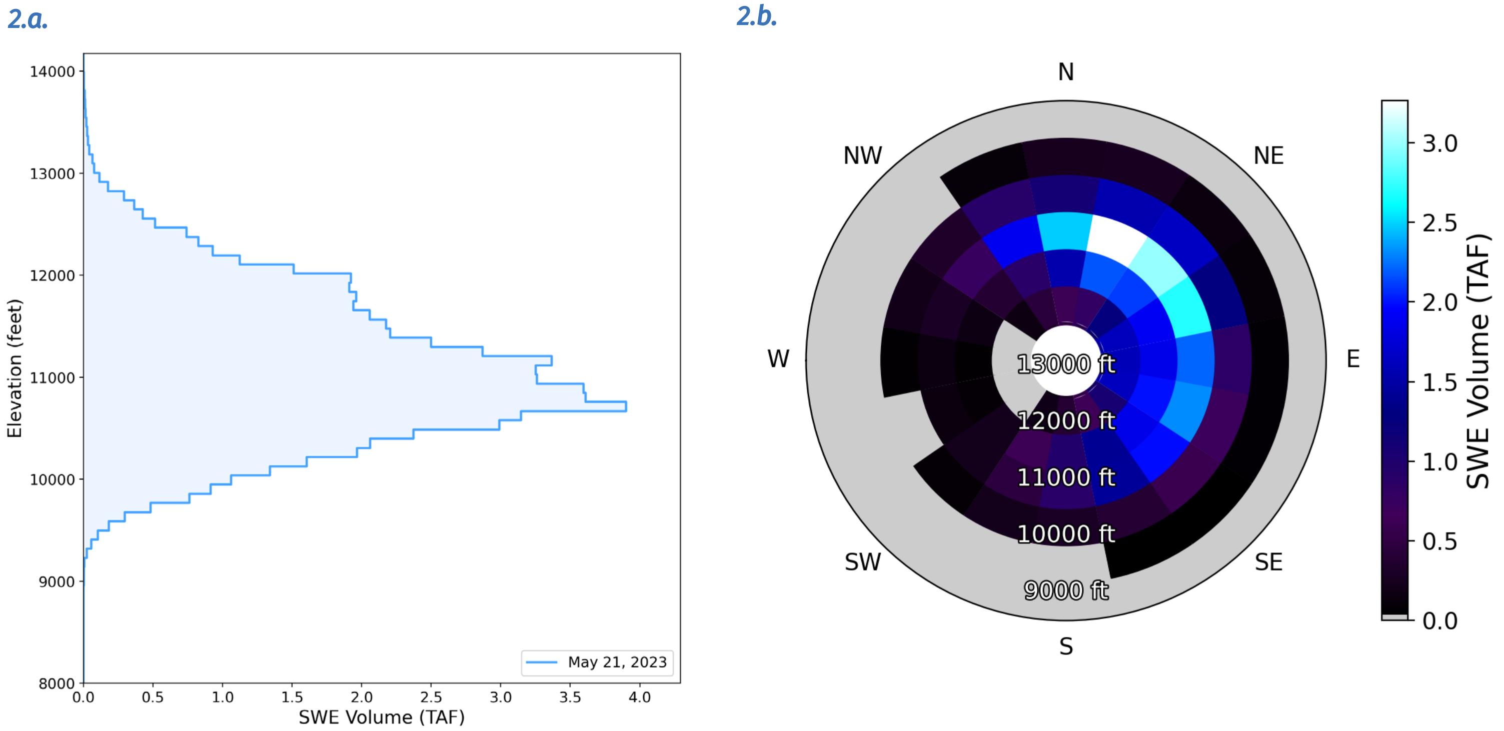


Figure 2.a. *Distribution of SWE volume (TAF) across elevations.* ***Figure 2.b.*** *Distribution of SWE volume (TAF) by aspect and elevation for the May 21 survey. See* ***Figure 7*** *and* ***Figure 8*** *for more descriptive plots.*

