Review of

Improved workflow for customized ICESat-2 ATL06 elevations

captures seasonal mountain snow depths at sub-kilometer scale

Zikan et al. 2025-4813

General comment

This article presents a workflow using ICESat-2 elevations and reference snow-off digital terrain models to map snow depth in four mountainous study sites in the western US over a total of 586 km². The accuracy and precision of the retrieval is evaluated with reference snow depth from automatic weather station and from airborne lidar. The benefits of several steps of the workflow is tested (slope related correction, negative values filtering, coregistration strategy). An empirical definition of areas where snow depth surveyed with ICESat-2 is likely to be informative and valuable is proposed and used to estimate the coresponding area in the Idaho state (US).

The article reads well. The methodology and results are well presented. Some results are insightfull, such as the impact of the coregistration strategy and of the slope related correction. However, the quantification of the improvement brought by this specific workflow in comparison with previous studies is lacking. This work builds upon workflows presented in previous work which it aims to improve (Enderlin et al., 2022 ; Besso et al., 2024). I would expect a part of the discussion to be dedicated to a comparison of uncertainty and precision metrics to highlight the improvement brought by this workflow. Without this, it is hard to evaluate the benefits of it. A comparison with the results in Deschamps-Berger et al. (2023) and Chen et al. (2025) could also be included since they share a common general framework of differencing with external elevation models. Regarding the comparison with Besso et al. (2024), see the comment about Line 103-105.

César Deschamps-Berger

Minor comments and suggestions

Suggested modifications are in ***bold italic*.**

L14 Provide the RMSE and R2 with 2 decimals precision, like in Table 4.

L25 Order chronologically the citations.

L28 Precise whom Decadal Survey it is or turn the sentence in passive mode « Goals of global snow water equivalent (SWE) at 1–4 km resolution and ~100 m SWE resolution ***were set*** for mountain regions to meet snow observation needs for water management (Decadal Survey...) »

L31 « ; » replace with « but » or another similar conjunction.

L31 Maybe also state that SWE cannot be directly observed at the relevant scale and resolution ?

L34 « In this paper**,** » comma.

L35 It is implied but state clearly that this refers to airborne and terrestrial lidar.

L37-38 no need to repeat « airborne and terrestrial Lidar » the second time ?

L41 Some quantified values of the ICESAt-2 snow depth error found in previous studies would be welcome. See for instance, Fair et al. (2025).

L43 « for static terrain ...for spatio-temporally evolving terrain » This formulation got me confused and is innacurate since Lu et al. (2022) also apply their method on land masses.

L64 « can be applied in shallow to moderately sloped terrain » I thought that one of the conclusion of the article is that snow depth below 0.5 m are not well monitored with ICESat-2 ?

L65 « covered by the USGS 3D Elevation Program (3DEP) or the Swiss national DTM (swissALTI3D) » Move to Discussion.

L70 Say that the high-frequency acquisition provides continuous acquisitions along-track.

L72 « Launched in 2018, ICESat-2 has a 91 day polar orbiting cycle but it points off-nadir outside of the polar regions ***to increase coverage and to map vegetation***, repeating reference ground tracks in mid-latitudes every 3 years ***only***. » Suggestion.

L74 « of repeat reference ground tracks » => « tracks »

L75 I would turn this sentence in passive mode : « the spatio-temporal restriction ***can be circumvented*** ». And cite the works which did that.

L79 I would split this sentence in two. If I understood correctly, something along : « We conduct our analysis using observations from four Idaho study sites for which ***ICESat-2*** acquisitions were tasked ***to cover/overpass*** an automated weather station within each site. ***This resulted in shifting the satellites tracks within a 30 km radius around the stations and enabled the comparison of satellite and*** in situ snow depth data from 2020–present, as described below »

L81 « 2020–***present*** » find a formulation that will remain true in a few years

L84 « ATL06 » as I understand the workflow, ATL06 is not used but an ATL06-like product (L100). Should it say here that this study uses a hybridized product based on ATL08 and ATL03 resulting in a ALT06-like product ?

L89 NMAD. You may want to cite the original article as well, Höhle and Höhle (2009).

Höhle, J., & Höhle, M. (2009). Accuracy assessment of digital elevation models by means of robust statistical methods. *ISPRS Journal of Photogrammetry and Remote Sensing*, *64*(4), 398-406.

L91 « where there is no vegetation but ***where*** differences in surface elevation must be resolved on the order of centimeters in order to capture important variations in snow and ice volume »

L95 « vertical accuracy is expected to exceed » not sure if it exceeds in absolute value (Accuracy_ATL06 > Accuracy_ATL08) or in quality (ATL06 better than ATL08, Accuracy_ATL06 < Accuracy_ATL08)

L100 Move (Besso et al., 2024) and (Shean et al., 2025) together at the end of the sentence.

L101 I would avoid mentionning the « SlideRule atl06 function » which is a bit cryptic. Simply list what corrections and filters are applied or not.

