Review of Spatially distributed snow depth, bulk density, and snow water equivalent from ground-based and airborne sensor integration at Grand Mesa, Colorado, USA

Meehan et al., The Cryosphere Discussion

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This article investigate various ways to spatialize snowpack bulk density based on density retrieved from ground penetrating radar (GPR) transect and quasi simultaneous snow depth retrieved from airborne lidar. The approach used is based on advanced technologies as opposed to labor-intensive, human made, snowpit measurements. The topic is very important in snow water equivalent estimation as more snow depth maps become available but the density remains rarely measured and even more rarely spatialized.

The work is interesting, well presented and will be of interest for people engaged in water resources estimations. I have the following concerns that should be adressed.

1. I am generally unsure about the way some statistics metrics and analysis are presented. A large importance is given to correlation, covariance, R and R^2 values in a too simplistic way (e.g. see comments about L340, L349). It is not clear what makes a R^2 value a proof of a significative correlation (see comments about L414). In addition, it is not clear if some correlation between snow densities and wind proxy are not expected considering the topographic predictors used to model the density (see comment about L353). Some additional figures would help to get a better feeling of the results, such as scatter plots between the estimated density, SWE, snow depth and the observed values at the pits.

2. The article is rich, maybe too rich, in methods and results which are diseminated all along the manuscript. For example results about the error estimation based on sensitivity analysis are given in the method (L247), a description of how other uncertainties are calculated is given in the results (L416-417), new methods are presented in the results (L346, L383) or discussion (L443). I would encourage the authors to move the different paragraphs in homogeneous sections.

Minor comments

L13 A bit surprising to focus here on spaceborne measurement while they are absent of the rest of the article.

L13 "*enables landscape-scale snow covered area*" can "*enable*" be grammatically used like that? I acknowledge that the coauthor team has a much better command of English than I do. I still pointed out some gramatical things that seemed odd to me. Please consider it as genuine questions.

L18 "*essential snow physics*" is a word missing?

L23 "*The root-mean-square error between the distributed estimates*" A doubt remains whether this RMSE is i) between modeled density and snowpit density measurement or ii)

the variability of the various models. In the latter case, I would not call it RMSE as there is no independant reference.

L24 maybe keep depth and SWE with the same unit, cm?

L25 "*Wind, terrain, and vegetation interactions display corroborated controls on bulk density that show model and observation agreement.*" I thought that one conclusion of the article was that snowpit are too sparse to sample the terrain variability.

L29 "*declining **of***"?

L35 "*from ground observations is not possible*" this should be tempered. See for instance

Molotch et al. 2004, "Estimating the spatial distribution of snow water equivalent in an alpine basin using binary regression tree models: the impact of digital elevation data and independent variable selection" https://onlinelibrary.wiley.com/doi/10.1002/hyp.5586

L38 "*instruments, which*" delete the ","?

L40 "WorldView" Snow depth maps were also calculated from Pléiades images (Marti et al., 2016; Shaw et al., 2019; Shaw et al., 2020; Deschamps-Berger et al., 2020; Eberhard et al., 2021). Replace WorldView with "high-resolution satellite stereo images" and maybe keep Marti et al., 2016 and McGrath et al., 2019.

Marti, R., Gascoin, S., Berthier, E., de Pinel, M., Houet, T., and Laffly, D.: Mapping snow depth in open alpine terrain from stereo satellite imagery, The Cryosphere, 10, 1361–1380, https://doi.org/10.5194/tc-10-1361-2016, 2016.

Shaw, T. E., Gascoin, S., Mendoza, P. A., Pellicciotti, F., and McPhee, J.: Snow depth patterns in a high mountain Andean catchment from satellite optical tristereoscopic remote sensing, Water Resour. Res., 56, e2019WR024880, https://doi.org/10.1029/2019WR024880, 2019.

Shaw, T., Caro, A., Mendoza, P., Ayala, Á., Gascoin, S., and McPhee, J.: The Utility of Optical Satellite Winter Snow Depths for Initializing a Glacio-Hydrological Model of a High-Elevation, Andean Catchment, Water Resour. Res., 56, e2020WR027188, https://doi.org/10.1029/2020WR027188, 2020.