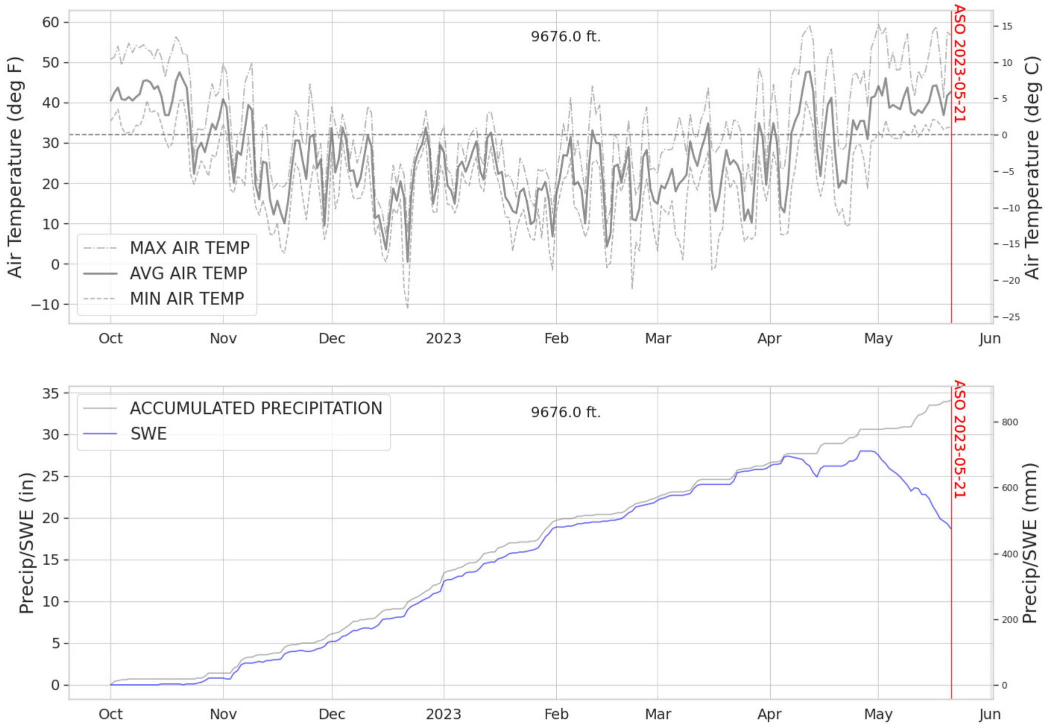


Figure 3. *Daily meteorological conditions at Sawtooth (1251) (elevation 9676 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records 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. Beginning in late December, much of the northern Front Range saw snow accumulation outpace the median, and remain above normal until an early peak in April. Recently, the extended unsettled weather has kept SWE values at the SNOTEL sites bouncing along just below the peak value.
- A strong, southwesterly wind event on April 3rd deposited a substantial dust load over most of the Colorado mountains, including the St. Vrain & Lefthand basins. Although covered intermittently by recent snowfall events, this dark dust layer has been enhancing snowmelt and runoff rates for the past month, contributing to faster-than-normal ablation at many Front Range stations.

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 St. Vrain & Lefthand Basins, the mean snow depth uncertainty was 0.7 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 0.011 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)
Sawtooth	9620	5/21/23	94	96	2
Wild Basin	9560	5/21/23	46	46	0
Copeland Lake	8573	5/21/23	0	0	0
				Mean	0.7

Evaluation of snow density

Physically based model - iSnobal

- As this is the first survey of the season in the St. Vrain & Lefthand basins, the iSnobal model is only now being updated with data from the May 21st airborne survey.
- The mean spatially distributed snow density from the open-loop model on May 21st is 483 ± 20 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 St. Vrain & Lefthand basins, we expanded our density analysis to include nearby sites in the nearby Colorado River at Windy Gap, Big Thompson, Poudre, and Boulder Creek watersheds.
- The mean snow density reported on May 21st from six locations (**) was 442 ± 38 kg/m^3, with a range of 395-505 kg/m^3. (** Sawtooth, Wild Basin, Bear Lake, Long Draw Reservoir, Lake Irene, and University Camp SNOTELs.)
- Due to an inconsistency in the reported depth on the day of the airborne survey, we used the May 20th Lake Irene density value for this analysis.

