Reviewer 2
Paper Summary:
The authors compare two relatively new methodologies for using UAVs for mapping snow depths in forested and open prairie environments with in situ ground validation GNSS surveys. They present a very thorough analysis involving an impressive collection of data from 19 unique survey dates from two distinct environments over the course of a single winter season. The time and effort taken to plan, collect, and process such a comprehensive dataset cannot be overstated! The results of the comparison on the ability of both the UAV-lidar and UAV-SfM to estimate snow depths are not necessarily new, but to my knowledge, they have not been compared as extensively with both the successes and failures of both methodologies clearly presented. In open environments, the UAV-lidar and UAV-SfM snow depth mapping capabilities are similar, but in vegetated areas, the UAV-lidar methods excel by having the ability to penetrate through vegetation and measure sub-canopy snow depth. However, in densely vegetated, tight canopy environments, even the UAV-lidar mapping method cannot penetrate the canopy and therefore cannot produce reliable snow depth estimates. An added benefit of using the UAV-lidar over UAV-SfM for snow depth mapping is the insensitivity of the lidar to homogeneous surface conditions and variable/poor solar illumination, both of which contribute to substantial errors in UAV-SfM mapping. In-addition, the increased vertical accuracy of the UAV-lidar sensors can be used to better detect patterns in snow distribution and depth previously not obtainable over basin-wide study sites in complex landscapes. The authors do a nice job at presenting their findings in a well-written manner using suitable figures. As an added bonus, the authors also discuss the cost difference between the UAV measuring methodologies, and calculate a metric that assigns a dollar value to each centimeter of improved RMSE between methods. This cost analysis is of interest, but probably has less relevance for the future, as the price for the type of equipment used in this study continues to decrease dramatically year-by-year. I recommend the publication of this paper pending minor revisions addressing the suggested comments and technical edits.
A PDF supplement has also been uploaded that contains all the suggested edits/comments. In the technical edits section, this PDF supplement has all changes highlighted in **BOLD.**
An example of the suggested changes to Figure 7a has also been uploaded as Figure 1 – Slide 1.JPG. This example figure provides a visualization of the changes being suggested for Figures 7a, 8a, 9a (applies to General Comment at Line 270/295/300).

First, thank you for this detailed review and you will find our responses in red below the corresponding comment.

General Comments:
Line 59 – ‘differencing snow-covered (hereafter snow) and snow-free (hereafter ground)…’ Double check terminology throughout paper for consistency. The following different term are used: bare-ground, bare ground, ground, surface, bare surface. Personally – I like the use of the term bare-ground.

We refer to ‘surfaces’ which can be either snow or snow-free. “Bare’ refers to points left after vegetation point removal for either a snow or snow-free surface. ‘Ground’ implies a snow-free surface. We have edited the paper to make the terminology more consistent, following these rules throughout.

Line 59 – ‘Digital Surface Models (DSMs)’ I think you are actually referring to the Digital Terrain Models (DTMs). Change this reference throughout the paper.

I agree that DSM may not be appropriate here as its definition implies that it is the top of the surface whether that be the soil surface in open areas or the top of the canopy in forested areas. A DEM is closer to our meaning in that it is a bare-surface raster grid, with trees and vegetation excluded, referenced to a vertical datum. A DTM on the other hand has various definitions, some of which are incompatible with what we are describing in this paper:

1) DEM can be synonymous with DTM in some countries https://gisgeography.com/dem-dsm-dtm-differences/
2) In the US and other countries, a DTM is not a DEM, but is a vector data set composed of regularly spaced points and natural features such as ridges and breaklines. A DTM augments a DEM by including linear features of the bare-earth terrain. https://gisgeography.com/dem-dsm-dtm-differences/
3) DTM: bare-earth representation with irregular spaces between points (non-raster). Behrendt, R. Introduction to LiDAR and forestry, part 1: a powerful new 3D tool for resource managers. The Forestry Source, p. 14-15, set. 2012.