Deschamps-Berger, C., Gascoin, S., Berthier, E., Deems, J., Gutmann, E., Dehecq, A., Shean, D., and Dumont, M.: Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne laser-scanning data, The Cryosphere, 14, 2925–2940, https://doi.org/10.5194/tc-14-2925-2020, 2020

Eberhard, L. A., Sirguey, P., Miller, A., Marty, M., Schindler, K., Stoffel, A., and Bühler, Y.: Intercomparison of photogrammetric platforms for spatially continuous snow depth mapping, The Cryosphere, 15, 69–94, https://doi.org/10.5194/tc-15-69-2021, 2021.

L42 LiDAR and photogrammetry

L43 "*whereas*" I do not see opposition between the two parts of the sentence.

L51 "*in space more significantly*" => "more in space"

L54: give the spatial variability scale of snow depth as well.

L65 Similar, other works looked at converting snow depth to SWE, see for instance and the citations therein:

Winkler, M., Schellander, H., and Gruber, S.: Snow water equivalents exclusively from snow depths and their temporal changes: the Δsnow model, Hydrol. Earth Syst. Sci., 25, 1165–1187, https://doi.org/10.5194/hess-25-1165-2021, 2021.

Fontrodona-Bach, A., Schaefli, B., Woods, R., Teuling, A. J., and Larsen, J. R.: NH-SWE: Northern Hemisphere Snow Water Equivalent dataset based on in situ snow depth time series, Earth Syst. Sci. Data, 15, 2577–2599, https://doi.org/10.5194/essd-15-2577-2023, 2023.

L71 "*more simple*" => "simpler"?

L116 "*from mean density measured in snow pits with the airborne LiDAR snow depths*"? not clear, please rephrase.

L131 Cite some of these works.

L202 Please repeat here the IOP date.

L212 What is NV5 Geospatial?

L210 "*the local distance between two point clouds*" This sounds like a significative difference with most snow depth studies (e.g. ASO Painter et al., 2016) in which the snow depth is calculated along the vertical direction as the difference between gridded products. I think it should introduce a discrepancy as well with the snow depth measured in snowpits.

L219 "*lidar*" written LiDAR elsewhere

L219 Could the statistics of the elevation difference over stable terrain (snow free, unchanged) be used to estimate the uncertainty?

L224 "*We applied a k-d tree searcher (Bentley, 1975) to co-register the LiDAR coordinates within a 1 m radius of the GPR TWTs*" I understand co-registration as moving one the elevation dataset for instance with a translation vector (X,Y,Z). Is it the case here? If so, can you cite an article using this k-d tree searcher algorithm? It does not seem very common.

L226 "*By calculating the maximum cross-correlation lag on continuous segments of transect data*" not clear what this operation is.

L239 2.4.3 Error and uncertainty are described at various places of the article (L247, L416-417, L443). This is confusing. Please reorganize it.

L249 "*are spatially uncorrelated suggesting that the errors are random and can be treated with filtering.*" = >"are spatially uncorrelated and can be treated with filtering." "filtering" is quite vague, not any filter would be adapted.

L252 "*we reduced the random error to ± 30 kg/m3 by filtering outliers*." Not clear whether you optimized filtering until this error level was reached or if it is a fortunate consequence.

L256 When was the last snowfall prior the IOP?

L312-318 This paragraph does not match the title of this section. It could be move in 2.6, in a section gathering all the spatialisation methods used.

L327 What is the spatial resolution of the density maps? All this smoothing must reduce the actual resolution of the maps.

L340 "*The in situ snow depth observations (hs,Pit and hs,Probe) compare well with the LiDAR snow depths throughout the entire domain (R2 = 0.61, RMSE = 11 cm, ME = 0 cm), however within the open and forested domains individually, LiDAR and GPR estimated snow depths are uncorrelated with in situ snow depths (Table 1).*" This is puzzling. Can a set of points be correlated while two subsets including all the points are not correlated? A simple scatter plot, even in supplement, would help get a better feeling of the data agreement.

L346 "*The GPR data were acquired within a few metres of, but not directly beside the faces of snow pits, which necessitated a radius for pairing observations. The choice of 12.5 m matches that of the filtering during the sensor integration step (Section 2.4.3)*"

This should be in method, not results.

L348 "*Measurements accumulated over 12.5 m distance introduce inherent variability on the order of 10 % (Section 3.3), which, along with differences between representative observation scales may explain the weak correlation between estimated density and the in situ measurements.*" This should go in discussion.

L349 "*weak correlation*" sounds contradictory with the 13% RMSE mentionned which sounds good.

