

Authors' Response to Reviewer Comments for "Review article: Using spaceborne lidar for snow depth retrievals: Recent findings and utility for global hydrologic applications"

The authors thank both reviewers for their insightful comments for the improvement of this manuscript. For this response, the original comments are in orange, and the authors' responses are in blue. We also acknowledge the comments from a community member, which we also address here.

Reviewer #1

The literature review is broad and offers a valuable overview of available approaches, and the explanation of basic principles serves as introduction for readers new to the technique. However, the level of detail and technical terminology is at times quite dense. I recommend adding a detailed schematic figure, similar to Figure 4, that visually represents key concepts such as along-track resolution, across-track resolution, and beam footprint for example. This would aid in comprehension and serve as a quick reference.

This is a good suggestion. We added a new figure early in the text to coincide with the basic lidar principles. This figure outlines the three concepts raised by the reviewer (along-track resolution, across-track resolution, beam footprint).

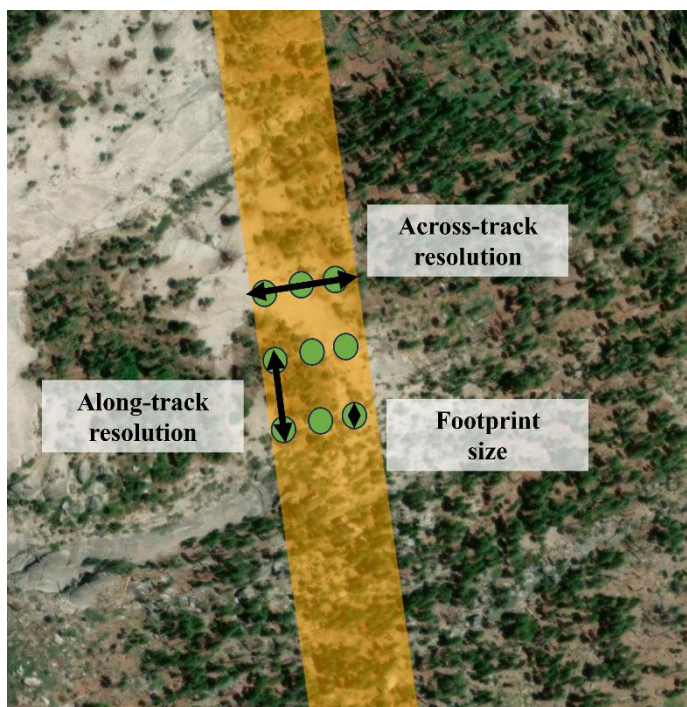


Figure XX. (a) Sample lidar swath (orange) to demonstrate along-track resolution, across-track resolution, and footprint size. In this example, the swath width (across-track resolution) is approximately 120 m, the footprint size is 10 m, and the along-track resolution is 50 m. These values do not reflect any active or proposed spaceborne lidar mission, and were arbitrarily selected for visualization purposes.

The discussion regarding error sources is informative. An easily accessible recap table summarizing these uncertainty sources and their associated uncertainties would enhance the reader's ability to grasp and compare the contributions of each factor.

This is another good suggestion. We added a table that summarizes each error source: terrain characteristics, DEM accuracy, vegetation, and lidar penetration. A range of potential biases is also given for each error source. Note that the final table looks more refined when compiled into Latex; the below table is for easy reference for the reviewers.

Table 1. A summary of the error sources discussed in Section 6. The given biases in the right column represent maximum biases reported in available literature, though because undergrowth (*) has not been formally assessed for DEM generation, the given value is speculative.

Error Source	Impact to Lidar	Expected Biases (cm)
Terrain characteristics	Complex topography (surface roughness, slope) makes precise geolocation of the return signal difficult.	>100 (ATL06/ATL08) 60 (ATL06-SR) for slope > 20°
DEM accuracy and co-registration	Reprojecting to match reference DEMs can cause geolocation uncertainties.	<10 (lidar DEMs) >100 (coarse DEMs)
Vegetation	Dense vegetation canopies weaken the return signal. Undergrowth introduces uncertainties in snow-free DEMs.	~60 (forest cover ~60%) ~100 (heavy undergrowth)*
Lidar penetration in snow	The lidar signal experiences scattering within a snowpack, increasing the time it takes to return to the detector.	<10 (Greenland firn)

