Responses to Dr. Harpold's comments (Page numbers and line numbers referred here are from the non-markup version manuscript)

Responses to the major comments

1. Improvements in writing and framing: The paper could be substantially improved by better highlighting and framing the novelty of this work. The abstract does not highlight novelty; tell the reader more simply what the 2-3 most important points of the work are. The introduction seems to wander and needs to have several sentences pointing back to why this work is needed. I suggest adding a guiding statement to the paragraph beginning on line 24. Something like "The consistency of snowpack distributions across vegetation and topographic gradients is difficult to measure and predict". Just a thought, but something is needed to help lead the reader more clearly through the introduction.

The results are lacking in several ways. First organizationally they are hard to follow. Why not organize them around the same ideas in the same order as the discussion? Throughout the results more specifics need to be included. What are the statistics describing the linear correlation (4385, line 11)? How much less in cm or % (line 13, 4386)? How much does it increase and what are the fluctuations (4386, line 26)? These are just a few examples. Imagine the figures and tables are not easily seen (which they are not): tell the reader what the results are quantitatively.

Response: Thanks for your suggestions and we improved highlighting and framing of the work. Therefore, in consideration of comments from both reviewers, we restructured the findings of the work into three main take-home points and are highlighted them through the manuscript. Also, we changed the structure of the results and now is consistent with the discussion and more specifics are included in the results.

Changes in the manuscript:

(1) We now structure our findings to highlight three main take-home points:

- *The fraction of pixels for which Lidar measured snow depth in dense forest depends on the pixel size, or averaging area, used when processing the raw Lidar point cloud.*
- *Other than elevation, aspect and slope also control the distribution of snow depths.*
- *In mixed-conifer forest, for area under the canopy, the effect from canopy overwhelms effects from slope and aspect, in most sites, and the interactions between these features could be observed from the data.*

(2) The explanations in the results were rewritten to include more specifics and the structure now is in the same order as discussion. See Section 3, page 15-16.

2. Unclear methods for residual: Was the elevation-dependent snow depths estimated the same equation at each site (i.e. the average of all watersheds) or was a different relationship developed for each watershed (seems more appropriate)? If a single relationship was used, how was the decline in Wolverton snow depths are

higher elevations accounted for (i.e. did it reduce the slope of the line and if so, can you fairly assume this is not a function of moisture depletion and changing orographic effects?). I am skeptical that a single linear relationship is appropriate given the steepness and orientation to typical storm tracks is not the same in all watersheds. Please justify the use of a single orographic relationship. I am unclear how the snow depth residual versus slope can nearly always be negative (Figure 6a), when it is a mixture of positive and negative as a function of aspect and penetration factor. I would double-check your data analysis used in 6a.

Response: The elevation-dependent snow depths were not estimated with the same equation at each site we used four individual models. Furthermore we compared the difference between them using four models versus one, and it does not make much difference in terms of estimation bias (See attached Figure #1). However, in the text we now present the overall linear model for all sites. For the decline in Wolverton, we plotted the raw pixel snow depth versus elevation and it seems that the variability starts to increase drastically after that elevation threshold, which is near tree line, this is likely due to wind redistribution or exhaustion of perceptible water both of which are beyond the scope of this paper. Thus we filtered those data from our revised analysis. Figure 6a is correct because the mean of residuals is below zero does not mean there is no residual that is greater than zero. And since the residuals are averaged into different variable's bins, it is possible that the mixture is not zero. Under the new framework of the manuscript, the figure is just used for checking existence of the effect from the variable, not quantifying the effect.

Changes in the manuscript:

(1) *Text on how the residuals are calculated was added in Section 2.5, starting from page 13 line 253.*
(2) *Justification of using either one model versus four models was added in Section 4.2, starting from page 19 line 402.*

3. Relative importance of predictive variables not discussed: One of the major short-comings of the manuscript is that it does not talk about the relative importance of the predictive variables in controlling the distribution of snow depth: slope, aspect, and vegetation canopy. I think this limits framing and describing the novelty of the work. While I realize that a full statistical model with interactions may be beyond the scope of the current work, some ability to quantify the relative importance of these variables would strengthen the paper. Beyond this, a more informative discussion of the interaction of the predictive variables is needed. This is begun in the last paragraph on line 4389, but not clearly framed around all the findings.

Response: Thanks for the suggestion and we agree that the relative importance of predictive importance should be included and discussed and in the revised manuscript. We used random forest with regression trees to check the relative importance of the predictive variables and the interactions between vegetation and other predictive variables are now discussed as well under the canopy effect, we show the interactions by filtering the northness into flatter terrain showing the snow depth difference *between open area and under the canopy is more stable above the rain snow transition elevation.*

Changes in the manuscript:
(1) Results and discussions about relative importance of variables were added in Section 3 (page 15 line 317) and Section 4.2 (page 19 line 405)
(2) Interactions between physiographical variables were discussed in Section 4.3 (page 21 line 441)

4. Explanation for differences between open and under canopy locations is not well supported: The authors provide one plausible hypothesis for the increasing differences between open and under canopy snow depths with increasing elevation. Namely, that the same density of vegetation intercepts more snow as precipitation increases. I find this interpretation difficult to understand and not clearly supported by evidence. I suggest making this point clearer and looking for more supporting evidence. When one looks at the figure supporting this assertion (presumably Figure 5a), you really only see a clear pattern in in one watershed (Providence) and mixed or no relationship in the others. Why is this? The authors suggest that changes slope and aspect alters the relationship in middle elevation bands for Wolverton, is this consistent with the proposed hypothesis?

I can think of an alternative hypotheses that the authors should either consider or refute: vegetation structure and forest canopy organization change with elevation in ways that affect interception, i.e. more sparse canopy coverage promotes accumulation in open areas or denser vegetation (where present) at higher elevations (in a related note, I ask for penetration factor plotted against elevation).

