SnowEx 2021 SWE Report

Cameron Pass Site, CO

Survey Date: March 19, 2021

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: March 19, 2021
Report Delivery Date: November 10, 2023

Full site SWE: 11.3 ± 0.6 TAF

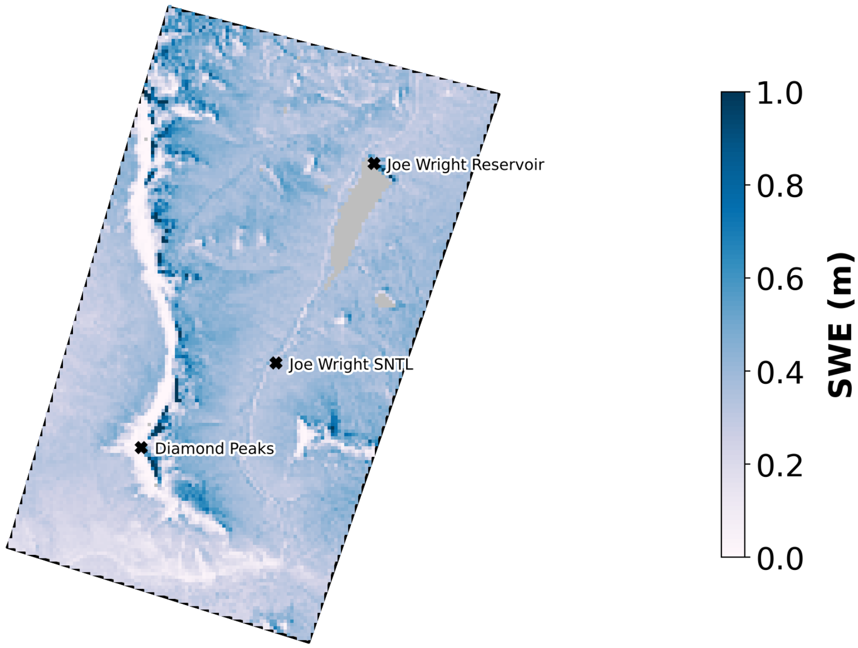


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the Cameron Pass site.

Site	Estimated SWE (TAF) March 15
Full Site	11.3
Uncertainty range	*10.8 - 11.9*

2.

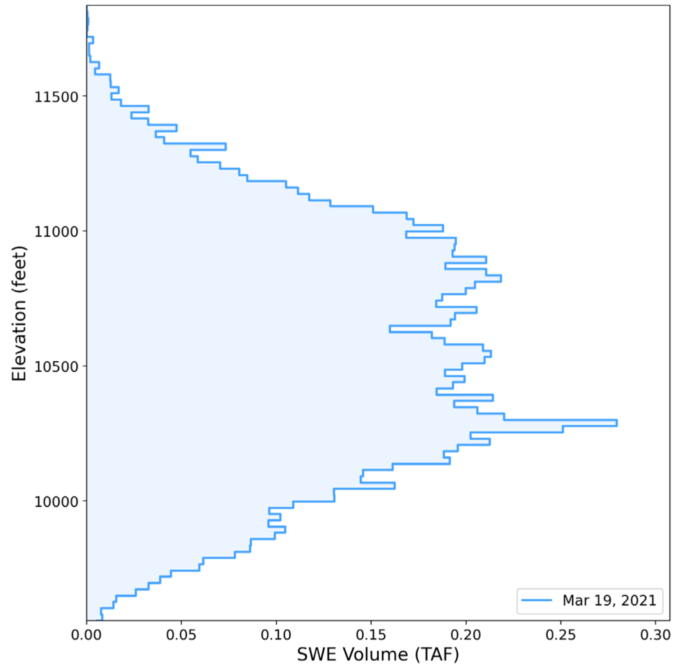


Figure 2. *Distribution of SWE volume (TAF) across elevations for the March 19 survey. See* ***Figure 7*** *for more descriptive plots.*