The case study adds significant value to the work; however, clarification is needed for lines 214–218. The assumption that no snowpack change occurred during the eight days between March 4 and March 12, based on sub-zero temperatures and the absence of melt and sublimation, is reasonable but should be reinforced. For instance, as shown by Spehlmann et al. (2023), sublimation rates in tundra environments can reach up to 0.15 mm/day. Assuming a snow density of 200 kg/m³ over 8 days, this would translate to a change of approximately 6 mm in snow depth, which is negligible relative to the expected measurement uncertainty. Strengthening this explanation will add robustness to the argument. Moreover I would use km/h instead of kt, for being coherent with SI.

Thank you for the referenced work. We have added detailed on sublimation in the case study section, using the proposed reference as a basis. We also adjusted the wind speed units to km/h, per the reviewer’s suggestion.

“Temperatures were well below freezing during the observation period, so we also assume melt and sublimation were negligible. This is supported by observations from Spehlmann et al., (2023), who found that sublimation rates in tundra winter were approximately 0.15 mm/day. Wind speeds on and before the date of the ICESat-2 overpass were low (<20 km/hr), and they remained low up to the UAF lidar acquisitions.”

In line 447, the authors refer to previous studies on the interannual repeatability of snow patterns. For completeness, I suggest including Premier et al. (2021).

We added the suggested reference.

Reviewer #2

To be a review, I miss a proper review design methodologically; for instance, I would like to know which databases were used, how the search was conducted, and which keywords were selected, among other details. I support the idea of including a case study to contextualize the review, but when reading, I lose track of the paper's storyline upon reaching this section. Therefore, I suggest going to a more classical review, which has a proper review design structure, and where the application case is part of it, but better contextualized. If that is not possible, I would suggest removing the case study. Alternatively, another option would be to switch to a research article where the case study plays a more key role in the manuscript on its own.

Thank you for sharing your concerns. We understand the need for details on how we conducted our review, so we added more details on the review process in the Introduction section.

“In this paper, we review the current status of research using spaceborne lidar, and evaluate its potential to derive snow depth to meet the research and operational needs of the hydrology community. Our review is based on an extensive literature search using SciSpace, Web of Science, and research previously published by the authors. Based on our literature search, we determined that existing research on the subject concentrates on the currently operational ICESat-2 mission.”

Because of the delay between our initial submission and our response to reviewers, we conducted an updated literature review for the paper. This search returned one more study of relevance, which we add to the main body of the text. The reference is shown at the bottom of this document – see the tracked changes or updated manuscript for added discussion of the study.

For the case study, we propose revising Section 5 to instead show an intercomparison example that highlights the process to derive snow depth with ICESat and ICESat-2. The example would not have a direct comparison between ICESat and ICESat-2, but would instead show snow depths in a manner similar to Figure 2. This updated Section will be reflected in the final revised draft.

The authors mentioned “utility for global hydrologic application,” but rather, all highlighted studies along the paper are locally based with a global spread. I would suggest changing this part of the title.

We propose removing “global” from the title, so that the title is:

“Review article: Using spaceborne lidar for snow depth retrievals: Recent findings and utility for hydrologic applications”

I miss any reference to the fact that a case study application is going to be carried out in the manuscript.

We added text that makes it clear that there is a case study in the manuscript.

“We focus on the currently operational ICESat-2 mission, with a summary of snow observations gathered from previous studies. A case study using ICESat-2 is given to demonstrate snow depth retrievals over the Alaskan tundra. We also outline best practices...”

I would enrich the introductory section in two aspects. On the one hand, the authors claim in the title to adopt a global hydrological perspective; to emphasize this further, I would include some contextualization about the global snow-related hydrological studies carried out, highlighting their weaknesses in capturing, for instance, snow depth dynamics. On the other hand, I would also include some details about which other satellites have been used to monitor snow variables at the global scale (i.e., snow cover fraction, snow water equivalent, snow albedo, snow grain size). You can use this to highlight the limitations and challenges from a remote sensing perspective in retrieving snow properties from spaceborne instrumentation.