To me this is the most interesting result of the paper. I suggest bringing it more forward and adding more discussion (alternative hypotheses) to the discussion (and abstract).

Response: Upon consideration of this and reanalysis the snow depth differences between open and under canopy locations increase primarily with elevation in the rain-snow transition zone, this is because the snow depth increase versus elevation is nonlinear in this region and the gradient of that nonlinear curve is larger in the open area than under the canopy. Above this elevation the difference becomes more stabilized without the influence of other predictive variables. (See attached figure #2). And the figure showing penetration fraction against elevation is shown. Also, the canopy-coverage effect on accumulation in open areas and under-canopy is quantified in the multivariate regression models of both cases. And the relative importance of variables shows that vegetation structure does exert different effects on snow in open areas and under-canopy.

Changes in the manuscript:
(1) The result is changed and we discussed about the causes of our new findings in the

discussion.

Responses to detailed comments

1. See numerous comments in attached pdf

Response: Changes made to address the comments

2. What is the calculation of the standard error
3. Is snow depth normally distributed across these ranges of elevations (I doubt it)? Why not use percentiles to describe its variation at a given elevation (4384, line 21-22).

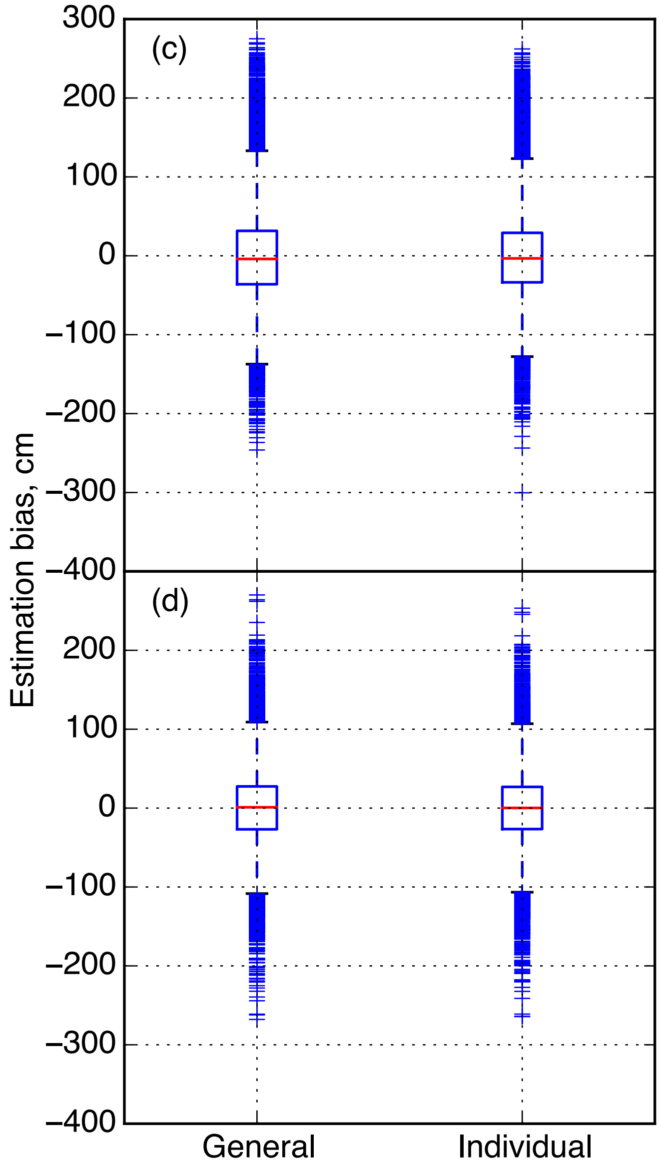
Response: Responding to both questions, we used standard deviation as the standard error. And the snow depth is normally distributed across most ranges of elevations, except for the highest elevation areas at Wolverton, we have changed the standard error to percentiles.

4. Why do you do Gaussian smoothing on the residual with a 5 m radius? Justify this better or explain sensitivity to other smoothing lengths.

Response: We did a sensitivity test to other smoothing lengths and it turns out the smoothing result is not quite sensitive to the radius when the radius is larger than 1.5 m, and the standard deviation begins to stabilize after 5-m radius, so we chose 5-m (See attached Figure #3). And have added this as a panel in Figure 3.

5. Consider using lidar (lower case) instead of LiDAR: "Let's Agree on the Casing of Lidar". http://www.lidarnews.com/content/view/10908/198/

Response: This link could not be opened when I checked it out. I Googled about Lidar and the title of Wikipedia is written as "Lidar". So I agreed and I changed all the acronyms in the manuscript.



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Estimation bias, cm
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Figure 1