DTM is an acronym with various definitions that may complicate its application here as we are considering both bare ground and snow surfaces beneath a forest canopy. We feel that it is more appropriate to call these “snow DEM” and “ground DEM” as I am filtering out vegetation points and focusing on the extracted “bare surface” points. Deems et al. 2013 uses DEM to describe snow and bare ground surfaces.

Line 134 – ‘flight parameters to maximise mapping efficiency were set to…’ What about limiting the scan angle? The Riegl lidar can scan 360 degrees, what level of off nadir scan angle did you limit the data collection/processing to and why?
The Riegl scanner does scan in a 360º configuration. While data can be limited to specific scan angles at collection it was not limited in our application, as there is no increase in performance/accuracy to do so – the mirror is rotating the full 360º. The scan angle was not limit in processing the data either. The laser is relatively low powered and we have found that returns at angles shallower than 70º from nadir are rare. Hence, we did not limit the available data to perform our analysis – any points available were used to optimize the surface feature extraction.

Line 135 – ‘100 m flight altitude above the surface…’ Did the mission planning software make use of terrain following mode to ensure consistent flight altitude above ground? If so, what source of terrain information did you use?

Yes used terrain following with respect to a SRTM DEM. Have added ”The UgCS flight control software was used to generate flight paths with these parameters and terrain following with respect to an underlying SRTM DEM”

Line 148 – I deleted the term differential: differential GNSS corrections (code-based) are significantly less, accurate than RTK/PPK/PPP (carrier phase methods) – I suspect even though the Leica GS16 unit is DGPS capable, you used the more accurate carrier phase correction methods.

Correct, we were using the carrier phase methods. ‘differential’ has been removed

Line 150 - suggest removing the term ‘random within the survey areas and’ if the transects were also selected to most efficiently survey the greatest variety of vegetation types.
Agreed – we have removed that text.

Line 152 – ‘provided a real-time-kinematic (RTK) survey solution …’ While conducting your manual surveys did you make use of the RTK capabilities – or did you post-process the rover data as indicated at line 153?

The difference between the rover and base was established during the surveys with RTK. Because the base position was not known in advance to the surveys the RTK observed rover positions needed to be adjusted to absolute locations in post processing once the base position was established through the PPP step – an offset needed to be calculated and applied to survey points. In post processing the only adjustment was made to the base position not the relative rover-base positioning. This is clarified as: ” Post-processing with Leica Infinity software (version 2.4.1.2955) established the absolute positions of the rover points by maintaining the RTK rover-base position but adjusting the base station absolute location to that established by the PPP tool.”

Line 152 – ‘accuracy of < ±2.5cm.’ Can you provide a reference for this?
Not shown here but the uncertainty is computed in real-time as part of the RTK and PPP based solutions see below and was consistently less than of < ±2.5cm –not based on a reference.

Line 154 – ‘(https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php)’ Add this website to the references section
Have added this to the references.

Line 154 – ‘absolute base station location.’ How long did you collect your raw GNSS data for and what were the PPP computed standard deviations for the base station locations? Did you always use the same base station location for every flight?

Due to the logistics of conducting campaigns at multiple sites, raw GNSS data was only logged when we were on site with different tripod setups. Therefore logging varied in duration between 2.5 and 9 hours. The PPP computed standard deviations were consistently less than 2cm –often better. For simplicity the uncertainty of the survey solution was presented to be ± 2.5 cm. This value is based propagating a conservative uncertainty of the PPP based solution 2cm and the RTK solution off 1.5cm. sqrt (2^2+1.5^2)=2.5. We have updated section 2.2.3 to reflect this.