These are good suggestions. We added the following discussion on the current status of global snow monitoring, while also considering other satellites that have been used:

Many properties of snow are currently observable globally by satellites, including snow extent and albedo. Spaceborne technologies, notably multispectral imagers, have been most successful at mapping snow cover on the global scale. Currently, methods exist for mapping snow cover with the Landsat collection (Dozier et al., 1989; Gascoin et al., 2019), Sentinel-2 (Gascoin et al., 2019), the Moderate Resolution Imaging Spectroradiometer (MODIS; Hall et al., 2002), and the Visible Infrared Imaging Radiometer Suite (VIIRS; Riggs et al., 2017). Methods also exist for retrieving the albedo and optical grain size of snow using MODIS and Sentinel-3 (Kokhanovsky et al., 2019; Painter et al., 2009). Retrieval methods for snow depth and SWE are documented for sensors such as the Advanced Microwave Scanning Radiometer 2 (AMSR-2; Tedesco et al., 2019) and Sentinel-1A (Oveisgharan et al., 2024). While these approaches offer valuable information at global and regional scales, they are challenged by multiple factors, including snow conditions (e.g., dry, wet, deep, or shallow snow), vegetation, and topography. Because of these challenges, we lack information about snow depth and SWE at the recommended scales needed to inform climate and water resource applications.”

Lines 38-39, which are/could be these key watersheds?

We added mention of potential watersheds for routine monitoring:

“...satellite altimetry could theoretically be used for routine measurements of snow depth over key watersheds, such as the Tuolumne River Basin in California, USA or the Alps in Europe.”

Line 41, could you elaborate more on the idea of the potential of snow-depth observation for hydrological operational purposes?

We adjusted the text:

“...and evaluate its potential to derive snow depth to meet research and operational needs to accurately derive SWE.”

The section is too short. If the authors want to give it the entity of an individual section, I suggest going in-depth into the actual principles used by lidar technology. If not, I would move this paragraph into the Introduction.

We understand the reviewer’s concerns about Section 2. We believe that adding more depth to the lidar technology would be outside the scope of this study, but we also think the current section has too much jargon that does not fit in the Introduction section. We instead propose moving Section 2 to the start of Section 3:

“A full list of known spaceborne lidar platforms and their operational periods may be found in Figure 1. The space-based lidar instruments listed have two primary measurement modalities: waveform-based and photon-counting. Waveform lidar systems record the change in amplitude, or signal strength of the return over time. The shape of the received waveform is sensitive to terrain characteristics such as surface roughness, which may cause centimeter-to-decimeter levels of bias in the final elevation measurement (Dong and Chen, 2017). Photon-counting lidar systems offer an alternative by time-tagging and geolocating received photons relative to a transmitted signal (Luthcke et al., 2021). Received photons are distinguished as signal or noise using automatic classification algorithms that are based on either histograms of detected photons (Neumann et al., 2019) or more complex algorithms using iterative nearest-neighbor filters (Neuenschwander and Magruder, 2019) or photon-density approaches (Herzfeld et al., 2017). While these systems provide improved along-track spatial resolution compared to waveform-based platforms, their lower transmitted energy results in greater attenuation through surfaces with low reflectance, which may limit measurement coverage.

In the following subsections, we describe the individual spaceborne lidar missions that have been used for snow studies. A summary of the technical specifications for each spaceborne lidar is given in Table 1. We recognize here that the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission...”

Figure 1 and Table 1 are not part of this section; however, they appear here. I would move them to section 3.

We shifted Figure 1 and Table 1 to be within Section 3 in the compiled PDF. This also required a small shift for Figure 2, though it is still within Section 3.

I suggest rephrasing the introductory paragraph. I had some difficulties having an overview of all the missions. First, I would introduce all missions, and then I would refer to Figure 1, where they are all listed. Second, I would explain why some of them are not further considered. Finally, I would present Table 1, which displays only the characteristics of this selection.

