Answer to comments

Evaluation of snow depth retrievals from ICESat-2

using airborne laser-scanning data

tc-2022-191

We thank the three reviewers for their detailed comments on the article. We took into account several major comments which led to simplifying the manuscript. We removed some parts of the work which did not seem relevant anymore. In detail, we now only present the snow depth derived from the elevation models at 15 m. We removed the snow depth derived from ICESat-2 only data. We also simplified the presentation of the results by only presenting snow depth derived from ATL06 h_li, excluding the previous comparison between h_mean and h_li elevations. We detail these choices and modifications in detail below.

RC1: 'Comment on tc-2022-191', Anonymous Referee #1, 08 Nov 2022

There has been increasing interest in using ICESat-2 data for snow depth measurements in mid-latitude locations. This manuscript analyzes the ICESat-2 ATL06 product for its ability to retrieve snow depth in the Tuolumne Basin of California. ATL06 snow-on data is compared to snow-off DEMs generated from ATL06, the Airborne Snow Observatory, Pleiades, and the Copernicus-30 InSAR dataset. The authors found that snow depths were generally most accurate when comparing ICESat-2 to ASO or Pleiades, though accuracy deteriorates with increasing slope.
I do have a concern with the broader narrative that I think needs to be addressed. Early in the text, it is mentioned that current airborne and spaceborne methods of retrieving snow depth suffer from limited spatial and temporal coverage, and ICESat-2 is presented as an alternative. However, the results make it clear that deriving snow depth from only ICESat-2 data is currently impractical, so ICESat-2 snow depth coverage is limited by the same issues as airborne/spaceborne methods. So, my questions are: currently, what are the advantages to using ICESat-2 for snow depth retrievals? Will we get to a point where we can reliably use the "IS2-IS2 DEM" method on a broader scale? I would be very interested to see the authors' viewpoints.

We now comment on the advantage of this approach compared to the series of DEM approach:

"The advantage of combining ICESat-2 with external DEMs to retrieve snow depths compared to times series of DEMs, is that the former method only requires a single DEM to then retrieve snow depth for all further ICESat-2 data which are freely available. On the contrary, the acquisition of a time series of DEMs requires costly and repeated airborne campaigns (Painter et al., 2016) or satellite tasking (Deschamps-Berger et al., 2022)."

Agreeing with a comment from reviewer 2, we removed the presentation of the IS2-IS2 results. However, based on our experience, we added a comment on the possibility of using ICESat-2 data only in discussion:

"ATL06 snow-off segments might be used as snow-off elevation reference. This would prevent mixing various sources of dataset and allow relying solely on free, open access data. However, in the three years of the study period, only 2% (25 km²) of this mid-latitude

basin were observed without snow (Figure S11). Assuming the 8.2 km² y-1 coverage rate remains steady, more than 50 years will be needed to cover half of the basin. Besides, this rate might decrease in the future as more and more ATL06 segments will be redundant and the proportion of areas seasonally snow-covered to be mapped will increase. Thus, we do not foresee the possibility to map snow depth out of the polar regions with ICESat-2 data only. At best, it might be possible to retrieve snow depth at a few points using a method of interpolation at the crossing points of tracks (Moholdt et al., 2010). More overlapping segments should be available in the Arctic and Antarctica thanks to the repeated orbits in the polar regions."