Line 174 – '<2.5 cm.' Do you mean +/- 2.5 cm as mentioned earlier in the text? Is this value based on the specs of the Leica GS16 GNSS survey equipment or was it based on the PPP online standard deviations? How did you obtain this value?
See comment above

Line 181 – '< ±2.5 cm' Same comment as above? Is this value based on the specs of the Leica GS16 GNSS survey equipment or was it based on the PPP online standard deviations? How did you obtain this value?
See comment above

Line 205 – 'vegetation height (open <0.1 m, shrub <0.5 m, and trees >0.5 m)…' These values differ from what is in the Figure 4 caption. Which vegetation height classes did you use, and how did you choose the class heights?
The caption for figure 4 and text were slightly incorrect due to relics of an earlier edit. Vegetation height classes were open <0.5 m, 0.5 m ≥ shrub ≤2 m, and trees >2 m. Vegetation classes were selected with a simple metric to differentiate vegetation based on the height data at hand. There will be variability in shrub heights, but for simplicity we used 0.5m and 2m thresholds as they were consistent with field observations at the various sites and thresholds previously reported in the snow hydrology literature which ranged from 0.5m to 3m in Marsh et al. (1997) and 0.3m to 2m in Rasouli et al. (2019).

Marsh, P., Pomeroy, J.W., Pietroniro, A., Neumann, N., Nelson, T., 1997. Mapping Regional Snow Distribution in Northern Basins Inuvik Area. Saskatoon, Saskatchewan. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.712.6847&rep=rep1&type=pdf

Rasouli K., Pomeroy J.W., and Whitfield P.H. (2019) Are the effects of vegetation and soil changes as important as climate change impacts on hydrological processes? Hydrology and Earth System Sciences: 23, pp. 4933-4954 DOI: 10.5194/hess-23-4933-2019

Line 223 – I deleted reference to RTK - In line 55 you indicate the rover survey points were post-processed, therefore I am assuming you used a PPK GNSS solution here?

RTK with a post processing of the base position to account for PPP. See comments above.

Line 230 – 'points extracted from the point clouds or interpolated surfaces…' This sentence is confusing. It is unclear whether you extracted the UAV snow depth values from the point clouds or the interpolated DSMs? Which one was it?

Caption was in error and is corrected as “Plots are segmented for vegetation class (rows), sites (columns) and observation method (colours).”

Line 256 – Figure 6 - Please add to the caption a description of which metrics are visualized by the whiskers of the boxplots.

Have added: “Median is indicated by the line inside the box, the upper bound is the 75th percentile and the lower bound is the 25th percentile and whiskers represent the range of values beyond the box.”

Line 266 – ‘The noisy UAV-SFM points in the middle of the slope challenge the snow surface extraction even without the presence of vegetation leading to an underestimation of the snow surface.' Do you have any idea on why the SfM product detected something in the open areas on the slope? Why does it lead to an underestimation of snow in this area? Based on the Figure 7a cross-section it looks like the UAV-SfM red points are equal to or above the green lidar points. Why did the interpolation go so low? Did the interpolation treat missing points as 0 or bare ground values?

Looking closer at the UAV-SfM noise in Figure 7a there was some vegetation mid slope near to the transect. The lidar was able to differentiate it well but the SfM-generated vegetation points occupied a larger space and intruded on the transect line. Therefore when vegetation was removed it led to a gap in the UAV-SfM point cloud at this point in the transect, which when interpolated through led to the underestimation in the snow surface. When gaps are present the interpolations are sensitive to edge points which tend to have poor quality and therefore challenge the validity of the resulting surface.

Have added: “These vegetation points occupied a larger space than the UAV-lidar and intruded on the transect line. Therefore, vegetation removal from this point in the transect led to a gap in the UAV-SfM point cloud, but not the UAV lidar point cloud. Interpolating through the gap in the UAV-SfM point cloud resulted in underestimation of the snow surface.”

Line 270/295/300 – Figure 7-8-9 - Suggest using shaded/transparent colour bars on plot a) to indicate the extent of the tree features. This will help highlight the tree well extent and how the UAV-SfM interpolation result in deeper snow values across these features (I have uploaded an example Figure of 7a. that illustrates what I am trying to describe – Slide 1.JPG). Suggest using a more obvious colour in Figure b) for highlighting the SfM only classes. Suggest trying to match the tone of colours in Figure c) to more closely match that used in Figure b). Making the open areas a little bluer, and again highlighting the SfM only points in a more obvious colour. Figure 7b It sort of looks like the SfM only class occur near the edges of the study area in a just a couple areas. Is this related to steeper scan angles at the edge of the study site, perhaps coupled with steep terrain?