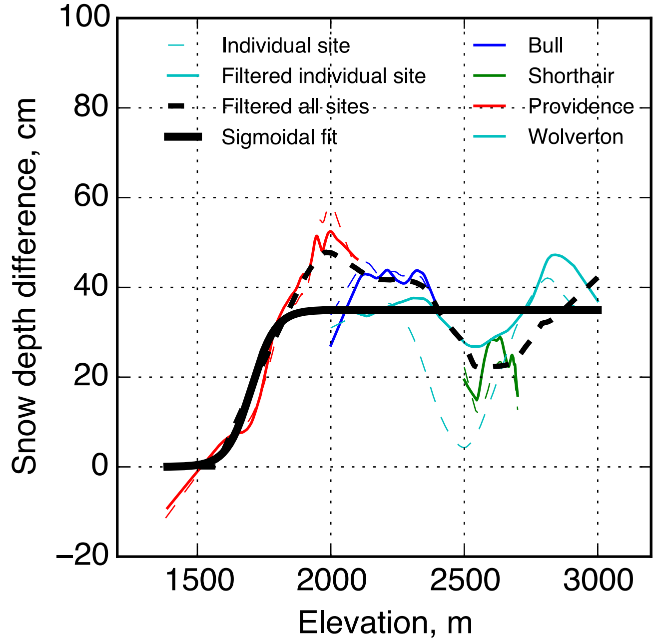
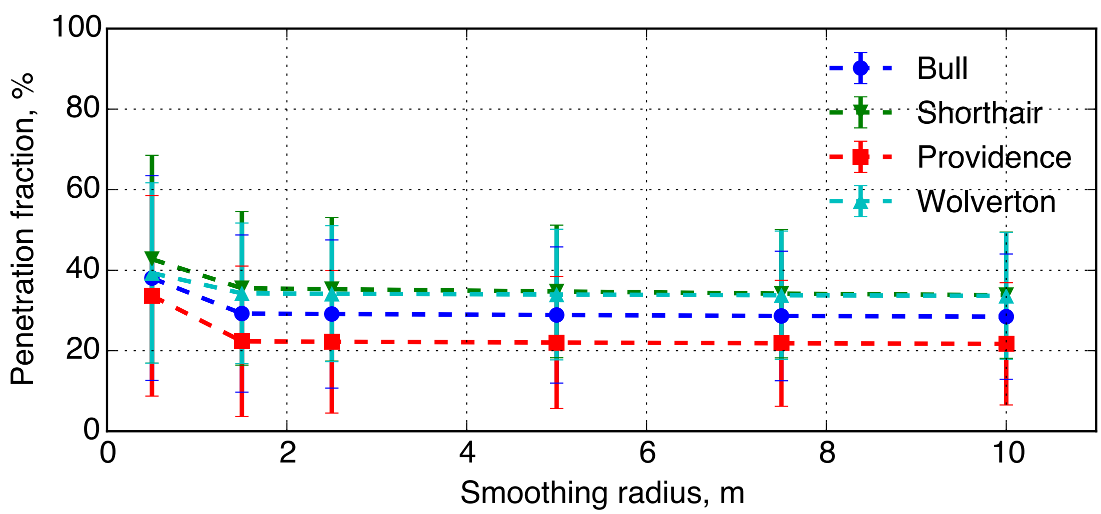


Figure 2



Fugre 3

Responses to Dr. Sturm's comments (Page numbers and line numbers referred here are from the non-markup version manuscript)

Responses to major comments

1. In this paper, the authors use airborne LiDAR data to assess primarily how the snow pack depth increases with elevation on the west side of the Sierras, and secondarily, how other factors (canopy cover, slope, aspect) affect the distribution of snow. The main conclusion (increasing snow depth with elevation to 3300 m) is not novel, nor is the basic technique of using airborne LiDAR to measure snow depth, but I suspect that what the authors have done is reach their conclusions regarding snow depth gradients using better and more comprehensive data than heretofore has been available. Unfortunately, the paper as written does not make clear what is novel and what is not in the study, and the paper suffers from too much detail in discussing secondary effects (slope, aspect, canopy), obscuring the main conclusions about elevation gradients. There is also a somewhat offhand attitude in the discussion of the choice of sites and why those might constitute an "upslope transect" along the western side of the Sierras. While the choice of sites may (or may not) have been chosen for the purposes of the present study, the paper would be improved if the authors were up-front in examining the choice of study sites, comparing and explaining why these sites can reasonably be used together. I think this approach works because storms come from the west, while the range runs north-south, thus the orographic lifting effect can be thought of as a two-dimensional problem. . ...but the authors need to explain and document this if it is true for the readers.

Response: Thank you for these observations, we have clarified what makes this research novel and we structured our findings into three main points, which are much clearer than in the original manuscript. For site selection, we could not do much about it because the sites were selected for multi-disciplinary investigation of the Southern Sierra Critical Zone Observatory. This is the only point-cloud data set currently available with snow-on and snow-off in the southern Sierra.

Changes in the manuscript:

(2) *We now structure our findings to highlight three main take-home points:*

- *The fraction of pixels for which Lidar measured snow depth in dense forest depends on the pixel size, or averaging area, used when processing the raw Lidar point cloud.*
- *Other than elevation, aspect and slope also control the distribution of snow depths.*
- *In mixed-conifer forest, for area under the canopy, the effect from canopy overwhelms effects from slope and aspect, in most sites, and the interactions between these features could be observed from the data.*

(3) *We changed the title to "Topographic and vegetation effects on snow accumulation in the southern Sierra Nevada: a statistical summary from LiDAR Data" rather than "Orographic …". because orographic lift is one of the findings*

from the data set but not the current main finding of this paper.

(4) *We rewrote our introduction as suggested and modified results and discussion in response to the specific comments.*

(5) *We added the rationale for using these sites for our analysis, in Section 2.1, page 8 line 152.*

2. One other area of confusion needs to be improved in the paper: the authors introduce 4 linear models of increasing depth with elevation (or at least I think it is 4 models (Table 3)). What is the point of having 4 models? For large scale studies, wouldn't a single, averaged linear model be of more use? And if four models is what is needed, what is the use of these models? This part of the paper would be improved if the linear model was actually presented as a formula, and more care was taken in explaining how the residuals (Figures 6 and 7) were computed.

Response: We investigated the difference between using 4 linear models instead of using one (see attached figure #1), and they did not make much difference in terms of estimation bias. Using 4 individual models is slightly better because each catchment area has its own microclimate that could affect the snowpack. We have provided a formula for presenting the model and a better explanation of calculating residuals.

Changes in the manuscript:

(1) *A figure comparing use of using one vs. four models is added (Figure 9) and discussed in Section 4.2 (page 19 line 402)*

(2) *Equations for the combined 4 areas are added for the linear model (Equations 2-3).*

(3) *We added text in Section 2.5 (page 13 line 252) to clarify the calculation of residuals*

3. Lastly, unless I missed it, there is no discussion of the accuracy of the snow depth measurements. . ..no check of the LiDAR results compared to ground measurements. I suspect the accuracy is order ±10 cm, but the authors need to address this question.