In addition to the changes above, we propose the following additions to the introductory (now second) paragraph:

“In the following subsections we describe the individual spaceborne lidar missions that have been used for snow studies: ICESat, GEDI, and ICESat-2. A summary of the technical specifications for each spaceborne lidar is given in Table 1. We also recognize retired and future missions shown in Figure 1 that included spaceborne lidar technology. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission included the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) as part of its scientific payload (Winker et al., 2009). [...] Similarly, the Cloud-Aerosol Transport System (CATS) was a lidar onboard the International Space Station with similar science objectives to CALIPSO (McGill et al., 2015). [...] The Earth Dynamics Geodetic Explorer (EDGE) and the Surface Topography and Vegetation (STV) mission concepts are proposed spaceborne platforms that may include lidar as part of their respective payloads. If launched, both missions would become operational in the 2030s (Figure 1). More information about these missions may be found in Section 7.5.”

It seems there is a connection between the two Lidar principles you state in Section 2 and the methodologies highlighted here. I suggest highlighting this fact more clearly than is currently done to facilitate the reader the linkages between sections.

We propose the following rewording in the text:

Line 137: “The listed studies perform snow depth accuracy assessments for ICESat, GEDI (waveform-based) and ICESat-2 (photon-counting) data products, with evaluation of land cover classification and terrain characteristics.”

Line 141: “Most of the featured studies derive snow depth using differential altimetry, though other methods have been proposed by the community for ICESat-2.”

Line 166: “The differential method is the most common and consistent way to derive snow depth from lidar, but Hu et al., (2022b) devised a new technique that exploits time delay due to light penetration into the snowpack (see Section 6.4) and ICESat-2 photon counts to infer snow properties.”

Lines 142-145. In the first of these two sentences (lines 142-143), the authors mention two different definitions for “residual” and “uncertainty”. However, in the second (lines 144-145), the authors state that they would “also” use both terms interchangeably. Could you please clarify this?

In Lines 144-145, we state that we use “accuracy” and “bias” interchangeably, not “residual” and “uncertainty”.

Table 2 and Figure 3. The authors listed seven studies. Are they the only studies carried out, or are they the most important ones? Could you clarify that? I understand that lidar spaceborne for snow depth is a novel topic, but since you claim this is a review paper, I would expect more relevant studies to have been highlighted; if not, the authors should clearly state that this is the case.

The studies listed/shown in Table 2 and Figure 3 are the studies known to the authors, or previously published by the authors, in scientific journals. The exception is Shean et al., (2021), which is a conference presentation, and is the only known study to document GEDI for snow depth applications. After our updated literature search, we found a new study currently in preprint, and it has been added to both Table 2 and Figure 3.

As stated before, I would contextualize better than is done that this case study is helping with your actual review work, or maybe I would remove it.

See the major comment for our full response.

It seems the terrain slope and roughness are key in the retrieval process. The limitations linked to the slope are well discussed; however, could the authors add something else regarding the effects of roughness?

We added the following to Section 6.1:

“It is therefore critical to identify roughness- and slope-based errors in both snow depth validation sources and in snow-free DEMs to quantify accuracy and uncertainty in lidar snow depth retrievals.

Several studies have quantified errors from surface roughness and slope in ICESat-2 surface heights and snow depths. [...] This error increases with surface roughness and slope, with Smith et al., (2019) finding <0.1 m accuracy in ATL06 over smooth surfaces and <1 m accuracy for rough surfaces. Errors in surface elevation also propagate to snow depths, with Enderlin et al., (2022) finding residuals and MAD values exceeding 1 m...”

Snow-off DEM accuracy is stressed as a fundamental aspect in the snow depth retrieval. Could you elaborate more about the order of magnitude of this accuracy? The authors mentioned 3 m uncertainties in Copernicus DEM; however, is it the only DEM available to carry out this type of analysis?

We added the following to Section 6.2:

“For example, Deschamps-Berger et al., (2023) found snow depth uncertainties greater than 3 m when using the Copernicus DEM, compared to 0.6-1.16 m uncertainties when using ASO or Pléiades.”

In general, optical and microwave remote sensing technology has difficulties in retrieving snow depths in vegetated areas, especially for retrieving under-canopy information. Is that the case also for spaceborne lidar? Could you comment on that in the vegetation section?

Yes – we added the following to the Vegetation section:

“The three studies generally had terrain biases of -0.17 to +0.59 m over regions of dense vegetation. Neuenschwander et al., (2020) additionally found that ICESat-2 was more likely to detect the surface under low canopy conditions, particularly at canopy cover < 10%.”