Snow course measurements

- The May snow course measurements were available at the time of processing, however, they were not included in our density analysis due to the amount of time since the surveys were undertaken (See **Figure 4**.)

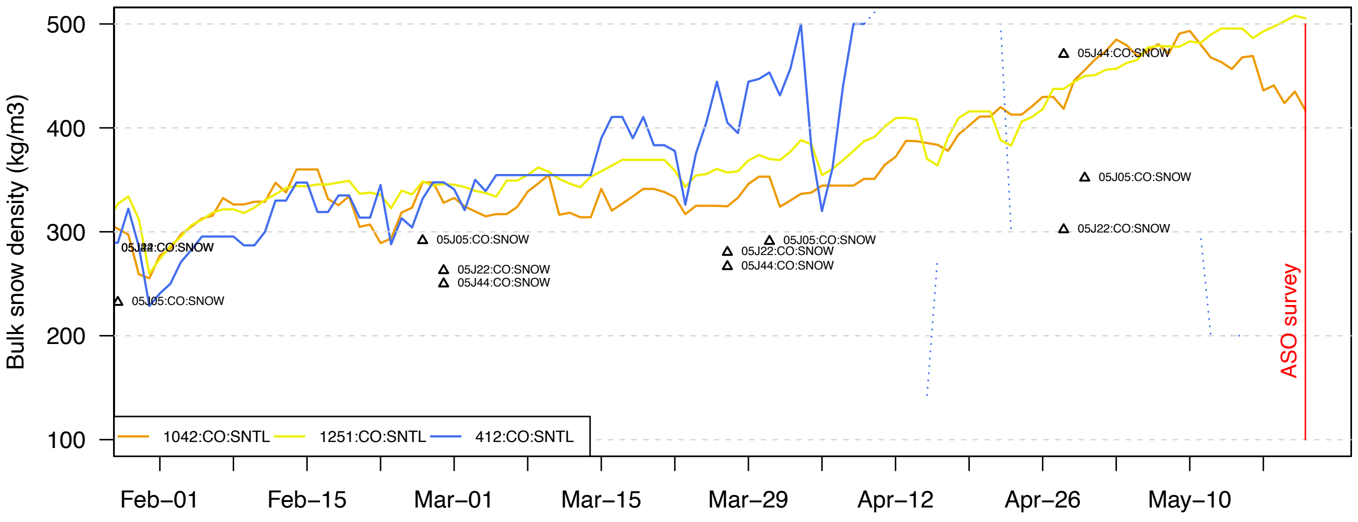


Figure 4. *Daily snow density timeseries at automated sensor locations in the St. Vrain & Lefthand Basins and neighboring basins. (Data source: NRCS)*