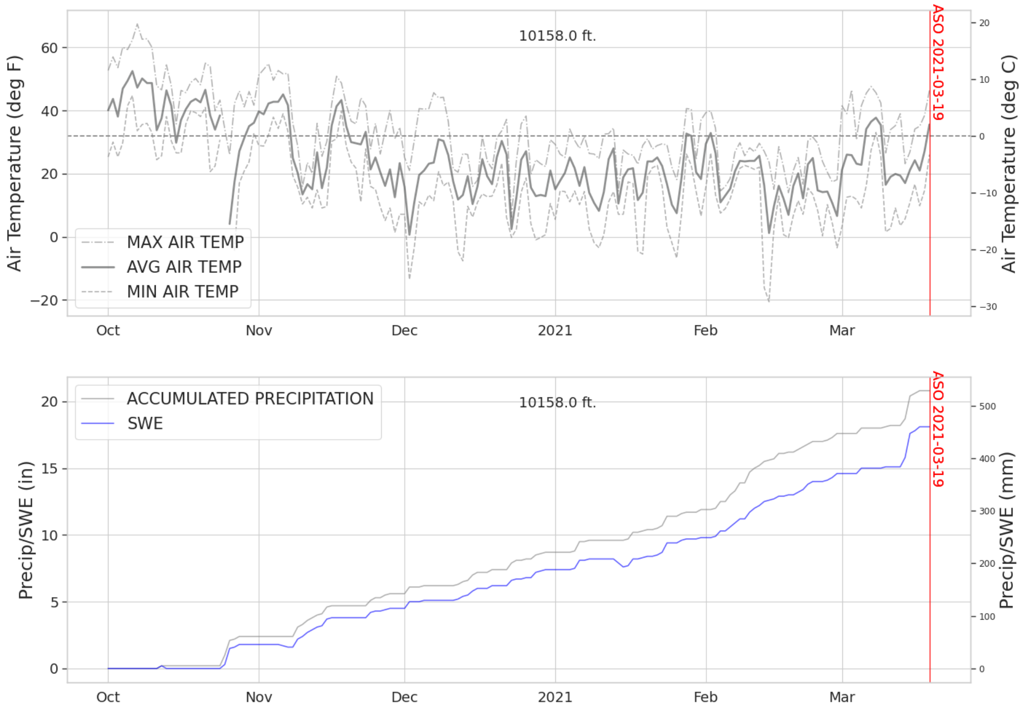


Figure 3. *Daily meteorological conditions at Joe Wright (elevation 10158 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.*

Summary of background conditions

- The 2021 snow season in the Cameron Pass site began with regular snowfall events commencing in late October 2020.
- The 2021 SWE series followed slightly below the 40-year median SWE from early November until a large snowfall event beginning March 14th boosted the snowpack to approximately the median value. The SnowEx flight was conducted shortly thereafter on March 19th, 2021.

Evaluation of ASO snow depth measurements

Point-to-point comparison of in-situ snow depth 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 the known and trusted SNOTEL station location in Cameron Pass, the snow depth difference was -4 cm. SnowEx in-situ measurements in Cameron Pass were conducted on March 19th, 2021, on the same day as the airborne survey. The standard deviation of biases determined in the relative registration step indicates a snow depth uncertainty of 1.8 cm.

Table 2. Comparison of ASO and snow pillow snow depths. Note: ASO long-term depth uncertainty is ± 5 cm. Snow depth comparisons to field-measured snow pits and courses are not included in this table; see discussion below.

Site ID	Elevation (ft)	Date	Site Depth (cm)	ASO Depth (cm)	Depth Difference (cm)
Joe Wright SNOTEL	10098	2021-03-19	168	164	-4

*Note: Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the site. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and enforces snow depth accuracy throughout the site. At 3 m resolution, the standard deviation of snow depth distribution was 0.028 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 1 cm.