“For instance, results from Deschamps-Berger et al., (2023) suggest that uncertainties in snow-free DEMs remain mostly constant until forest densities exceed 60%, with which large snow depth errors are observed.”

What is the penetration depth of the spaceborne lidar? It appears that most of the studies you mentioned in Section 6.4 are conducted on snow over ice, can that be extrapolated to seasonal snow over land?

This is a good question. For ICESat-2, the maximum penetration depth has not been formally quantified, but Lu et al., (2022) speculated that their retrieval method could estimate snow depth up to 10 m. Fair et al., (2024) found that, under realistic melting snow conditions, ICESat-2 has an average penetration depth of approximately 5 cm. We added these details to the paper, as shown below:

“Observed results from Fair et al., (2024) constrain average penetration depths (i.e., bias) in ICESat-2 data to 4-7 cm at the photon level...”

“...the authors speculated that it may be difficult to distinguish light penetration from other bias sources, such as topography or vegetation. Lu et al., (2022) tested their method over terrestrial snow and over sea ice, and they speculated that it would be effective for snow depths up to 10 m.”

Lines 344-345. I would encourage developing a further discussion about snow density and the use of constant or dynamic values. I suggest being inspired by the work done by the remote sensing community in retrieving SWE.

Thank you for the suggestion. We added the following to the paragraph of interest:

“Further uncertainties may be generated when converting lidar snow depths to SWE, with snow density having a strong influence on SWE uncertainty. Bulk snow density is estimated across a domain using snow pit profiles (Kinar and Pomery, 2015) or empirical, statistical, or physically-based models (Elder et al., 1998; Sturm et al., 2010; Painter et al., 2016). Snow pits provide direct measurements of snow density, though observations are subject to observer error, leading to SWE uncertainties of 10 cm (Proksch et al., 2016). Simulated snow density varies by the model used, with Raleigh and Small (2017)

finding an uncertainty range of 0.04-0.1 g cm⁻³. The authors also found snow density uncertainties strongly contributed to SWE errors when observed snow depths were greater than 60 cm.”

Line 371. I like the idea of relative error, which will help contextualize the order of magnitude of the actual bias of the methodology. Could other metrics commonly used by the hydrological community, for instance Kling Gupta Efficiency (KGE) use in this context?

To the authors’ knowledge, the KGE metric is not commonly used in the snow science community. We acknowledge its potential value for observation-model intercomparisons, though because the studies in Table 2 do not use KGE or other metrics, we will leave further discussion on their usage for a future study.

Line 410. Could you include some global hydrological studies? If they exist.

Most snow studies tend to focus on the watershed scale, meaning that hydrologic impacts are also examined at the watershed scale. So, global assessments of snow are limited beyond model intercomparisons and reanalysis products. We added citations to ECMWF’s global snow analysis paper, the GlobSnow model, and the Earth System Model-Snow Model Intercomparison Project (ESM-SnowMIP):

“Some of the limitations in snow depth retrievals from spaceborne lidar may be overcome with hydrologic models and reanalysis products, in particular the coverage and repeat times. Initiatives such as the Earth System Model-Snow Model Intercomparison Project (ESM-SnowMIP), the European Center for Medium-Range Weather Forecasts (ECMWF) operational snow analysis, and the GlobSnow model have performed assessments of snow observations and model outputs over the Northern Hemisphere (Drusch et al., 2004; Krinner et al., 2018; Luo et al., 2021). In addition, previous studies have demonstrated...”

Line 479. The authors note that spaceborne lidar provides reliable snow depth data in areas where the local slope is less than 20°. Would it be possible to give a percentage of the global seasonal snow area where this requirement is fulfilled?

This is a great question. It would be difficult to give a percentage on a global scale, but we note in the conclusion that this would lead to good representation in flat regions (e.g., tundra) and less coverage in mountainous regions.

“Recent developments show that spaceborne lidar provides useful snow depth data in areas where the local slope is below 20° and bare earth DEMs/DTMs are available. Over regions with consistent winter snow cover, these constraints are consistent with the Arctic tundra or valleys or plateaus in mountainous regions.”