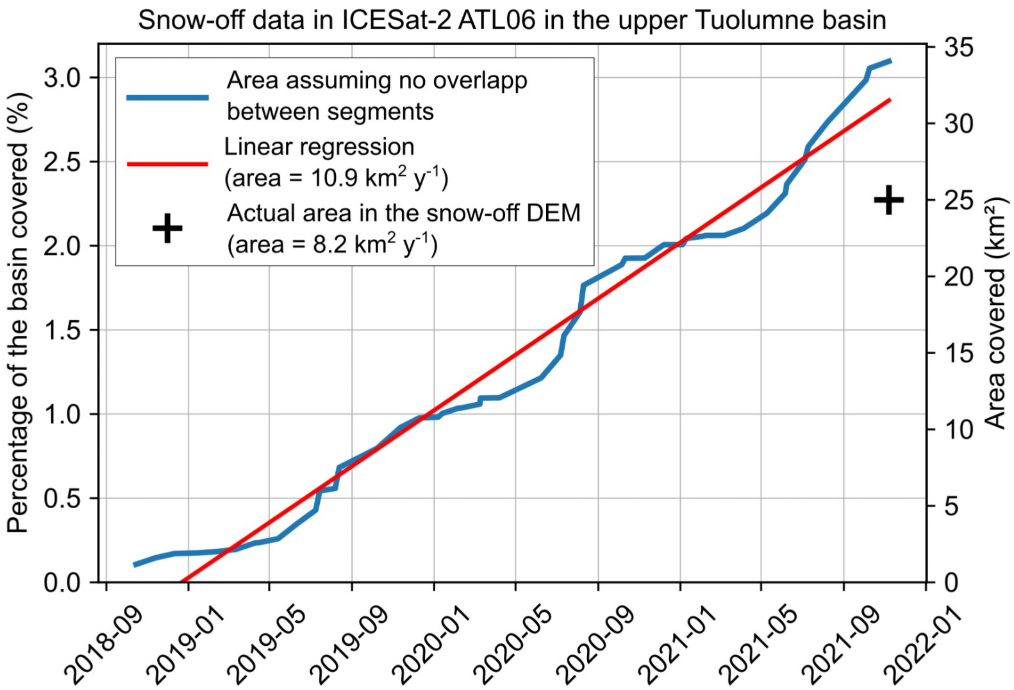

Figure S11. *Surface without snow available in ATL06 since the start of the acquisition (blue) and the related linear regression (red). Each segment of ATL06 is assumed to cover a square of 15 m by 15 m. Segments are assumed to not overlap which is an acceptable assumption for the first years of acquisitions.*

Another concern: A paper was recently published by Enderlin et al., (2022) that covers similar topics to this study. Namely, they conduct an investigation of ATL06/08 data over mountainous regions, and they found snow depth uncertainties similar to this study. I do not think a full comparison is necessary, but it would be important to highlight how this study differs from Enderlin et al., (2022) (or builds upon it).

We read with interest the paper published by Enderlin et al. (2022) which shares similar methodology with our work. From our understanding, they could not lead a robust estimation of the uncertainty of the snow depth retrievals due to a lack of validation data. We now discuss this in the introduction (see below) and relate their findings to ours in discussion:

"Other applications have emerged, including attempts to measure snow depth with ATL08 and ATL06 (Hu et al., 2021; Enderlin et al., 2022). Hu et al. (2021) measured snow depth with ATL08 data at few points (N=16) with slopes lower than 1.5° and snowpack shallower

than 0.35 m. They suggested that this product may not be suitable for rugged topography. Enderlin et al. (2022) compared ATL06 and ATL08 elevations with reference DEMs derived from satellite photogrammetry and airborne lidar to increase the number of snow depths retrieved. ATL08 snow depth retrievals were found to be hardly reliable in mountainous terrain, in agreement with Hu et al. (2021). However, they concluded that snow depth could be measured in mountainous terrain and over a glacier with ATL06 but lacked distributed validation data to estimate the uncertainty of the retrievals."

Minor Comments

Page 1, Line 13: "…and various snow-off elevation sources, including ATL06 snow-off data and external digital elevation models."

This sentence was modified.

Page 1, Line 26: "catchment" --> "catchments"

Modified.

Page 2, Lines 61-62: I suggest combining the last two sentences of this paragraph.

Modified these two sentences for:

"However, the orbit of ICESat-2 was designed to increase the spatial density of the tracks coverage for biomass applications in the mid-latitudes. Thus, outside of the polar areas, the tracks are offset and rarely perfectly overlap, which precludes a straightforward approach of retrieving snow depth by differencing snow on and snow off elevations along every ICESat-2 transect."

Page 2, Line 64: "…from the ICESat-2 ATL06 product"

This sentence was deleted.