Have modified the figures to have polygons outlining areas of interest in the cross sections and changed the colour scheme to more clearly show differences in point coverage. The SfM-only points occurred on the edges of the domain as this was nearing the edge of the lidar flight area (less overlapping scan areas reduces the point density and therefore reduces number of ground points)

Figure 9c) I suggest mentioning in the figure caption that the large dark areas of no lidar points represent the extent of the melt water ponds.
The figure caption is rather large already so prefer to leave this discussion in the text.

Line 288 – the negative UAV-SfM snow depth estimates discussed here are explained at lines 443-450. Perhaps also providing further explanation here might be helpful.
To simplify the results section would suggest that this explanation fits better into the discussion section as it is.

Line 316 – In the example of 7a, the interpolation resulted in erroneously deep snow depth estimates. This will not always be the case and in some instances can result in underestimations depending on the season, elevation, forest type, etc. Many studies have highlighted the differences in snow depths/characteristics between open/forested sites that will influence these interpolation errors. I think providing some further explanation on the type/magnitude of interpolation errors that may occur when using UAV-SfM techniques would help strengthen your findings/statement here.

Have added: "Open areas will have greater snow depths than forest areas (Troendle 1983; Swanson et al., 1986; Pomeroy et al., 2001; Mazzotti et al., 2019;) meaning UAV-SfM solutions, or any approach which requires interpolation of point cloud gaps beneath trees, will overestimate snow (Zheng et al., 2016)."

Line 318 – 'major improvement on previous attempts.' Can you provide some context on what is considered a major improvement, including references to previous studies/RMSEs?

Have removed "major" as that is an unquantifiable adjective. Have modified it to be "The ability of UAV-lidar to map snow-depths, with and without canopy cover, and capture tree wells with RMSE's ≤0.15 m is an improvement on previous attempts. This RMSE is comparable to previous efforts with UAV-SfM (Bühler et al., 2016; De Michele et al., 2016; Harder et al., 2016), airborne-SfM (Bühler et al., 2015; Nolan et al., 2015, Meyer and Skiles 2019) and airborne-lidar (Deems et al., 2013; Painter et al., 2016) that have been primarily focussed on mapping the snow depth of open snow surfaces. Applications of airborne-lidar to forested areas report similar errors (Zheng et al., 2016; Currier et al., 2019; Mazzotti et al., 2019) but the higher flight altitude of airborne platforms and their near nadir perspective limit point densities near tree centres that are necessary to capture tree wells."

Line 318 – 'previous efforts…' Can you provide some references?
Same as comment above.

Line 321 – '0.14 m RMSE (Deems et al., 2013).' Can you provide the actual magnitude of errors previously reported for comparison in the Deem et al., 2013? What is the significance of this 0.14 m RMSE?

Have removed this 0.14 m RMSE per comment from Reviewer 1

Line 342 – 'intermittent precipitation totaling approximately 100 mm' How was this determined/measured? What kind of uncertainties are associated with this reported precipitation value. I also want to confirm that you mean 10 cm of snow? This seems low for mountain snow.
There are a number of precipitation gauges (Geonor and Pluvio) within the Fortress mountain research basin. I say 'approximately' as this was an approximation of the raw storage gauges signals as the data QA/QC and undercatch corrections were beyond the scope of this project. And yes I do mean that this is approximately 10 cm of snow. It is low for a mountain situation but 2019 was a low snow year in this area and the February to April interval this is reflecting was a cold, dry period without any major snowfall events.
Have added; "measured at storage gauges at the study site"

Line 350 – 'and development of a tree well in the middle of the transect. The Figure 10b transect demonstrates the lack of wind redistribution in the canopies relative to the Figure 10c transect on the ridgeline.' It is unclear where the development of the tree well is highlighted/visible in Figure 10b. It also unclear how Figure 10b demonstrates the lack of wind re-distribution in the canopies. Please provide more detail here.
Have highlighted the tree wells with orange polygons in figure 10b. Have added the following to clarify the comment on demonstrating a lack of wind redistribution in the forest area. "The Figure 10b transect demonstrates the lack of wind redistribution in the forest; snow accumulation was consistently observed to be ≤ precipitation over the transect, versus the Figure 10c transect on the ridgeline, where the accumulation in the lee slope greatly exceeded the observed precipitation."