The airborne lidar data for this survey were collected by a third-party contractor using parameters different from conventional ASO surveys. During the time of survey, March 19th, 2021, the target area at Cameron Pass was almost completely snow covered with limited bare surfaces to use for the standard ASO relative registration procedure, which is designed to ensure homogenous snow depth accuracies throughout the domain. The relatively narrow road that traverses from the NE corner to the SW corner of the target domain and a ridgeline in the west were the only targets available for the relative registration of snowoff and snow-on elevation data sets, and as such we do not have relative registration control across the full target area. Though geographically constrained spatial distribution of registration control may be typical for more conventional topographic lidar surveys, for snow depth mapping it makes reliable assessment of the snow depth accuracy more difficult. We expect that this may introduce uncertainties into the snow depth values on the order of several cm.

The SnowEx field campaigns collected snow pit profiles of depth, density, and SWE within each field site. The field measurements were not specifically designed for assessment of lidar snow depth retrievals. Several sources of uncertainty make these pit data unsuitable for lidar snow depth comparison while remaining valuable for the site-wide snow density estimation. Pits were sampled in the days before and/or after the flight acquisition, which due to ongoing compaction will result in different depths from that at the time of the flight. Georegistration of the snow pits is uncertain (especially in forested areas), often placing the measurement location in the wrong 3m pixel. The precise location within the pit of the depth measurement is unknown, as is the contribution of fine-scale surface undulations to the ruler placement and depth measurement. Disturbance of the snow from pit digging and refilling can also contribute to (sometimes large) differences in depth from the airborne measurement where the pit measurements were conducted prior to the lidar flight. As such, we direct data users to the post-registration histogram of residual biases at bare targets to indicate the uncertainty in snow depth throughout the domain, and to the SNOTEL depth comparisons as a secondary confirmation of the snow depth accuracies.

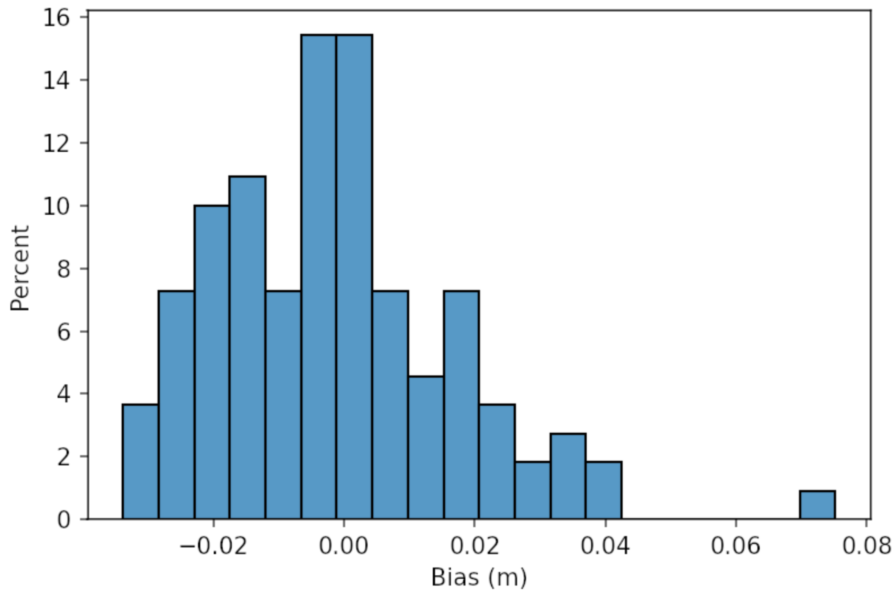


Figure 4. Histogram of residual biases after relative registration of the snow-off and snow-free elevation data sets. The median bias is -0.002 m and the standard deviation is 0.018 m.

In-situ measurements

Field collections

- ASO field team did not conduct field work coincident with this survey.
- SnowEx field teams conducted fieldwork on March 18th.
- The mean snow density from a 1.64 m snow pit at 9800 ft near Cameron Peak was 285 kg/m³.
- The mean snow density from a 1.08 m snow pit at 10200 ft near Michigan River was 226 kg/m³.