L103-105 « ATL06_SR derived snow depths have a Root Mean Square Error (RMSE) of 0.18 m in Tuolumne Basin compared to a 3 m resolution ASO DTM and a RMSE of 0.33 m in the Methow Valley in Washington compared to a 1 m resolution airborne lidar DTM (Besso et al., 2024). » These value of RMSE are misleading as they are not the RMSE at the ATL06_SR resolution of 20 m. This is the RMSE of the ensemble of median differences calculated for each day with ICESat-2 data. This can be verified in the code from Besso et al. (2024). For instance for the Methow Valley :

https://github.com/bessoh2/icesat2_sr/blob/main/methow_valley/notebooks/comparison_to_snotel.ipynb

In the box 56, the RMSE (0.33 m) is calculated on the object *comp_df*, itself defined in box 54 and 55. It is filled with median differences, one for each acquisition date.

When pushing the comparison of these results with Besso et al. (2024), this code might be useful to ensure the consistency of the variables compared.

L105 « Thus**, »** comma.

L111-114 That is a lot of acronyms, institutions name, and programs name. Could it be rather put in a table (acquisition date, resolution, program, provider…)? Possibly in supplement.

« Each site has a high-resolution snow-free airborne lidar DTM ~~raster~~ ***freely***(?) available ***acquired during various campaigns (Table XX)***. »

These information are repeated in the study sites description. Maybe that is even enough then.

L119 « 1.3 cm » source ?

L122 2.2.1-4 Could the basins presentation be ordered from north to south ? or another geographical logic ?

L127 « ~1300-1600 m to 1669–2013 m » keep the same precision for both ranges.

L186 « ICESat-2 snow depth precision or accuracy » I see the point in distinguishing precision and accuracy but please provide the definition used in this article. Is one the bias, the dispersion, the combination of both… ?

L191 « a ***minimal number of*** photon threshold » ?

L236 « The reference elevation for each ATL06_SR point is the mean elevation of the DTM within the corresponding ATL06_SR segment area (a 11 m by 40 m rectangle, oriented along the ICESat-2 track) » nice effort.

L238-240 « Although the terrain metrics... » I do not understand this. Isn't it the case for ATL06 products ?

L251 « To evaluate the scale... » I am unsure how the smoothing is done on ICESat-2 elevation : along-track or within a square, circle shape? The latter would make the number of data points smoothed variable.

L271 « and precision then present » add a comma somewhere ?

L282 « ***T***able 2 »

L287 The exact R2 values can be provided (0.47 and 0.00) instead of approximate ~.

L304 4.3 Are these results calculated after the slope correction or without slope correction ?

L342 Please provide the NMAD for Morse Creek snow-free terrain.

L363 « At the sites in this study**,** the individual ICESat-2 » comma.

L377 « In this study**,** » comma.

L401 « ICESat-2 observations are space » ?

L421 « including snow-free terrain » is it a problem ? Snow-free terrain is part of the snow depth variability.

L435 « and for snow depths > 0.5 m » I am not very convinced by this conclusion. I understand that the uncertainty of ICESat-2 retrievals, in absolute, does not depend on the snow depth value. Thus, an ICESat-2 snow depth of 0.25 m (+-0.5 m) is just as informative to me as 2.00 m (+-0.5 m). It is not because the measurement cannot be distinguished from 0, that it is not informative.

L446 It results a bit odd to do this analysis over the Idaho state. I doubt that the northern borders follow a relevant natural element. It could be interesting to do this analysis over an area free from subjective human borders (e.g. large area buffered around the AOI or over the mountain ranges to which the AOI belong as defined by the Global Mountain Biodiversity Assessment)

https://www.gmba.unibe.ch/tools/definitions/mountain_inventory_v1/index_eng.html

L456 delete «] »

L460 What method is used to produce 3DEP ? Any source ?

L484 « As previously identified, there is a progressive negative slope bias in the ICESat-2 data (Fig. 4, Deschamps-Berger et al. 2023; Enderlin et al. 2022) » I think the bias is getting progressively positive in Deschamps-Berger et al. (2023). Which does not change the general similarity of this result.

Figures and Tables

Table 2. Snow depth R2 = 0.00 ?

Table 4. I could be nice to have this table plotted for a supplementary figure.

Fig. 1. Make sure that writtings have a sufficient size (lat-lon in western US inset and UTM coordinates on the right pannels). In the legend, write HW21 in full letterrs, maybe even « Avalanche prone... »

Fig. 2. Add grids and make the x-ticks equivalent to the y-ticks.

Not mandatory at all, but it would be nice to add the borders of all the countries encountered in the inset.

Fig. 3. Text is small. Top maps as well. The legend of the histogram might be easier to understand by making the symbol for « Filtered to slopes below 20 degrees » in black (not a colour of the plot) and add an item for « All slopes » (i.e. full line).

Fig. 4a. It is not necessary to modify the plot but cumulative distribution might be easier to interprete as it gives a sense of what proportion of a site is above a given slope.
I would add title on each pannel and horizontal grid lines on b and c.

Fig. 5. Add grid and make the horizontal 0 m thicker.

Fig. 6. The text and the plots seem small.

Fig. 7. Add the grid lines on the plot. It is nice that the drop in snow depth at 2000 m in Mores Creek is caught by ICESat-2. Could it be worth mentionning in the text ?