Line 366 – 'In contrast UAV-SfM struggled with sensing snow depths in the short shrubs on the edges of wetlands.' This sentence contradicts the results displayed in Figure 5, which illustrated that the UAV-SfM had lower RMSE in the shrub class compared to the UAV-lidar. It also does not support the discussion starting at Line 286 and expanded at Lines 443-450, which discusses the challenges that BOTH lidar and SfM face in trying to measure below the canopy in dense shrub vegetation.

This sentence needed to be a bit more nuanced. This is not a comment on the RMSE differences and should not have highlighted the shrubs in particular rather this was based on the fact that there is a higher point cloud density for the lidar versus SfM in wetland areas. This is clarified as "In contrast UAV-SfM struggles with sensing snow depth on the edges of wetlands as seen by the concentration of lidar only areas at the wetland in the Rosthern study area (wetland area highlighted by red polygon in Figure 8b).

Line 467 – 'Observational approaches are also a challenge as typical in situ measurements are destructive, limited in extent, and often too limited to develop robust relationships of depth versus density at the small scales needed (Kinar and Pomeroy, 2015a; Pomeroy and Gray, 1995).' The methods developed by Proksch et al., 2015 do provide a method for measuring snow density at a much smaller scale applicable for these process-scale studies. The Proksch et al., 2015 methods have been recently rigorously applied to a set of snow on sea ice measurements by King et al., 2020, highlighting the ability to document the local-scale variations in snow density relatively quickly over larger spatial extents.

Proksch, M., Löwe, H. and Schneebeli, M., 2015. Density, specific surface area, and correlation length of snow measured by high-resolution penetrometry. Journal of Geophysical Research: Earth Surface, 120(2), pp.346-362.

King, J., Howell, S., Brady, M., Toose, P., Derksen, C., Haas, C., and Beckers, J.: Local-scale variability of snow density on Arctic sea ice, The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-305, in review, 2020.

These methods while very interesting and small scale are still destructive sample methods which means that their application to a UAV-based solution to SWE estimation, that captures local and landscape scale density spatial and temporal variability, will be limited. The small sample size and empirical calibration of the micro-penetrometer method results in uncertainty in its application.

This is communicated through a slight edit as " Observational approaches are also a challenge as typical in situ measurements are destructive, limited in extent, and often too limited to develop robust relationships of depth versus density at both the small local and large landscape scales needed (Kinar and Pomeroy, 2015a; Pomeroy and Gray, 1995). Opportunities may be available to pair UAV-lidar with other UAV-borne sensors such as passive gamma ray or snow acoustics (Kinar and Pomeroy, 2015b) to non-destructively develop high spatial and temporal resolution estimates of snow density and ultimately water equivalent.."

Line 474 – 'necessary spatial scales' – Please be more specific on what scales you are referring to.

Have removed this sentence as the scales are mentioned later in the conclusion section.

Technical Comments:

Line 13 – suggest changing to 'measure returns from a wide range of scan angles, **increasing the** likelihood of successfully…'

Changed

Line 51 – suggest changing to 'are valuable automated data sources, but **are spatially limited in extent and can often** suffer from location/elevation bias…'

Changed

Line 53 – suggest changing to ‘and so **may** not **be** suitable for snow hydrology calculations or model validations **in forested regions** even though they are often…’
Changed

Line 60 – spelling correction: quality
Changed

Line 62 – suggest changing to ‘pulse can be observed with **returns possible from within the canopy and from the sub-canopy ground surface.** In contrast UAV-SfM…’
Changed

Line 64 – spelling correction: variability
Changed

Line 80 – spelling correction: focused
This is correct Canadian English spelling.