Model evaluation & snow density adjustment

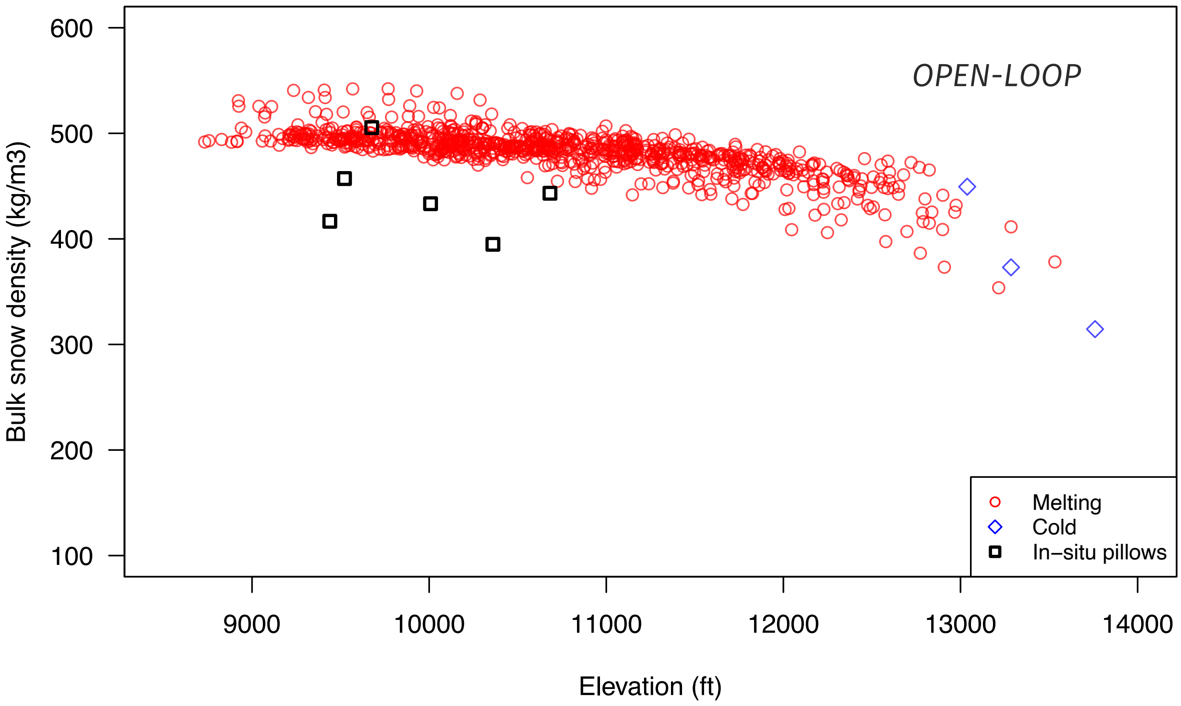
- The mean modeled snow density of 483 ± 20 kg/m^3 is higher than the in-situ guidance of ~440 kg/m^3.
- The distribution of modeled snow density with elevation (**Figure 5a**) suggests that the model is overestimating up to ~10600 ft (limited by the in-situ representation).
- At lower elevations (< 10600 ft), the model is reporting a mean bulk density of 495 kg/m^3 which is ~11% higher than the in-situ mean of ~440 kg/m^3 at the same elevations.
- To address these overestimation biases in the model, the bulk densities were reduced using a constant 9% reduction of bulk density. We applied this reduction across all elevations to preserve the model distribution with elevation and snow depth.
- Given the spread of in-situ guidance ~ 395 - 450 kg/m^3 we did not snap the adjustment to match the in-situ measurements, but more guided the model adjustment towards the in-situ measurements.
- The resulting mean-adjusted snow density across the basin was reduced to 440 ± 18 kg/m^3, and the mean in lower elevations (< 10600 ft) was reduced to 441 kg/m^3.
- After adjustment, the bias in snow density calculated using point-to-point comparisons at in-situ locations was reduced to -6 kg/m^3 from +38 kg/m^3 (model open-loop).

- Using the open-loop model density, the full basin SWE was 74 TAF and after snow density adjustments were applied, the basin SWE estimate was reduced to 67 TAF. The snow density adjustments decreased the basin SWE estimate by 9%.
- The in-situ measurements are constrained to elevations < 10600 ft, leaving higher elevation snow largely unconstrained. To address the remaining uncertainty in bulk snow density at high-elevation we have generated two snow density scenarios. In Scenario H, we adopt a density reduction of 4.5% (a smaller reduction than what was described above), and increase densities above 10600 ft by 4% - towards 440 kg/m^3. In Scenario L, we adopt a reduction of 11% (a larger reduction than what was described above), but reduce densities above 10600 ft by 4% - towards 408 kg/m^3.
- The resulting full basin SWE outcome for these scenarios were 73 TAF and 64 TAF respectively, and suggests that the basin SWE is sensitive to uncertainty in the snow density in the order of up to 3-8 TAF (or up to ~9% 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.