Response: Addressed in the revised manuscript.

Changes in the manuscript:
We added this in the last line in Section 2.3 (page 11 line 210) in the revised manuscript.

Responses to detailed comments

1. Abstract: I found this longer than needed and needless confusing. It seems like the first 7 lines were fine, then it bogged down in details that are not first order. For example, that canopy cover decreases from 80% to 0% with elevation is hardly a new result. Does it need to be in the Abstract? The last 7 lines make little sense until one reads the paper. I suggest deleting this or making clearer the meaning of the data.

Response: Abstract revised to meet with the restructured conclusions

2. Introduction:

Get right to it: this paper is not about ALL orographic systems....it is about the Sierras. Plunge in and talk about the current state of knowledge for the west side of the Sierras, and tell us what has been lacking in those data and how this study will fill that gap. On pages 4379 and 4380, you name the studies that have been done, but not what was found and why that information might be deficient. Tell us what the current numbers are for the snow gradients and why these numbers might be in error, then why your LiDAR data can help fix the problem.

Response: Thank you for your suggestions and we rewrote the introduction. Researchers have been successfully using regression trees or univariate regression to model the snow distribution on the west side of the Sierra. However, generally applicable regression coefficients could not be extracted from regression-tree models, and univariate-regression models do not account for the effect of additional topographic variables. And the relative importance of these variables has not been discussed. So the new three main points of the manuscript address these knowledge gaps.

Changes in the manuscript:

(1) Much of the introduction has been rewritten and we now introduce previous findings on snow distribution and knowledge gaps for the Sierra Nevada.

Page 4381, end of Introduction: It seems to me that the three state goals of the paper could be restructured a little differently and perhaps better. The prime goal could be the orographic gradient. In order to get that gradient, you have to deal with the other influences (slope, aspect, canopy), so you do. Also, there is a lot of discussion in the paper of canopy gaps vs. under-canopy snow. You should explain why knowing this is important (for example, is it to produce meaningful areal averages?).

Response: Now addressed please see main comment #1.

3. Section 2.1: Study Area: (see main comments). It is important that here you address why these areas were used, and why they can be used in concert. Looking at the map, they define a line parallel (rather than perpendicular to) the Sierras, which makes one a little suspicious. I was also struck by the differences in the areas. Two are nearly flat; Providence is almost below the rain line, and Wolverton has a huge elevation range. Without it, I suspect it would have been hard to reach the conclusions currently in the paper. You need to explain why you have confidence in using these sites together. Also, add to Table 1 the mean elevation and elevation range for each site.

Response: Now addressed in Section 2.1 (page 8 line 151). These are the only point-cloud snow-on and snow-off data currently available for the southern Sierra. Another compelling reason to use them together is that the elevation range, after combining, *covers from the rain-snow transition zone to above tree line.*

4. Section 2.2: Data Collection. It states that met data was used to determine if it snowed during the 4 days of data collection. Did it?

Response: No, it did not. See section 2.2 (page 9 line 176).

5. Section 2.3: Data Processing: Define all acronyms. Page 4383. I ended up drawing a little sketch to clarify the various surfaces. Maybe it is worth adding such a figure. Also, a little more descriptive names might help. For example, why a "Surface Model". Why not a "Canopy Top Model" and a "Snow Surface Model? Finally, some discussion of snow depth accuracy is needed. See the new paper in The Cryosphere by M. Nolan, C. Larsen and M. Sturm for a detailed discussion of this topic.

Response: We followed standard convention for naming of acronyms please see http://neondataskills.org/remote-sensing/2_LiDAR-Data-Concepts_Activity2/ We also addressed the accuracy of the snow depth this time.

6. Section 2.4: Penetration Fraction: Perhaps I failed to understand this completely, particularly the section on under-canopy vegetation. It seems like you are deciding that there is only one canopy (tree tops?) and if the laser gets below that canopy, you discount any shrub-like vegetation? Also, your test of the fraction seems incestuous. Did you test it against independent data?

Response: Because snow accumulates higher than most under canopy vegetation, over most of the domain, we assume that the snow would accumulate as it would in the open. There is no independent data to compare with at this spatial resolution. Musselman et al., 2013 addressed this question and is cited (page 11 line 223).

7. Page 4384, Line 17: This statement (". . .elevation was selected as the primary topographic attribute. . . " confirms what is effectively true for the whole paper and is why I suggest revising the paper so that primary goal is clear, and treating canopy, slope and aspect as variables that need to be dealt with in order to clarify the main elevation control.

Response: Orographic effect is verified with the Lidar data. But the main contribution of the paper are the additional variables.

8. Page 4386, Line 8: Is the decrease in snow depth above 3300 m real?

Response: We believe this is a real effect probably attributable to exhaustion of perceptible water and/or wind redistribution. However because of the relatively small area above 3300 m, it is highly variable and difficult to draw general conclusions from Wolverton data set without support from other data. Explained in the manuscript as above on page 15 line 308.