Line 87 – punctuation: ‘In dense forests, vegetation…’
Changed

Line 90 – suggest changing to ‘increase in snow accumulation **over** aerodynamically rough surfaces or **in** sheltered areas **where the wind speeds decrease and snow is deposited** – this includes forest edges…’
Changed

Line 98 – suggest changing to ‘varies across complex vegetated landscapes…’
Changed

Line 105 – suggest changing to ‘ability of the UAV-lidar and UAV-SfM **techniques for measuring** snow depth in open
Changed

Line 106 - (50.833 N, 115.220 W)
Changed

Line 108 – spelling correction: focused
This is correct Canadian English spelling.

Line 109 – suggest changing to ‘(Figure 1a – background center)…’
It is already directly identified as the a) panel so will leave as is.

Line 111 – suggest changing to ‘alpine ski resort in the 1960’s, **but is** currently a limited-use…’
Changed

Line 114 – suggest changing to 'Canadian Prairies were **examined** in this study.'
Changed

Line 117 – correction: remove negative sign if using 'W' to indicate west (51.941 N, 106.379 W) & (52.694 N, 106.461 W)
Changed

Line 125 – Figure 1 caption: suggest changing to 'Figure 1: a) Fortress Mountain Snow Observatory in Kananaskis, Alberta Canada, b) **Rosthern** and c) **Clavet prairie** study locations in Saskatchewan Canada. Data collection was on Fortress Ridge (**background center)** an area of high topographic variability and **a mix of** dense forests and clearings. The Clavet **photo** highlights the **transition zone between the open upland terrain and the lower elevation vegetated** wetland. The Rosthern scene highlights the low vertical relief **of upland areas** and isolated woodlands amongst cultivated fields.
Changed

Line 155 – suggest changing to 'GS16 rover points to **correct** for the PPP **updated** base station locations **were completed using** the Leica Infinity software…'
This section has been reworked and this edit no longer applies

Line 158 – 'suggest changing to 'To assess the accuracy of the **UAV snow depth measuring** methods, as well as provide insight into the **seasonally evolving** snow **depth/**distribution, **a total of** 19 **flight/manual** surveys were conducted **between all three study sites between** September 2018 to April 2019. These are summarised by date, **surveyed** surface, **UAV** data collected, and corresponding number of **manually surveyed** surface elevation points in Table 1.
Changed

Line 165 – suggest changing to 'difference between a bare ground DSM and a snow **surface** DSM.'
Changed but using DEM rather than DSM

Line 176 – suggest changing to 'Finally, overlapping scan data **from adjacent flight lines are** used to optimise the IMU trajectory, to align the scan lines and reduce the noise of the final point cloud within the RiPrecision tool. **This final step in noise reduction can improve the final product because the 1.5 cm laser data precision is greater than the post processed IMU trajectory accuracy.** (I used the 15mm stated precision of the Reigl sensor presented earlier in the text to get the 1.5cm value here)
Changed and absolutely correct on that last sentence to clarify matters.

Line 193 – suggest changing to 'For **the bare-**ground lidar scans, the height of vegetation…'

Changed

Line 207 – spelling correction: include
Changed

Line 214 – suggest changing to ‘2.3.6 **Point Cloud Density’**
Changed to ‘Point Cloud Coverage’ as density has a different meaning. Here I’m trying to quantify how gappy the bare point clouds are.

Line 221 – suggest changing to ‘3.1 **Accuracy of UAV-lidar versus UAV-SfM snow depth estimates**
Changed

Line 231 – suggest changing to ‘Plots are segmented for points extracted from the point clouds or interpolated surfaces **within each vegetation class** (rows), sites (columns) and observation method (colours).’ – See general comments above about clearing up the confusion concerning which product the points were extract from.
Changed

Line 232 – suggest changing to ‘The influence of vegetation on **estimating** snow depths **from UAVs can be** directly assessed by…’
Changed

Line 234 – suggest changing to ‘Open Prairie and **open** Fortress **RMSE values** are similar (0.09 m and 0.1 m RMSE respectively)…’
Changed

Line 235 – suggest changing to ‘equally successful **at** penetrating the open leaf-off deciduous tree canopy at the prairie sites as the closed needleleaf canopy at the Fortress site **based on the similar RMSE values within each site’s tree vegetation class.**’
Changed