In general, the location of the Figures does not help the reader to follow the text. I suggest placing them after they are referred to in the text and close to the citation.

We rearranged placement of the figures accordingly.

Figure 1. I recommend including a legend or further explanation about the colours used. Now, it is not clear what the authors mean by primary wavelength.

We added more information in the caption to provide context on the colors.

“...Bars are colored by the primary wavelength(s) for each platform: red for 1064 nm and green for 532 nm.”

Figure 2. The caption is not clear. What do you refer to by observed satellite laser altimetry maps using Landsat? Is Landsat used here for altimetry?

We revised the caption to prevent confusion.

“Observed satellite laser altimetry maps of the Tuolumne River Basin, CA (highlighted in orange), with Landsat imagery mosaics used as a basemap.”

Figure 3. It is not clear to me what the term “using Landsat imagery” means. I assume you want to indicate that the basemap used was taken from Landsat. If it is the case, I think it is not needed; if not, please clarify.

This is correct. We clarified this in the updated caption.

“Maps of the study sites listed in Table 2, using a basemap derived from Landsat imagery.”

Line 214. Figure 4b is not correctly cross-referenced.

Fixed.

Community Comments

This manuscript is presenting a review on using spaceborne lidar for snow depth retrievals. The authors gathered the recent studies on retrieving snow depth from spaceborne lidar data. They presented a case study over the tundra of Alaska to present accuracy estimates for several current methods. The manuscript is written well and presents the current status of research on using spaceborne lidar in retrieving snow depth to be used in operational hydrological studies. I recommend acceptance after minor revisions. There are some minor comments listed below:

We thank the community member for their comments on our manuscript. Because many of the comments given here were addressed in the reviewer responses, we summarize our changes to the community member's suggestions here.

- Line 209, Figure 4a must be Figure 5a
- Line 232, Figure 5 must be Figure 6
- Line 358, Figure 5 must be Figure 6
- In Figure 3 Hu et al. (2022a) must be Hu et al. (2022b) which is also given in Table 2.

These typos were all fixed.

- It would be good to include the size of the study areas in km² in Table 2, it may give an idea in using these observations for hydrological modelling that is stated in the Conclusion part.

Thank you for the suggestion. We added the areal coverage for all but the Hu et al., (2022b) and Lu et al., (2022) paper, because they focused on ICESat-2 tracks rather than specific domains.

- In Figure 6, it would be good to present the common points from ATL06, ATL08 and ATL06-SR with a different colour to present the consistency of the products in retrieving the snow depth.
- There is so much spatial variation in ATL06 and ATL06-SR products. Are these noises or that spatial variation exists along the track. Especially the snow depth larger than 1.2 m between 70.03° and 70.05 ° in Figure ATL06 is questionable. What is the reason to have this large snow depth. In scatterplot of ATL08 1.2 m is seen but it is not seen in snow depth figure of ATL08. 1.2 m snow depth is not presented in ATL06-SR snow depth and scatterplot figures.
- What is the reason to have a constant snow depth around 70.09 degree in ATL06 snow depth figure. It seems there is a gap of UAF snow depths in this area and an interpolation is applied in this region.
- It would be good to include ground elevation in snow depths of Figure 6. It would give us an idea how the ground elevation is changing along the track.

In response to other reviewers, Figure 6 (now Figure 7) has been overhauled to show an example elevation/snow depth retrieval using ICESat-2, specifically with the ATL06-SR product. The new example has filtering applied to remove faulty values, such as the 1.2 m noted by the community member. The changes also address the remaining comments on Figure 6 by (i) removing ATL06 from the figure, and (ii) adding surface elevation as a subplot to the figure.

- “Spaceborne lidar is currently unable to fulfill the revisit times necessary to achieve global SWE observations every 1-5 days.” I think this sentence is not correct. We can retrieve snow depth from spaceborne lidar but not snow density. Even data availability can be every 1-5 days, how can the snow depth retrieved from lidar can be used to obtain SWE?

This is correct – spaceborne lidar provides snow depths, but not snow density. So, it technically provides a SWE precursor rather than SWE. We revised this sentence to provide better clarification:

“Spaceborne lidar is currently unable to fulfill the revisit times necessary to retrieve snow depths for global SWE observations every 1-5 days.”

New References

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