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/m^3)	SWE (TAF)	Description
Adjusted density	**439**	**67**	**Adjusted density map & ASO depths**
M3W (May 21 value)	482	87	Modeled SWE
Open-loop	482	74	Modeled density map and ASO depths
Scenario L	417	64	ASO depths + partially adjusted snow density with an 11% global density reduction and an additional 4% reduction applied > 10600 ft
Scenario H	474	73	ASO depths + partially adjusted snow density with a 4.5% global density reduction and an increase of 4% > 10600 ft

5.a.



5.b.

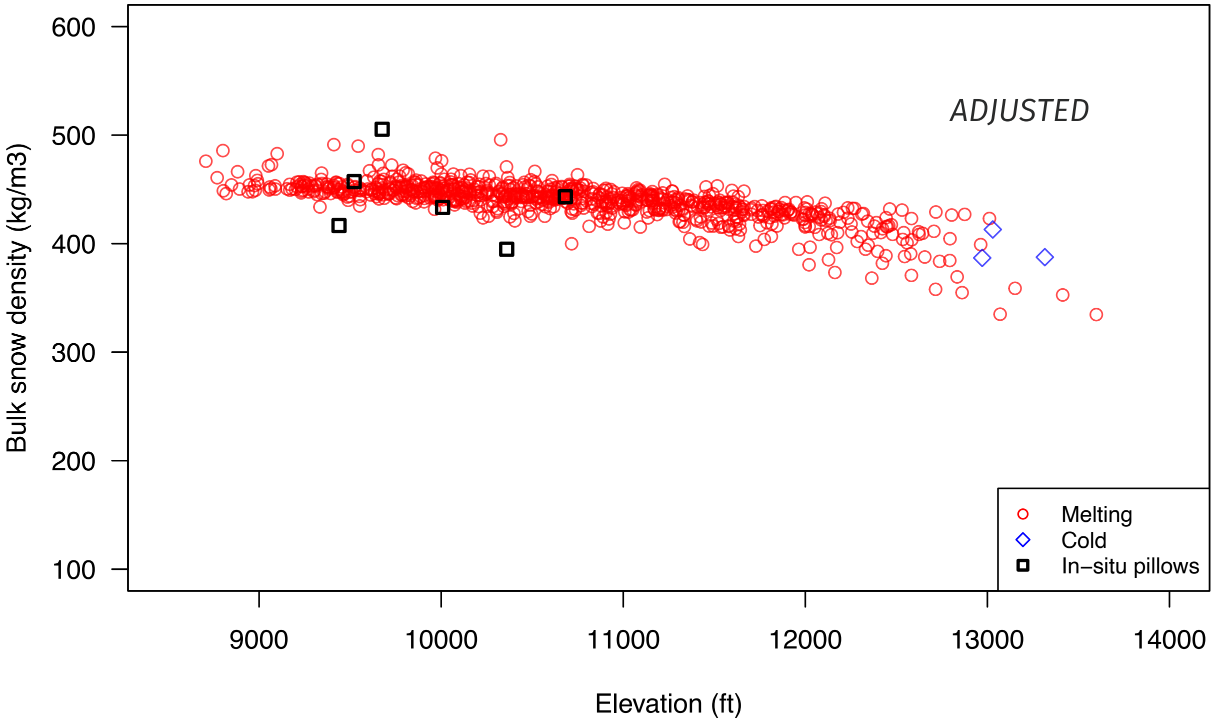


Figure 5. *Observed and modeled bulk snow density (kg/m³) by snow depth (m) for* ***a.*** *open-loop and* ***b.*** *adjusted densities. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