Line 238 – suggest changing to ‘The Open vegetation has a large RMSE range **between sites** (0.1 m in Prairie and 0.3 m in Fortress respectively) while vegetation **class** RMSEs range from…’
Changed

Line 240 – suggest changing to ‘UAV-lidar in the prairie Shrub case, **the difference between these techniques is only 0.04 m, which is** within the **+/- 2.5 cm** observational **uncertainty** of **the GNSS** survey equipment **used in this project.**
Changed

Line 247 - suggest changing to ‘manual **GNSS** surveys **using boxplots** (Figure 6). **The boxplots in Figure 6 illustrate that** the UAV-SfM snow surface elevations…’
Changed

Line 257 – suggest changing to '3.2 **Point cloud density'**

Changed to "Point cloud coverage" per previous comment.

Line 263 – suggest changing to 'could not reliably return surface points **with a density > 1 pt 0.25 m-2**whilst…'

Changed

Line 263 – punctuation: 'At Fortress, UAV-lidar…'

Changed

Line 265 – suggest changing to 'lack of UAV-SfM sub-canopy points identified within the treed vegetation class results in an interpolated snow surface that is erroneously deep under trees, completely missing the detection of the reduced snow depths which are clearly detected (green line) around the base of the trees by the UAV-lidar.'

Changed

Line 274 – suggest changing to 'c) with **the same** overlain transparent point type classification **colour scheme as shown in b).'**

Changed

Line 276 – suggest changing to 'The predominantly open nature of the Prairie sites demonstrates a minimal difference in **point density** between **UAV-lidar and UAV SfM measurement** techniques. The average **extent of the study domain covered with a point density of > 1 pt 0.25 m2 for** 5 coincident flights at the Prairie sites **was computed, resulting in the** mean coverage of 92% versus 83% **of the study area** for **the UAV-lidar and** UAV-SfM **respectively.**

Changed

Line 281 – suggest changing to 'These gaps in the **UAV-SfM** point clouds are interpolated and therefore will represent…'

Changed

Line 287 – suggest changing to 'both lidar pulses and SfM solutions interpret the vegetation surface as the **top of the bare-**ground **or snow** surface and therefore **little difference exists between these two DSMs during all measurement periods.** An additional challenge of **using the** UAV-SfM **techniques** is that large gaps **in points** appear beneath the tall wetland edge vegetation due to the inability to penetrate the sub-canopy, as visualized **in the cross-sections** of Figure 8a and 9a**,** where the estimated UAV-SfM snow surface is below the UAV-lidar ground surface.'

Changed

Line 316 – suggest changing to 'Sub-canopy snow depth mapping with UAV-SfM therefore becomes an exercise in **interpolating snow depth values observed in open** areas **without** vegetation **to areas with dense vegetation,** rather than sensing the actual snow depth under the canopy.'

Changed

Line 322 – suggest changing to '4.2 **Bare-ground point cloud density is critical'**
Ground in this case can be either 'ground' or snow so 'surface remains more appropriate.

Line 323 – suggest changing to 'The **increased** point **density** of UAV-lidar…'
Not so much density as lack of gaps aka coverage. Changed to "The increased continuous point coverage of UAV-lidar"

Line 325 – suggest changing to 'The point cloud cross-sections **illustrated** in Figure 7 emphasize **these findings, highlighting the** wider gaps in the UAV-SfM point cloud beneath individual trees that require interpolation **over longer distances resulting in greater potential for error.**' (The lidar data also requires interpolation)
Changed

Line 332 – suggest changing to 'In contrast, **mountainous regions** have much more complex topography…'
Changed

Line 337 – suggest changing to 'continuous bare-**ground** point cloud coverage.'
Ground in this case can be either 'ground' or snow so 'surface remains more appropriate.