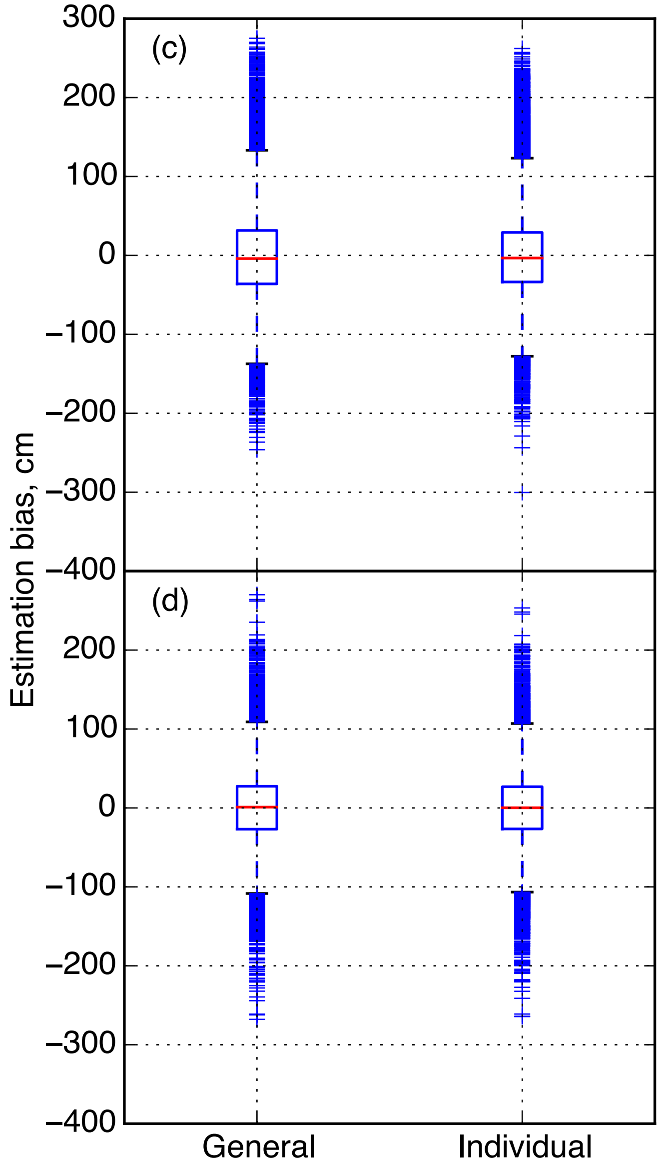
9. Discussion, Page 4387, line 7: This "linear model" seems important, but nothing is said

about its use. I assume it is used for water balance studies and the like, so it is important to have it as accurate as possible. You should explain why this model is important, and if developing a better model was a goal of the work. Also, why have 4 models? Why not a single, average model? Be sure to include the model as a formula so it is clear how it was done.

Response: We now present a single linear model that includes slope, aspect and penetration fraction for all four areas. Using 4 individual models is slightly better in predicting the snow depth. Either approach could be used depending on the site and question.

10. Discussion of vegetation effects, Page 4388: First, there are many types of vegetation. I think this section really refers to trees and tree canopies. Best to use more precise nomenclature here. Second, it felt like you were trying to glean too much from the data. There is some interaction between canopy density and snow depth, so that the decreasing canopy density with height is convolved with the increasing depth with elevation. I wonder if it is really necessary (and supported by the data) to dissect this combined effect in too much detail? I also wondered about rain-on-snow, which is not discussed much. It must also affect the interception by the canopy.

Response: We acknowledge that there are many other factors that influence under-canopy snow accumulation. However we did find, by constraining the combined effect of slope and aspect to flatter terrain, that vegetation effects saturate above a certain elevation. Below that elevation, the increase of the snow depth difference could be explained by rain-on-snow and nonlinearity of snow depth increase with elevation. These points are now discussed in section 4.3 and shown in figure 10.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Estimation bias, cm
General
Individual

Figure 1

List of relevant changes made in the manuscript (page numbers and line numbers referred here are based on the marked-up version of the manuscript)

1. **Title:** Changed from Orographic… to Topographic… in order to fit into the new take-home points of the paper

2. **Abstract:** On page 2 from line 17 to line 29, new take-home points are highlighted.

3. **Introduction:** On page 6 from line 91 to line 103, knowledge gaps of snow distribution in the Sierra are discussed. These unknown could be addressed using Lidar data.

Also, on page 7 from line 114 to 117, we added discussion about the knowledge gaps even after using Lidar, however could be filled with our new findings in this manuscript.

On page 7-8 from line 133 to 139, new questions specific to take-home points are carried out in the end of the Introduction section.

4. **Methods 2.1:** On page 8 from line 151 to 153, the rationale of using this data set is discussed.

On page 9 from line 161 to 165, some physiographic reasons why this data set could help us understanding the snow distribution in the Sierra were added.

5. **Methods 2.2:** On page 9 line 176, no precipitation was observed from the ground measurements.

6. **Methods 2.3:** On page 11 from line 201 to 212, error from Lidar is discussed.

7. **Methods 2.4:** On page 12 from line 230 to 232, sensitivity of smoothing radius was tested and discussed.

8. **Methods 2.5:** On page 12 from line 234 to 239, methods of analyzing the first take-home point are introduced here.

On page 13 from line 252 to 258, methods of calculating residual and residual analysis are added.

On page 13 from line 268 to 272, methods of analyzing relative importance of variables are introduced.

9. **Results:** On page 14 from line 279 to 283, new take-home point result is added in this paragraph.

On page 15 from line 315 to 339, more specific results and equations of linear models are shown.

9. **Discussion 4.1:** On page 17 from line 359 to 369, discussion of the new take-home point is discussed here.

10. **Discussion 4.2:** On page 19 from line 391 to 412, quantified effects of physiographic variables, relative importance of variables and justification of using one linear model vs. four linear models are discussed here.

11. **Discussion 4.3:** On page 20 from line 427 to 461, vegetation effects on snow accumulation along elevation are discussed, and the hypothesis which Dr. Harpold proposed in the comments is tested and discussed.

12. **Conclusions:** Conclusions of the new take-home findings and discussions are added here instead of the original findings.