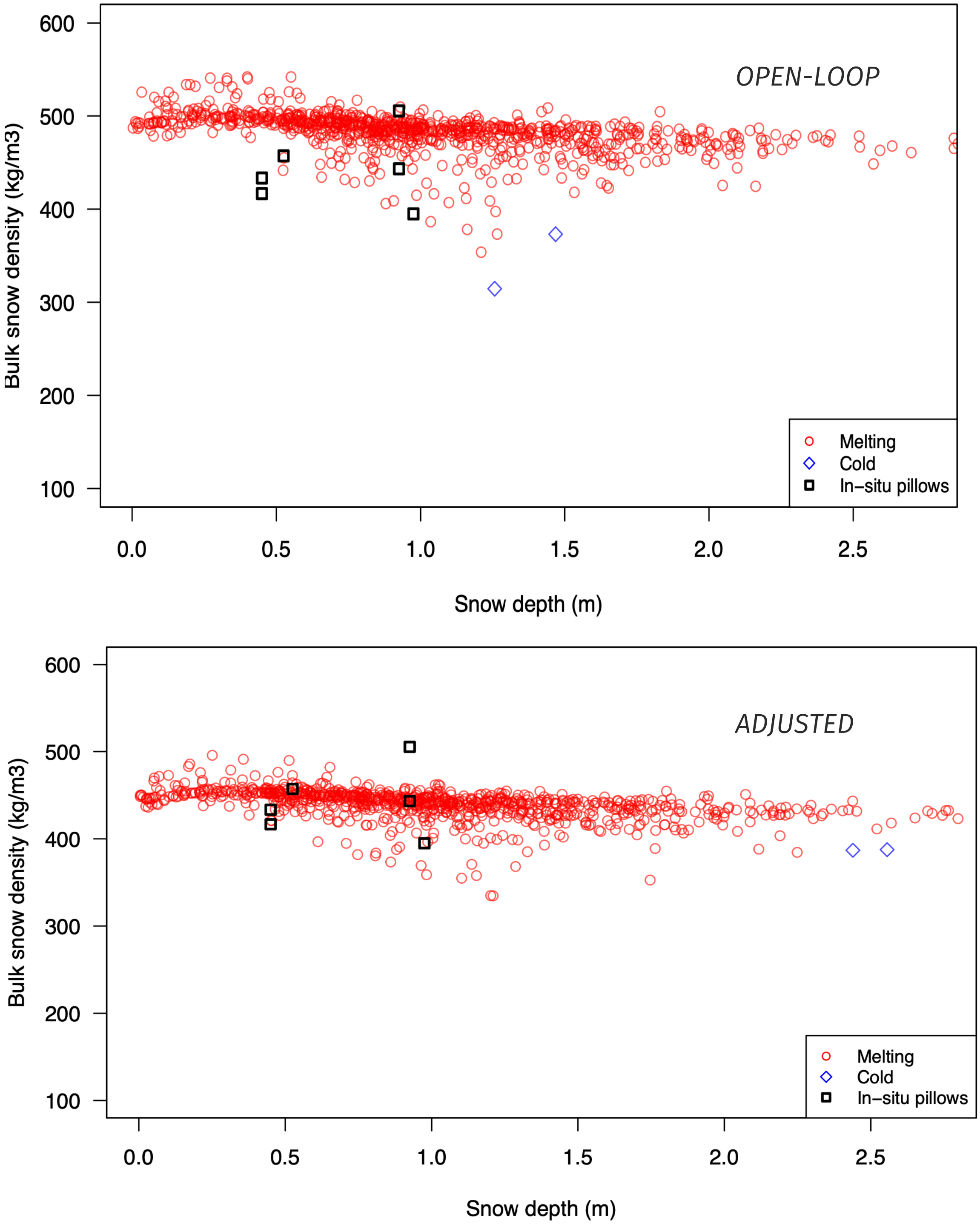


Figure 6. *Observed and modeled bulk snow density (kg/m^3) by snow depth (m) for a. open-loop and b. adjusted densities. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