Page 3, Line 77: What do we mean by "sparse"? For instance, could we reliably obtain ATL06 data from mid-latitude snow catchments?

This term was confusing in this sentence. We deleted it. We now more clearly comment on ATL06 availability in glacierized areas. Availability of the data for a mid-latitude catchment is answered in the first comment of this review.

"ATL06 was primarily designed to provide elevation measurements on land ice, yet its coverage extends beyond glacier areas such that ATL06 data are available even in mountain ranges with very limited glacier cover such as the Sierra Nevada (Smith et al., 2019)."

Page 4, Lines 117-118: I assume this is supposed to be the ICESat-2 elevation, but I still suggest being specific. Also, why was a cutoff of 45° selected?

This threshold was empirically determined. We changed the formulation:

"The elevation of the DEM is extracted at the ICESat-2 point position with a spline linear interpolation scheme (scipy.interpolate.interp2d). The slope and aspect are calculated from the DEM and extracted with the same method. The slopes smaller than 10° and steeper than 45° (empirical thresholds) are excluded to prevent errors in the co-registration vector calculation (Nuth and Kääb, 2011)."

Page 4, Line 123: Just for clarity, the vertical shift is applied to the DEMs, not the ATL06 data?

Indeed. We added in the text:

"After the horizontal co-registration vector is applied, a vertical shift is applied ***to the DEM*** *based on the mode of the elevation residual distribution (Table S1)."*

Page 5, Line 139: NMAD is first introduced on Line 121, so I suggest moving this citation there.

We moved the reference (Höhle and Höhle, 2009) where NMAD is first introduced.

Page 5, Lines 141-144: Is it known if the DEM sources (ASO, Pleiades) have uncertainties over slopes and vegetation? If so, then I suggest mentioning them here.

We completed this part to mention the error in the Pléiades DEM on steep slopes and cite the articles which explain how vegetation is treated in the various dataset:

"The uncertainty of airborne and satellite laser elevations increases when the slope increases as steep slopes spread the photons return timing compared to flat terrain (Deems et al., 2013; Treichler et al., 2017). ***This holds for photogrammetry derived elevation as well, due to the strong distortion of the images in the steep slopes (Berthier et al., 2007; Lacroix, 2016). Thanks to the spatially dense photon detection of ICESat-2, the uncertainty of ATL06 only increases for slopes greater than 60° (Figure S2).*** *We evaluate the impact of slopes on ICESat-2 derived snow-depth thanks to slope maps derived from the ASO DTM. Vegetation (bushes, isolated trees, forests) is also expected to impact the accuracy and precision of the ICESat-2 derived snow depths as vegetation is handled differently in each elevation source* ***(Deems et al., 2013; Smith et al., 2019; Piermattei et al., 2019)****."*

Page 6, Line 158: "photon" --> "photons"

Modified.

Page 7, Lines 165-166: It would be nice to have a figure that shows the tree cover density across the region of interest.

We modified the figures so that Figure 1 presents the study area and shows the tree cover density:

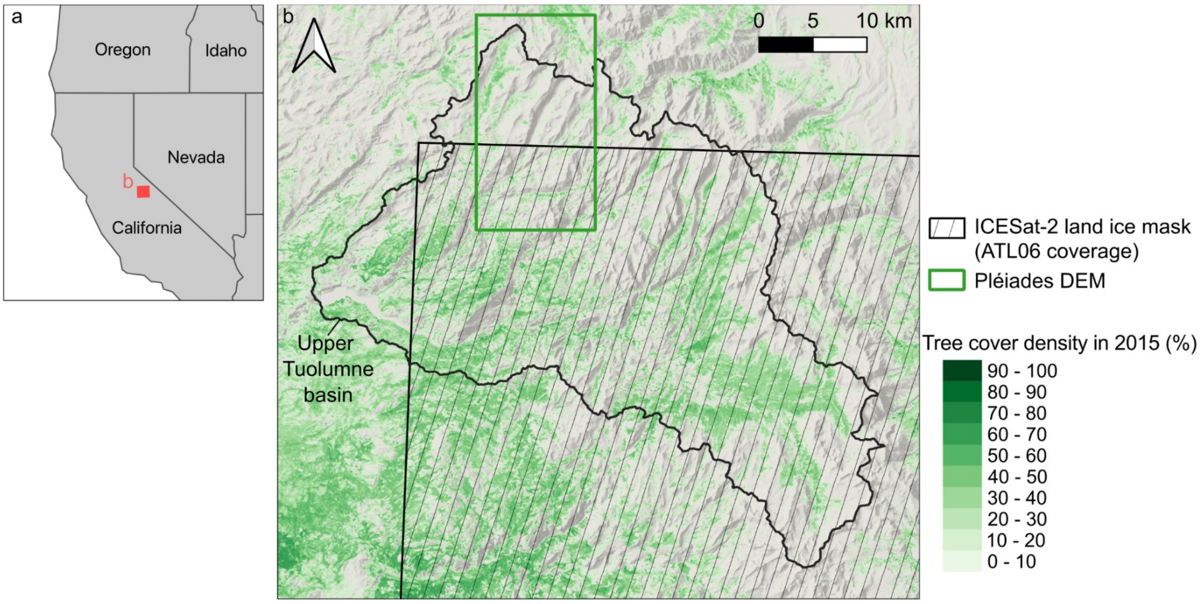

Figure 1. *The upper Tuolumne basin is located in California, USA (a). The basin is entirely covered by the ASO DEM (black contour) and partially covered by the ATL06 coverage (black hatch) and by the Pléiades DEM (green rectangle). The background map shows a hillshade of the topography and the tree cover density (green shades) (b).*

Page 8, Line 196: “w.e.” = water equivalent?

Indeed. This term was previously defined: « water equivalent (w.e.) »

Page 9, Line 216: “i.e. as often done” is not needed.

Deleted.

Page 9, Section 3.5: I think it is important to note the substantially higher uncertainty in the IS2-Pleiades measurements, especially for the 15 m retrievals.

This part was largely modified following this comment and comments from the other reviewer. We excluded the results at the highest resolution to focus on the results at 15 m. At this scale, the IS2-Pléiades are indeed not as good as the IS2-ASO. We comment on this through the article, in the results and discussion.

Page 9, Lines 228-229: I suggest moving Figures S5 and S6 to the main text. The difference in uncertainty between beam strengths is significant, and I would like to see the authors’ interpretation of these figures.

We had to keep the balance between this suggestion and request from reviewer 2 to reduce *the discussions on snow depth residuals. As an attempt to conciliate both views, we propose to let these figures in the Supplement but to add comment about the difference between strong and weak beam in the main text:*

"Considering separately the snow-on points of the strong or the weak beam yield lower precision and larger biases for the strong beam on 12 March 2019 for IS2-ASO and IS2-Pléiades (Figure S5 and S6 a to c). The bias of IS2-ASO from the weak beam are smaller than the one from the strong beam at most dates but the impact of the beams strength on the precision is not systematic at all dates (Figure S5 and S6 d and e)."

Page 12, Lines 302-303: Based on the results, it appears that accurate ICESat-2 snow depths are also limited to areas where DEMs are available (see major comments above). It would be important to mention this in the Discussion.

We answered the related major comment above.

Page 12, Line 305: "ALT06" --> "ATL06"

Modified.

Figure 1: I have a few suggestions here. First, Figure 3 is essentially the same as Figure 1a, but it provides more information. I suggest replacing 1a with Figure 3, then highlighting the March 2019 track on there.

Second, I'm not sure why 1b, 1c, and 1d are here. I think they would flow better with the text if they were their own figure after Figure 2.

Third, there is a non-negligible number of negative ICESat-2 snow depths in 1c. I suggest linking discussion of Figure 4 with the overall distribution of 1c.

These figures were modified following these comments. We deleted Figure 3 as it was hardly readable and created a new Figure 1 showing the study area and the dataset extent.