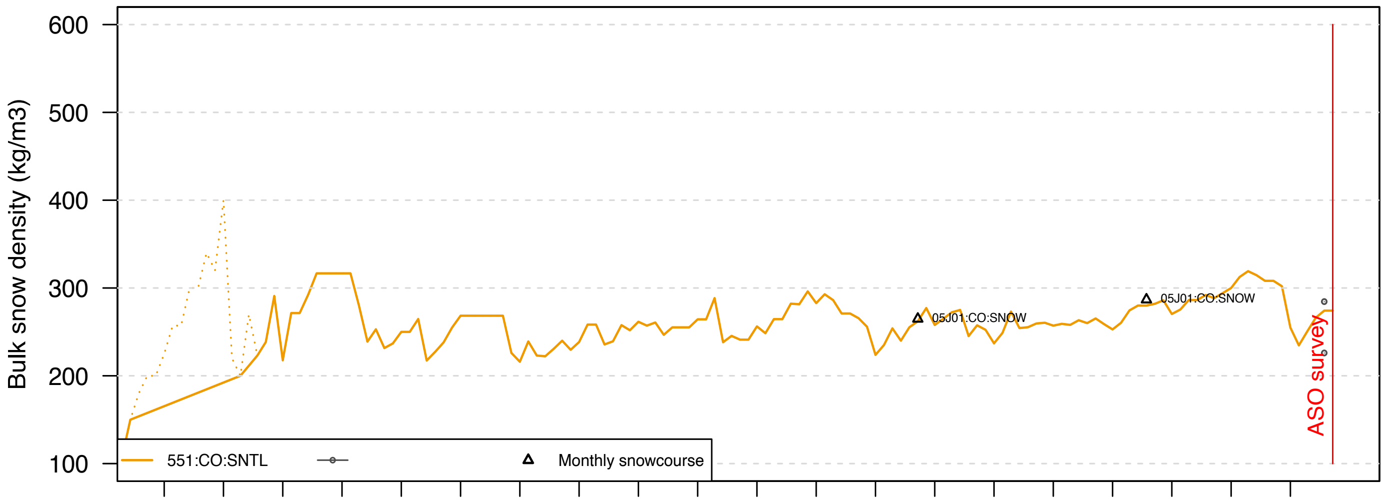


Figure 5. Daily snow density timeseries at Joe Wright SNOTEL. (Data source: NRCS).

Sensor measurements

- The snow density reported from the Joe Wright SNOTEL site on March 19th was 274 kg/m³.

Snow course measurements

- The March snow course measurements were not available for this airborne survey at the time of processing.