Additional data/ remarks

Snow albedo

- Well-illuminated survey targets with clear skies above the flight altitude are required for robust albedo retrieval. Challenging weather conditions in the Front Range basins in recent weeks have pushed us to conduct operations very early in the morning, when cloud cover is minimal. The May 21st survey over the St. Vrain & Lefthand basins was conducted 4:30 - 8:30am MDT, under poor illumination conditions. As such, we cannot produce albedo products for this survey.

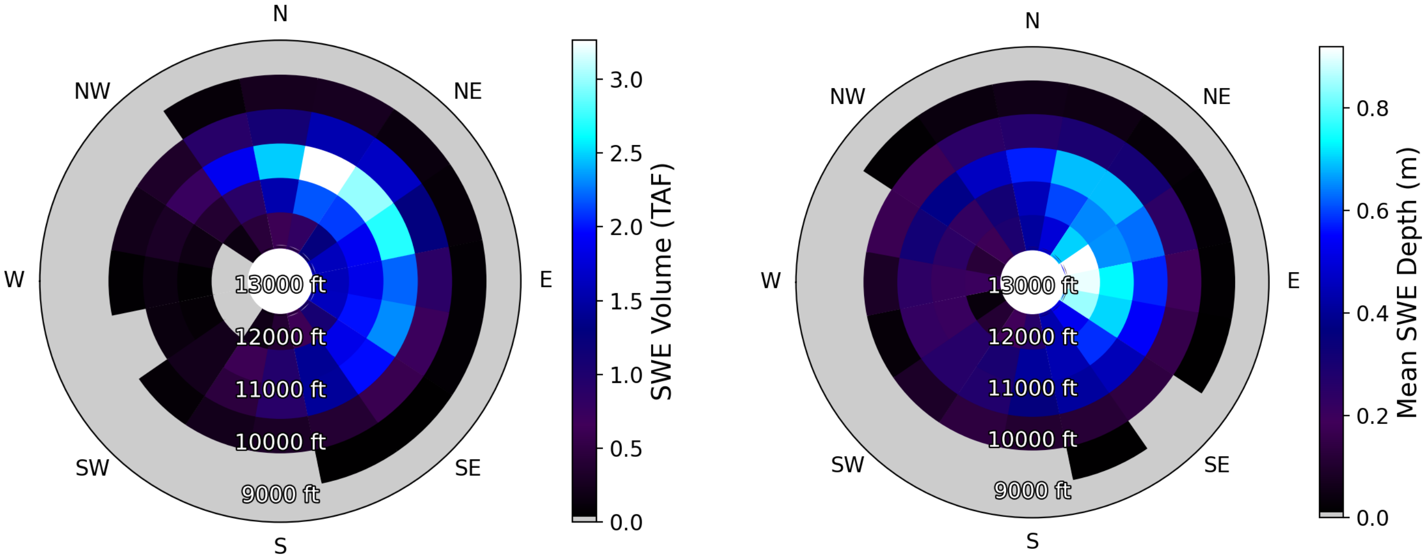
Clouds

- 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 21st survey of St Vrain & Lefthand basins, we encountered several patches of atmospheric moisture across the basin, particularly located in the northwest corner of the domain. Flight line overlap and penetration through atmospheric moisture/clouds enabled us to retrieve a snow depth signal in many of these areas. Remaining areas of the basin that were masked were mostly over partially covered snow areas. These patches were estimated to mask < 0.2% of the basin (1.09 km^2); and an even smaller portion of the snow-covered area.
- As the clouds masked partially covered snow, we did not apply backfill to the snow depth or SWE maps. Instead we estimate the potential SWE that has been masked by atmospheric moisture/clouds to be 0.16 TAF. This value is not included in our estimate of total basin SWE on the front page, but is used in our uncertainty estimates.