We added a comment about the presence of negative snow depth:

"Negative snow depths in IS2-ASO represent 10% of the snow depths (Figure 3c). They are found over shallow snowpacks and in areas with slopes greater than 10°."

Figure 2: Interesting result! The titles of the plots need to be switched. Also, it is evident that the photon count has a wide distribution in April and May, when there is still a reasonable fraction of snow on the ground. Are there any concerns of misclassification of ICESat-2 segments during the melting season?

Thank you for your positive comment. We shifted the titles.

We cannot assess errors of the classification method due to lack of validation data. It is true that misclassifications might happen due to seasonal changes in the albedo of the snowpack (snow aging) and of the snow-off terrain (land cover type, vegetation). However, we cannot *calculate seasonal variations of the n_fit_photons thresholds as the distribution of snow-off and snow-on points is very unbalanced during the year (Figure below). This figure shows the monthly distribution of snow-off and snow-on points (not included in the manuscript). We added new thoughts derived from this comment in the conclusion:*

"We used the photon counts variable provided with ATL06 segments to determine the snow cover of each segment. It remains uncertain whether the thresholds found here could be transferred in regions with different vegetation cover, terrain roughness and cloudiness, all of which affect the number of returned photons. In addition, the optimal thresholds for a given region might vary seasonally due to the evolution of the snow albedo and to the vegetation phenology. Further development of this approach could benefit from using higher resolution snow cover maps derived from Sentinel-2 or Landsat images to refine the thresholds or evaluate the snow cover uncertainties (Gascoin et al., 2019)."

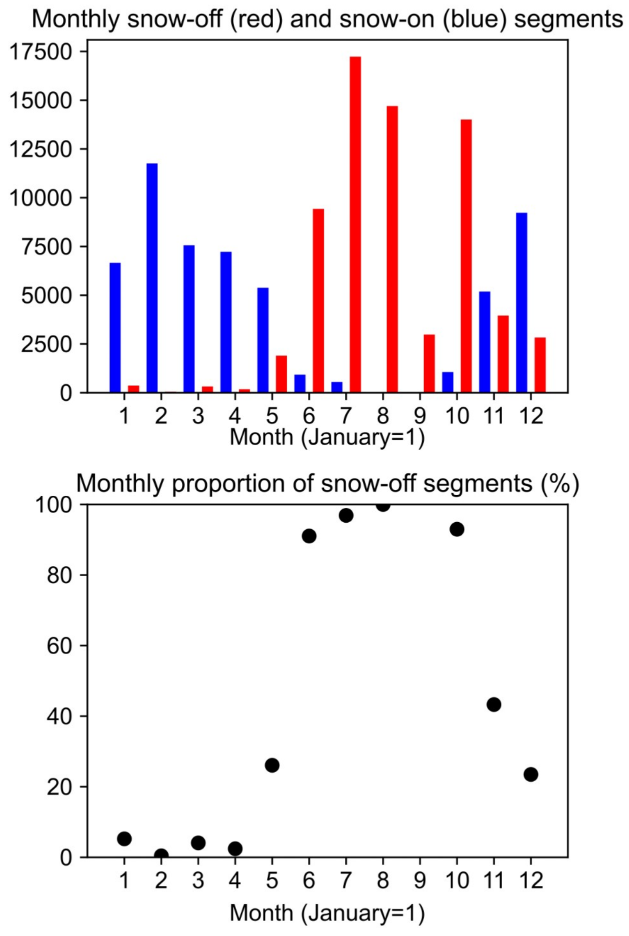

Figure (not added in the manuscript). Monthly distribution of snow-off (red) and snow-on (blue) segments (upper panel) and proportion of snow-off segments (lower panel).

Figure 3: The ICESat-2 lines could be thicker here – they are difficult to see even with the magnification.

We deleted this figure as it was, indeed, hardly readable.

Figure 4. Please extend the y-axis limits for 4b, so that we can see the full extent of the uncertainty. Same suggestion for 4i.