Density evaluation

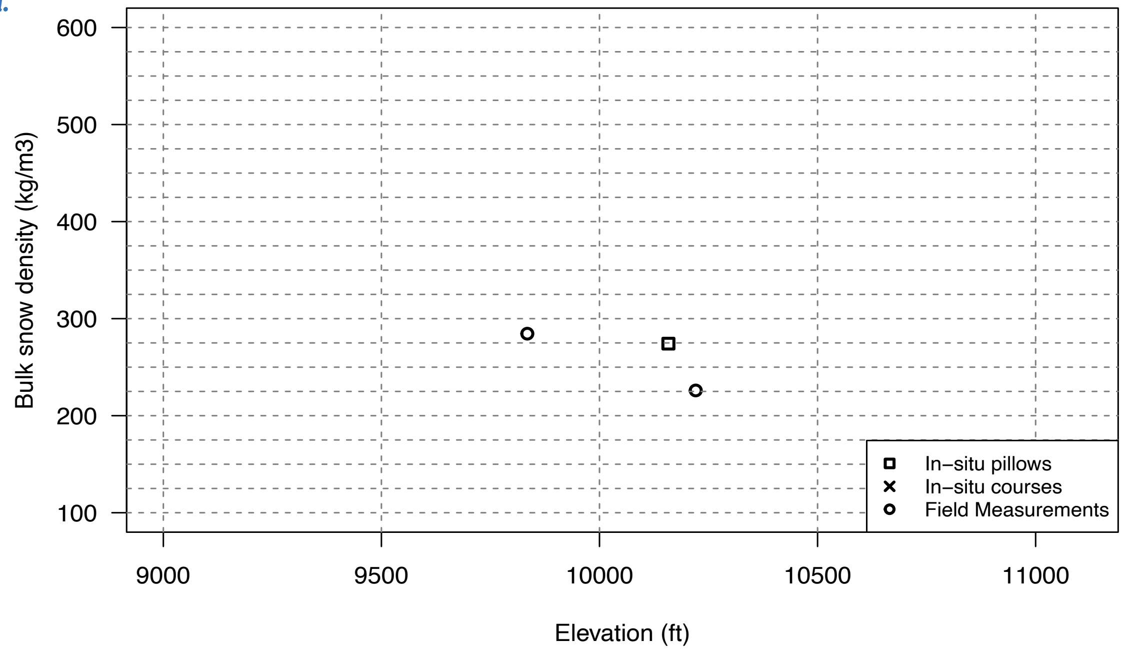
- The in-situ measurements span a range of values between 226 - 274 kg/m³, and suggest a scalar based density map where density is correlated with depth. The in-situ measurements were sampled coincidently with the airborne survey and are weighted heavily in our evaluation. There is some remaining uncertainty in snow density in the lower and upper elevations and snow depths.
- To address this uncertainty in bulk snow density, we have generated two snow density scenarios. In Scenario H, we increased the density map globally by approximately 4.5% - towards a value of 272 kg/m³. In Scenario L, we decreased the density map globally by approximately 4.5% - towards a value of 249 kg/m³.

- The resulting full site SWE outcomes for these scenarios were 11.9 TAF and 10.8 TAF respectively, and suggest that the site SWE is sensitive to uncetainty in the snow density in the order of approximately 4.5% of the total site SWE. These scenarios span beyond the full range of the in-situ measurements and should be interpreted as guidance on sensitivity to snow density rather than equally probable SWE 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 ASO 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
ASO	364	11.3	ASO depths
Scenario L	345	10.8	Decreased density map globally by 4.5% + ASO depths
Scenario H	380	11.9	Increased density map globally by 4.5% + ASO depths

6.a.



6.b.