~~Orographic~~ Topographic and vegetation effects on snow accumulation in the southern Sierra Nevada: a statistical summary from Lidar~~DAR~~ data

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Abstract

Airborne light detection and ranging (Lidar~~DAR~~) snow-on and snow-off measurements collected in the southern Sierra Nevada near peak snow accumulation and in the snow-free season in the 2010 water year were analyzed for ~~orographic~~ topographic and vegetation effects on snow accumulation ~~during the winter season~~. Combining point-cloud data from four sites separated by 10 to 64 km, ~~and together covering~~ with total surveyed area over 106 km^2, it was observed in that the mixed-conifer forest the percent of pixels with snow-depth measurments is sensitive to the sampling resolution used in processing the point cloud. This is apparently due to Lidar not receiving returns from under the denser canopy. From the 1-m gridded data, it was observed that in addition to elevation effects, snow depth has a strong dependency on slope, aspect and canopy penetration fraction. A multivariate linear model built using all physiographic variables explained 15 to 25% more variability in snow depth than did a univariate linear model with elevation as a single predictor. However, the weight that each physiographic variable exerted on snow depth varied across different elevation ranges, as well as with different canopy-cover amounts. The difference between mean snow depth measured in open area and under canopy increased with elevation in rain-snow transition zone from 1500 to 1800 m and stabilized at about 25 to 45 cm above about 2000 m elevation, with the range reflecting the effects of other topographic variables. ~~area, the 1-m elevation-band-averaged snow depth in canopy gaps as a function of elevation increased at a rate of 15 cm per 100 m until reaching the elevation of 3300 m. The averaged snow depth of the same elevation band from different sites matched up with minor deviation, which could be partially attributed to the variation in other topographic features, such as slope and aspect. As vegetation plays a role in the snow accumulation, the distribution of the vegetation was also studied and shows that the canopy coverage consistently decreased along~~

~~the elevation gradient from 80% at 1500 m to near 0% at above 3300 m. Also, the absolute difference of the averaged snow depth between snow found in canopy gaps and under the canopy increased with elevation, and decreased with canopy coverage disregarding the variation of other topographic features. The influence from the forest density on snow accumulation was quantified based on the snow-depth residuals from 1-m elevation-band-averaged snow depth and the attribute penetration fraction, which is the ratio of the number of ground points to the number of total points per pixel of LiDAR data. The residual increases from -25 cm to 25 cm at the penetration fraction range of 0% to 80%; and the relationship could be modeled by exponential functions, with minor fluctuations along the gradient fraction of canopy and small deviation between sites.~~

1. Introduction

In the western United States, ecosystem processes and water supplies for agricultural and domestic use depend on the mountain snowpack as~~is~~ the primary source of late-spring and early summer streamflow ~~and is associated with agricultural and municipal water supplies~~ (Bales et al., 2006). Knowledge of spring snowpack conditions within a watershed is essential if water availability and flood peaks following the onset of melt are to be accurately predicted (Hopkinson et al., 2001). Both topographic and vegetation factors are important in influencing the snowpack conditions, as they closely interact with meteorological conditions to affect precipitation and snow accumulation distribution in the mountains (McMillen, 1988; Raupach, 1991; Wigmosta et al., 1994). However, the distribution of mountain precipitation is poorly understood at multiple spatial scales because it is governed by processes that are neither well measured nor accurately predicted (Kirchner et al., 2014). Snow accumulation across the mountains is primarily influenced by orographic processes, involving feedbacks between atmospheric circulation and terrain (Roe, 2005; Roe and Baker, 2006). In most forested regions, snow accumulation is highly sensitive to vegetation structure (Anderson, 1963; Revuelto et al., 2015; Musselman et al., 2008), and canopy ~~snow~~ interception, sublimation and unloading result~~s~~ in ~~smaller~~ less accumulation~~s~~ of snow beneath the forest canopies in comparison with canopy gaps (Mahat and Tarboton, 2013).

The Sierra Nevada is ideally suited for studying mountain snow distribution and related hydrologic processes because it serves as a barrier to moisture moving inland from the Pacific, ~~provides~~ has an ideal ~~mountainous region~~orientation for producing orographic precipitation, and thus exerts a strong influence on the upslope amplification of precipitation (Colle, 2004; Rotach and Zardi, 2007; Smith and Barstad, 2004). Recent studies have revealed some insights of snow-depth dependency on orographic and topographic effects in the Alps (Grünewald et al., 2013; Grünewald, et al., 2014; Lehning et al., 2011), suggesting that similar studies could be extended to the Sierra Nevada. And among the forested regions of the mountains, the mixed-conifer and subalpine zones cover most of the high-elevation, seasonally snow-covered area. ~~The geographic, topographic, and vegetation conditions make the Sierra Nevada a natural laboratory in the western United States for studying mountain snow distribution and related hydrologic processes (Grünewald et al., 2013; Grünewald, et al., 2014; Lehning et al., 2011).~~

~~In order to have a better knowledge of precipitation and snow accumulation in the Sierra Nevada,~~ M~~m~~anual snow surveys, one-time surveys, and remote-sensing products are used to estimate precipitation and snow accumulation in the Sierra Nevada~~and analyzed~~ (Guan et al., 2013). *In* ~~-~~*situ* ~~observations~~ , operational measurements of snow water equivalent (SWE) ~~were obtained~~come from monthly manual snow surveys and daily snow pillow observations (Rosenberg et al., 2011). Cost, data coverage, accuracy (Julander et al., 1998) and basin-scale representativeness are issues for *in situ* monitoring of SWE in mountainous terrain (Rice and Bales, 2010). Satellite-based remote sensing, such as MODIS, has been used to map snow coverage in large or even global areas. ~~Fractional snow coverage, grain size and albedo have retrieved from MODIS data (Hall et al., 2002; Painter et al., 2009; Rittger et al., 2013), however the products do not fit catchment-size studies owing to its low spatial resolution.~~ However, i~~I~~t ~~also~~ only provides snow-coverage information in canopy gaps, and no direct information on snow depths (Molotch and Margulis, 2008). There is also the SNOw Data Assimilation Systems (SNODAS) that integrate data from satellite and *in situ* measurements into a physical snowpack model, which provides SWE and snow~~-~~depth ~~information~~ estimates (Barrett, 2003). However, since ~~Since the spatial resolution of~~ SNODAS ~~is 1 km and its products~~ has~~ve~~ not been ~~globally~~