L353 (and L383) Isn't there strong correlations between Sx, the Wind Factor and the topographic predictors used to estimate the densities? In that case, isn't it expected, by construction, that the densities and the wind proxies will be correlated?

L355 "***suggests** that the method retrieves density patterns which are related to the degree of exposure and shelter due to topography and vegetation*" => to discussion

L361 "*The larger (roughly 10 m) spatial support of the LiDAR – GPR estimated densities cannot directly sense subpixel correlation lengths and **potentially** missed a zero-to-five-metre scale-break that is more comparable to the spatial support of in situ density observations*" The existence of the scale break sounds like speculation/discussion, not results. Besides, it sounds obvious that a measurement with a support of N m cannot be used to measure spatial variability at scale < N m.

L364 "*the expected variability among co-located ρ is approximately 2 %,*" Based on which semi-variogram? Not clear. Again, this sounds more like discussion to me.

L367 "*to resolve spatial patterns*" => "to resolve spatial patterns at finner scale." There might be spatial pattern of larger scale than 100 m.

L368 "*depth and density **formulate** TWT and SWE,*" formulate is not clear. By definition, the SWE is the product of depth and density.

L370 3.4. Please provide metrics comparing the density modeled and measured (mean, median bias, standard deviation, RMSE...).

L376 "*This coincided*" what is "this"?

L378 "*as the random field contains little meaningful spatial information*" This is quite expected (idem L388). By construction it is spatially random. I am not sure what is the point of this randomly distributed density. Is it used in other studies?

L379 "*spreads the strengths*" formulation unclear.

L391 "*The lack of a large-scale topographic trend in density, such as one driven by elevation or aspect, evinces the role of forest vegetation on density.*" is this supported by a figure showing density against elevation or aspect? I don't understand the link between the two parts of the sentence, the elevation/aspect and the forest vegetation.

L407 "*with an appropriate correlation length and prior mean and spread but maintain a larger bias*" too many "and", hard to understand.

L409 "*covariance exists*" it always does, doesn't it? Do you mean that it is large or small?

L410 "*has a negative bias of approximately 7 %*," hard to compare with the other bias mentionned above which is in kg m-2.

L414 "*R2 = 0.16*" seems like weak correlation. What is the R2 of "*the errors among snow depth and density are uncorrelated*"?

L417 "*Following from the propagation of errors for relative errors in snow depth and density, we estimated the SWE uncertainty to first order (Raleigh & Small, 2017)*." this should be in methods and better explain.

L418 "*The distributed relative SWE uncertainty is presented in Fig. 10 and is negatively correlated with the distributed SWE (R2 = 0.44).*" I understand this as: the larger the SWE, the smaller the error. But I understand that the inverse was true for snow depth and density (L414-415). Sounds inconsistant.

L435 "*Sensitivity analysis*" how does this articulate with the SWE uncertainty in 3.7. I understand that the uncertainty is estimated in two ways: by comparison with the snowpits values and with the sensitivity analysis. This should be clarified in the relevant parts (methods, results) and evaluated.

L440 "*the leading source of error in our density measurement is spatial misalignments*" but further, the impact is estimated to be of 1 kg/m², that is way less than the 15 kg/m² reported or, I guess, the difference with the snow pits.

L441 It is not clear what this cross-correlation is exactly but if it provides the misalignment value, could it not be used to correct it?

L445 What does integration mean?

L447 "*up to 2 %*" use consistent units, kg m-2 in the same sentence.

L455 "*the choice of uncertainties propagated*" it makes it sound like these choices are purely subjectives and not well informed.

L456 "*uncertainty in midwinter tends to reduce at peak SWE*" cite a relevant source for this statement.

L457 "*remarkably difficult*" does the mean density of several snowpits work as well (L475)? If so, the remarkable difficulty is rather to spatialized the density.

L465 "*improved ...importance*" increased?

L470 "*can be treated as random normal*" Say clearly if it has a normal distribution or if it is assumed.

Fig 3, 4, 5, 7: Divergent color map (red, yellow, blue) is not really appropriated for variables which are always positive. It is traditionnaly used for variables centered on zero (yellow).

Fig 3. Could be moved to supplement.

It should be considered to put in a single figure (with adapted colorbar) the snow depth, the density and the swe map. It is hard to identify the patterns similarity as long as they are spreaded over different figures.

Fig 7. This could be moved to supplement and rather show the density map used most in the article (mean of the models).

Figure B1 what are the grey bars? I would move this figure to main manuscript.
Figure C1. Could be merged with Fig 8.