Thank you for this suggestion. We considered it but actually realized that the box in 4b was based on very few segments (N=4). Thus rather than changing the y-scale and losing visibility of the boxes with a significant number of segments, we propose to change the opacity of the boxplot according to the sample size.

The plot 4.i was deleted after suggestions from reviewer 2.

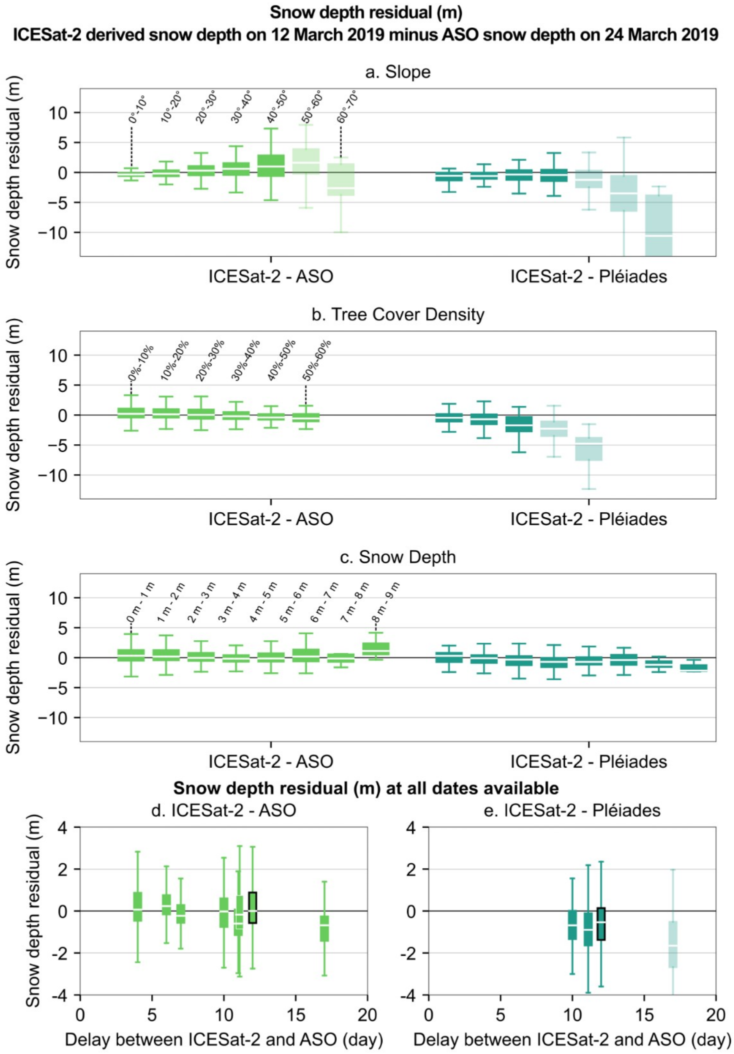

***Figure 5.** Snow depth residuals (ICESat-2 derived snow depth minus ASO snow depth). Each group of boxplots (or color) corresponds to a snow-off DEM. Within each group, the boxplots are classified by terrain slope (a), tree cover density (b) and snow depth (d). The snow depth derived from ICESat-2 and the ASO DEM are the most accurate and precise for all tree cover densities. Snow depth residuals when an ASO snow depth map is available at less than 20 days (d, e). Transparent boxplots show the data where less than 100 points were available. The black boxplot is the residual on 12 March 2019 shown in upper panels. Note that the sampling of the breakdown variables differs due to the different coverage of the snow-off DEMs.*

Also, it is interesting that IS2-ASO residuals become increasingly positive with slope, whereas the IS2-Pleiades become negative. Any thoughts on why there is such a difference between the two?

Unfortunately we do not have an explanation for this but find it consistent with a previous comparison of the ASO DTM and the Pléiades DEM. We added a comment on this:

"The lidar airborne and satellite snow depth uncertainties differ largely in slopes with the increase of the bias for IS2-ASO with slope compared to the constant bias for IS2-Pléiades (Figure 5a). This discrepancy between the two DEMs is observed as well even when they are co-registered together (Figure S2 in Deschamps-Berger et al., 2020) but remains unexplained."