broadly evaluated (Clow et al., 2012), its potential for studying the snow distribution in mountainous areas remains uncertain. Also, owing to its 1-km spatial resolution, the snow depth that SNODAS provides is a mixed representation of both open and canopy-covered areas. ~~SNODAS could not be used for studying the snow distribution on catchment scale in the Sierra Nevada.~~An orographic-lift effect is observable in most of the above data (Howat and Tulaczyk, 2005; Rice et al., 2011), and a binary-regression-tree model using topographic variables as predictors has also been used for estimating the snow depth in unmeasured areas (Erickson et al., 2005; Erxleben et al., 2002; Molotch et al., 2005). However, regression coefficients could not be estimated accurately for most of the predictors, except for elevation, and the consistency of the orographic trend as well as the relative importance of these predictors is still unknown owing to lacking representative measurements across different slopes, aspects and canopy conditions. And the stability of the variance explained by the model also needs to be tested with denser measurements.

In recent years, airborne Lidar~~DAR~~ has been employed for high-spatial-resolution distance measurements (Hopkinson et al., 2004), and has become an important technique to acquire topographic data with sub-meter resolution and accuracy (Marks and Bates, 2000). Therefore, Lidar~~DAR~~ provides a potential tool to help understanding spatially distributed snow depth across mountainous regions. With multiple returns from a single laser ~~beam~~pulse, Lidar~~DAR~~ has also been used to construct vegetation structures as well as observe conditions under the canopy, which helps produce fine-resolution digital elevation models (DEMs), vegetation structures, and snow-depth information. However, the snow depth under canopy can not always be measured because of the signal-intensity attenuation caused by canopy interception (Deems and Painter, 2006; Deems et al., 2006). A recent report applied a univariate-regression model to the snow depth measured in open areas using Lidar; with a high-resolution DEM used to accurately quantify the orographic-lift effect on the snow accumulation just prior to melt (Kirchner et al., 2014). From this analysis it could be expected that Lidar data might also help explain additional sources of snowpack distribution variability in complex, forested terrain.

~~Even without LiDAR surveys, Erickson et al., (2005) and Erxleben et al., (2002) have used intensive *in situ* SWE measurements with binary regression tree, linear and nonlinear multivariate regression models for studying the topographic and vegetation controls on the spatial distribution of snow in the Colorado Rocky Mountains. But the studying sites were smaller than catchment size, and the results were site dependent as well as the sampling schemes have to be taken into consideration. Recent snow distribution modeling methods developed upon LiDAR measurements have been focused on fractal analysis and linear regression. Even the fractal distributions of snow depth do not vary with sites on local scale from 1 to 1000 m (Deems et al., 2006) and the topographic dependency of spatial snow-depth distribution have been explored (Kirchner et al., 2014), consistency of the topographic and vegetation effects across sites still need to be addressed.~~

The objective of this work reported here is to improve our understanding of the ~~effect of elevation, slope, aspect and canopy cover~~ topographic and vegetation effects on snow accumulation in the mixed-conifer forest. We investigated these by using ~~LiDAR~~ Lidar data collected in four headwater ~~catchments~~ areas in the southern Sierra Nevada and address the following three questions. First, is it possible to have snow-depth measurements in forested mountain terrain from all pixels on a fine sampling resolution (1 to 5m) using Lidar data? If not, how does the percentage of pixels measured change with the sampling resolution. Second, what is the importance of slope, aspect and canopy penetration fraction on snow accumulation, relative to elevation; and are effects consistent across sites? Third, what is the snow-depth difference between open and canopy-covered areas; how does it change with elevation; and is the difference stable with respect to other topographic variables? ~~First, is there a consistent orographic effect on snow accumulation across catchments; and what attributes could account for variability across and within sites? Second, what is the snow-depth difference between canopy gaps, versus under canopy, along elevation; and is binary classification for canopy cover adequate to the differences? Third, how does forest density influence the snow accumulation in canopy gaps and if there are patterns, are they consistent across catchments?~~

2. Methods

2.1 Study Areas

~~The~~ Our study areas are~~is~~ located in the southern Sierra Nevada, approximately 80 km east of Fresno, California (Figure 1). The f~~F~~our headwater-catchment research areas, Bull Creek, Shorthair Creek, Providence Creek, and Wolverton Basin were previously instrumented, including meteorological measurements, in order to have a better knowledge of the hydrologic~~al~~ processes in this region (Bales et al., 2011; Hunsaker et al., 2012; Kirchner et al., 2014). The sites were chosen as part of multi-disciplinary investigations at the Southern Sierra Critical Zone Observatory, and are also the main instrumented sites in the observatory. Wolverton is approximately 64 km ~~away in the~~ southeast ~~direction~~ of the other three sites (Figure 1) and is located in Sequoia National Park. Both snow-on and snow-off airborne ~~LiDAR~~ Lidar were flown in 2010 (Table 1~~, only later date collections were processed~~) over these sites. The elevation of the survey areas ~~covers~~ is from 1600-m to 3500-m elevation.~~,~~ ~~over which~~ V~~v~~egetation density generally decreases ~~with biotic zones of~~in high-elevation subalpine forest, ~~and~~ with Wolverton also having a large area above treeline ~~in Wolverton~~ (Goulden et al., 2012). The precipitation has historically been mostly snow in the cold and wet winters for elevations above 2000 m, and a rain-snow ~~transition~~ mix below 2000 m, where most of Providence is located. The comparison between Providence and the other sites can help in accessing if observed trends are consistent above and below the rain-snow transition. Also, various elevation spans of sampling sites is important in understanding the stability of the relative importance of physiographic variables across heterogeneous topography.