Other

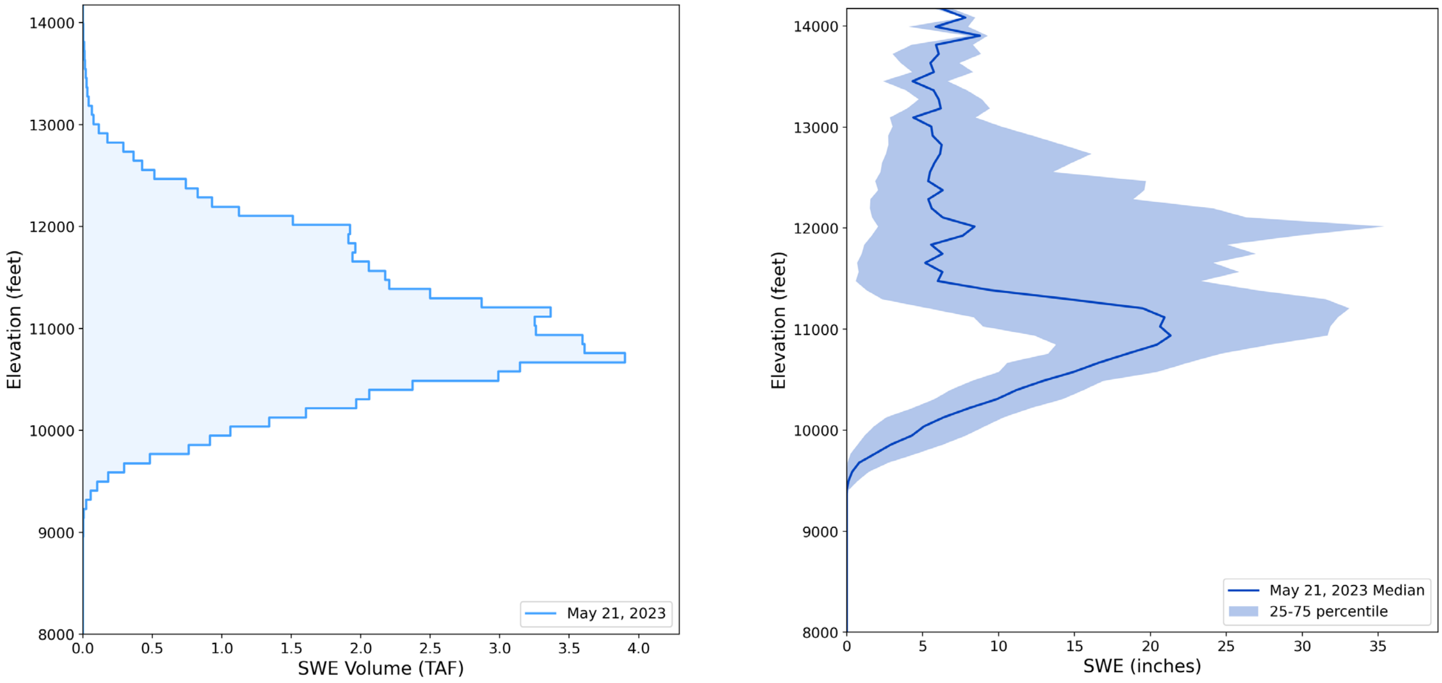
- Please refer to the text files included in the data package for SWE volume per elevation band and other summary statistics.

Additional data / remarks


7.a.

7.b.

Figure 7.a. & 7.b. SWE volume (TAF) and depth (m) by aspect and elevation for May 21 survey.


8.a.

8.b.

Figure 8.a. Distribution of SWE volume (TAF) across elevations for the May 21 survey. 8.b. Distribution of SWE depth (in) across elevations; solid line represents median SWE depth (in), lighter color bands represent the 25th to 75th percentile.