Figure S1: It would be nice to have a sample MODIS image or snow/no-snow map to get a better idea of what the snow coverage looked like for the study period.

Thank you for this suggestion. Instead of a single sample image which would very much depend on the chosen date, we propose to include the map below showing the spatial distribution of the mean annual snow cover duration in the Tuolumne river basin during the study period (four hydrological years). This map was computed from the same daily gap-filled MODIS time series that we used to determine the photon count threshold.

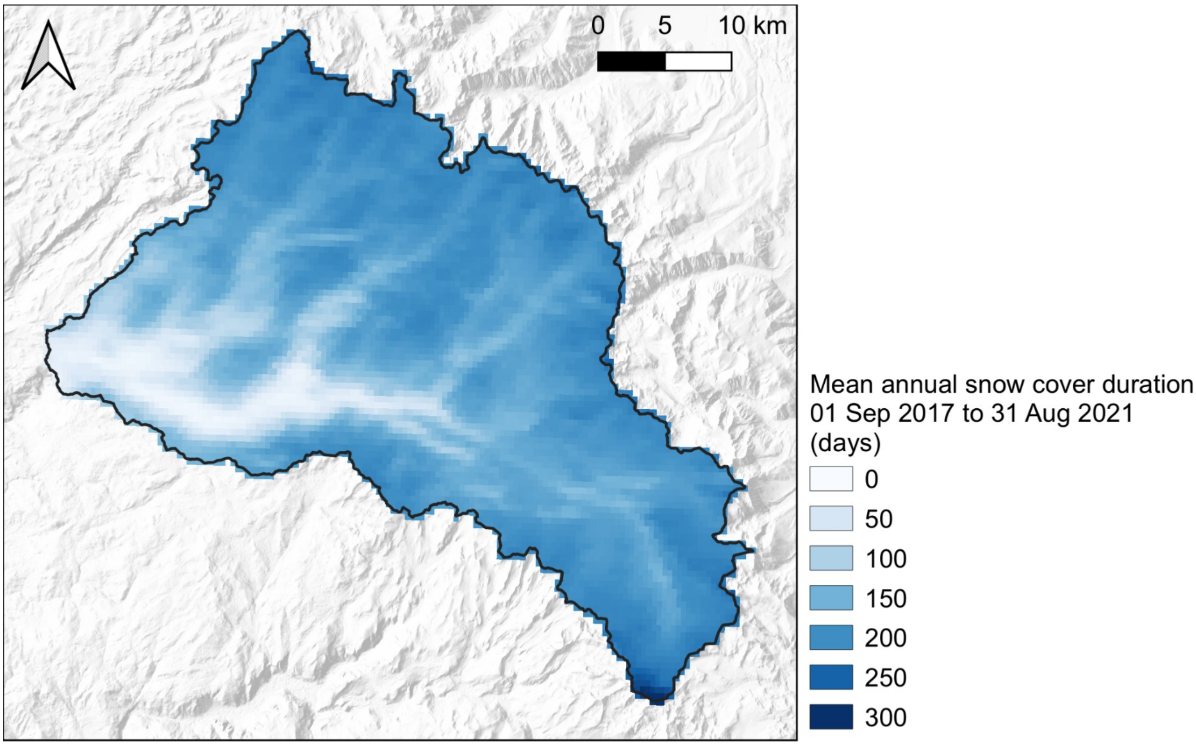

***Figure S1**. Map of the mean annual snow cover duration in the upper Tuolumne basin calculated from a time series of MODIS images (MOD10A1).*

References

Enderlin, E. M., C. M. Elkin, M. Gendreau, H. P. Marshall, S. O'Neel, C. McNeil, C. Florentine, L. Sass, (2022). Uncertainty of ICESat-2 ATL06- and ATL08-derived snow depths for glacierized and vegetated mountain regions. Remote Sensing of Environment, 283, 113307, doi: 10.1016/j.rse.2022.113307

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