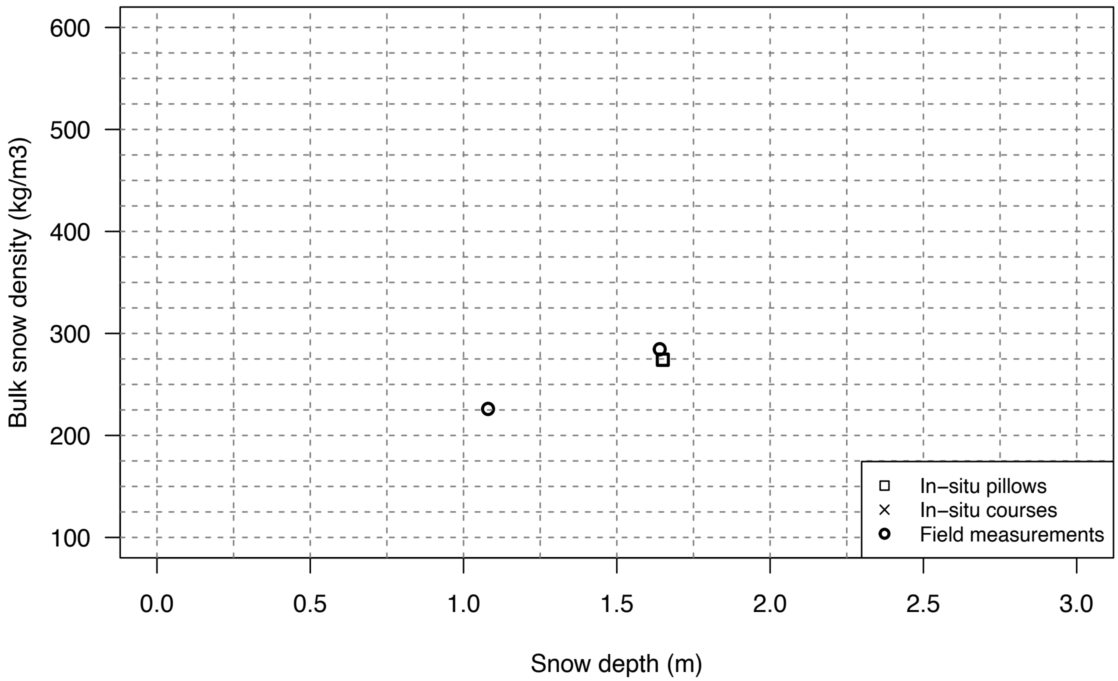
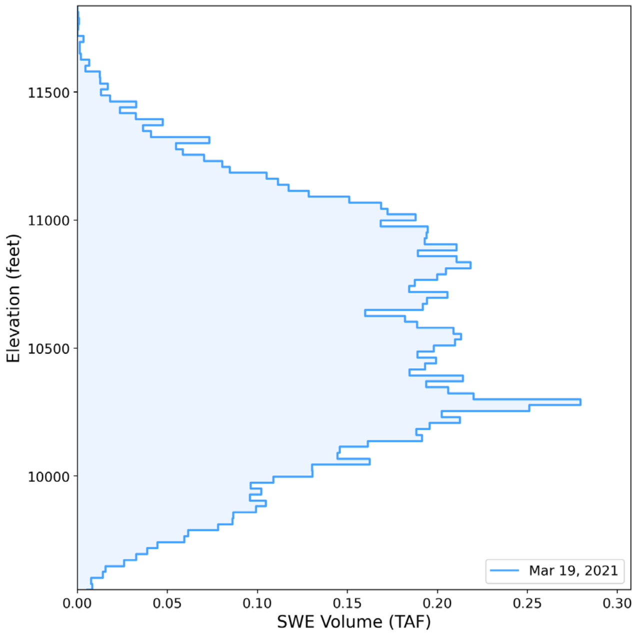


Figure 6. Observed bulk snow density (kg/m³) by a. elevation (ft) and b. snow depth (m). The horizontal axes on these plots span the elevation and snow depth ranges across the full Cameron Pass target area.

Additional data / remarks

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

7.a.



7.b.

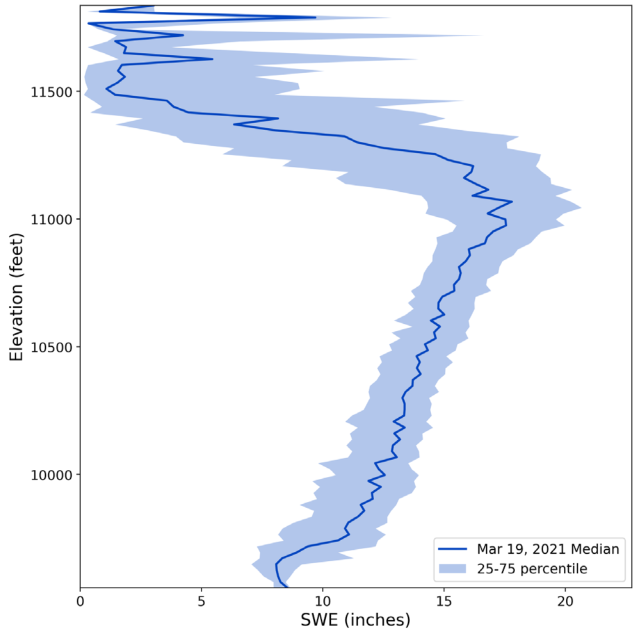


Figure 7. Difference plots of SWE volume (TAF) and depth (in) across elevations. 7.a. Distribution of SWE volume (TAF) across elevations. 7.b. Distribution of SWE depth (in) across elevations; solid lines represent median SWE depth (in), lighter color bands represent the 25th to 75th percentiles.