Line 338 – suggest difference word choice for: foreshadow
Changed to 'Two examples are presented here to exemplify analyses the possible with UAV-lidar'

Line 340 – suggest changing to 'Differences between open and forest snow cover processes can be **explored** by **examining** the difference in snow depth…'
Changed
Line 342 – suggesting changing to 'UAV-**lidar measured** change in snow depth visualizes…'
Changed

Line 343 – suggest deleting line: 'The upper, open terrain clearly demonstrates the influence of blowing snow redistribution' because this sentence is ambiguous.
Line deleted

Line 343 – suggest changing to 'In the Figure 10c transect **cross-section** there was accumulation of up to 2 m over the **September-April time** period on lee slopes, whilst the upper windswept portions of the ridge demonstrate snow erosion **between February and April.**"
Changed

Line 346 – suggest changing to 'The dynamics and extents of blowing snow sources **(grey/red)** and sinks **(blue)** are clearly visualized in **10a, which closely match the findings of** Schirmer and Pomeroy (2019) using SfM **for this same study region.**
Changed

Line 347 – suggest deleting line: 'Considering the forest slope brings out features that UAV-SfM cannot observe.' Because this sentence appears as a fragment
Deleted sentence

Line 349 – suggest changing to 'there is a general decline in snow depth **from February to April** (due to melt on the south facing slope).'
Changed

Line 360 – suggest changing to 'wind-blown snow from **open** upwind sources and are typically associated with…'
Changed

Line 366 – suggest changing to 'Areas that the UAV-lidar was able **to** measure correspond to areas…'
Changed

Line 390 – suggest changing to 'This gradient in dust and albedo **is likely associated with** the increases in snowmelt rates **observed** downwind of the grid road.'
Section has been reworked.

Line 405 – suggest changing to 'UAV-lidar, relative to UAV-SfM, provides **the ability to measure** snow depth below vegetation…'
Changed

Line 408 – suggest changing to 'and cheaper **equipment,** subscriptions to virtual reference station networks if available in the study area **(requires only a rover and not a base station),** or equipment rentals are all viable alternatives to lower costs.'
Changed

Line 410 – suggest changing to 'The main cost difference **between UAV-lidar and UAV-SfM platforms** is therefore in terms of the **UAV** sensor **payload.**'
Changed

Line 412 – suggest changing to 'like consumer grade UAVs (DJI Phantom 3 < $2,000 CAD), **to** more expensive options like…'
Changed

Line 413 – suggest changing to 'Current integrated lidar systems suited to **UAV** snow mapping'
Changed

Line 423 – suggest changing to 'In contrast, **most current** UAV-lidar **configurations** need larger platforms that require more cycles of large battery sets to cover similar areas, which represents a **logistical** challenge in **keeping the batteries warm and charged in** cold and remote areas.'
Changed

Line 428 – suggest changing to 'Despite the lower **initial purchase** cost and **longer flight endurance,** the errors and artefacts that UAV-SfM **measuring techniques** introduce in sub-canopy **snow depth measurements,** as detailed in sections 4.3.1 and 4.3.2, **suggest that UAV-SfM is not able to directly measure snow depth** in **densely vegetated environments.**'
Changed

Line 434 – suggest changing to 'Precise classification of surface points from snow and ground scans **are** needed to resolve…'
Changed

Line 435 – suggest changing to 'The accuracy and resolution demands **are such** that bare-**ground** surface classification techniques **developed** for airborne platforms to resolve topography and hydrography at watershed scales from **lidar** last returns **may** be unsuitable for resolving snow depths.'
Have changed this sentence with respect to Reviewer 1 comments

Line 438 – suggest changing to 'filtering tools and associated parameters to **be able to reliably detect the sub-canopy bare-ground surface and** achieve desired quality…'
Changed

Line 441 – spelling correction: 'large-scale'
Changed

Line 448 – suggest changing to 'the areas of negative snow are limited to areas where snow depth is **relatively** shallow **in comparison to the** deep snow in the wetland edges.'
Changed

Line 452 – suggest changing to 'snow depth estimation in **these** hydrologically significant snow accumulation areas.'
Changed

Line 453 – suggest changing to 'ground surface, but **current** sensors **with these characteristics** may exceed **the payload capacities** of most UAV platforms. Advances in bare surface classification/**filtering** software…'
Changed