2.2 Data Collection

All~~Both~~ airborne LiDAR surveys were performed by using Optech GEMINI Airborne Laser Terrain Mapper. The scan angle and scan frequency were adjusted to ensure a uniform along-track and across-track point spacing (Table 2), and six GPS ground stations were used for determining aircraft trajectory. The snow-on survey date was close to April 1st, which is used by operational agencies as the date of peak snow accumulation for the Sierra~~time~~. Since the snow-on survey ~~lasted~~ required four days to ~~finish data collection over~~cover the four study areas, time-series *in situ* snow-depth data measured continuously from Judd Communications ultrasonic depth sensors ~~of the meteorological stations~~ at Providence, Bull and Wolverton were used to estimate changes in snow depth during the survey period.~~ for checking if precipitation had occurred during survey dates and~~ While no snow accumulation was observed, ~~also taking~~ snowpack densification and melting observed from the time-series data were taken into considerations (Hunsaker et al., 2012; Kirchner et al., 2014). The snow-off survey was performed in August ~~when~~ after snow ~~was~~ had completely melted out in the study areas.

2.3 Data Processing

Raw ~~LiDAR~~ Lidar datasets were pre-processed by NCALM and are available from the NSF Open-Topography website (http://opentopography.org) in LAS format. The LAS point cloud~~s~~, including both canopy and ground-surface points, are stored and classified as ground return and vegetation return.~~;~~ E~~e~~ach point is also attributed with the total number of returns and position of all returns from its source laser pulse~~beam~~. The 1-m resolution digital-elevation models, generated from the ~~LiDAR~~ Lidar point-cloud datasets, were downloaded from the OpenTopography database and further processed in ArcMap 10.2 to generate 1-m resolution slope, aspect, and northness raster products. Northness is an index for the potential amount of solar radiation reaching a slope on a scale of -1 to 1, calculated from:

$$N = \sin(S)\times\cos(A), \tag{1}$$

where N is the northness value; S is the slope angle of the terrain; and A is the aspect angle. Northness is also the same as the aspect intensity (Kirchner et al., 2014) with 0° focal aspect. Since in this analysis the snow-depth comparison is only discussed between north and south facing slopes, northness is used instead of aspect intensity for simplification. To construct the vegetation structure from ~~LiDAR~~ Lidar data, points that are from the first return of the laser pulse~~beam~~ are used to generate 1-m gridded digital~~-~~surface models. And 1-m resolution canopy-height models were ~~was~~ built by subtracting the digital-elevation models from the digital-surface models.

The snow depths were calculated directly from the snow-on ~~LiDAR~~ Lidar data. By referring to canopy-height models, all ground points in snow-on ~~LiDAR~~ Lidar datasets were classified as under canopy or in canopy gaps. That is, if the point was ~~under~~coincident with canopy of >2-m height, it was classified as under canopy, and otherwise in a canopy gap. After classification, snow depths were calculated by subtracting the values in the digital-elevation model from the snow-on point-measurement values. The calculated point snow-depth data were further assigned into 1-m raster pixels, averaged within each pixel, formatted and then gap filled by interpolation with pixel values around it. Since the measurements collected under canopy were insufficient within each pixel (Figure 2) and varied across the transition from the tree trunk to the edge of the canopy, interpolation was not applied to data under the canopy. The error rate of the calculated snow depth should be mainly from the instrumental elevation error, which is about 0.10 m (Kirchner et al., 2014; Nolan et al., 2015).

2.4 Penetration Fraction

The o~~O~~pen-canopy fraction is a factor that represents the forest density above a given pixel and is ~~often~~ used to describe the influence of vegetation on snow accumulation and melt. However there is no algorithm to directly extract this information from ~~LiDAR~~ Lidar data. Here we use a novel approach we call penetration fraction to approximate the open-canopy fraction from the ~~LiDAR~~ Lidar point cloud. Penetration fraction is the ratio of the number of ground points to~~and~~ number of total points within each pixel. Because the electromagnetic radiation from both ~~the LiDAR~~ Lidar and sunlight beams are intercepted by canopies, the open-canopy fraction is used here as an index to represent the fraction of sunlight radiance received on the ground under vegetation. Therefore, penetration fraction of ~~LiDAR~~ Lidar is actually another form of estimating the open-canopy fraction (Musselman et al., 2013). Penetration fraction was calculated as the number of ground points divided by total points in each pixel (Figure 3a). However, under-canopy vegetation can also intercept the ~~LiDAR~~ Lidar beam causing a bias. To eliminate this bias, the canopy-height model was used to check if the pixel was canopy covered by using a threshold value of 2 m; and if not, the local penetration fraction of the pixel was reset to 1 because the open-canopy fraction of a pixel could not be entirely represented by the penetration fraction. A spatial moving-average process was applied using a 2-D Gaussian filter with a radius of 5 m to account for the effect of the vegetation around each pixel. Finally, we tested the sensitivity of smoothing results to the radius of the filter and found it is not sensitive when the radius is greater than 1.5 m (Figure 3b).

2.5 Statistical Analysis

The 1-m resolution snow-depth raster datasets were resampled into 2-m, 3-m, 4-m and 5-m resolution. The percentage of pixels with snow-depth measurements was calculated by using the number of pixels with valid data divided by the total number of pixels inside each survey area. The sensitivity of the percentage changes across different resampling resolutions and the consistency of the percentages across study sites at the same resampling resolution were analyzed by visualizing the percentages against sampling resolutions at all sites.

Using elevation, slope, aspect, penetration fraction~~vegetation structure~~ and snow ~~-~~depth retrieved from ~~LiDAR~~ Lidar measurements, ~~orographic~~ topographic and vegetation effects on snow~~pack~~ accumulation were ~~analyzed statistically~~observed using residual analysis. Owing to orographic effects, there is increasing precipitation along an increasing elevation gradient in this area (Kirchner et al., 2014). Therefore, elevation was selected as the primary variable ~~topographic attribute~~to fit the linear regression model for calculating the residual of snow depth. All snow-depth measurements from ~~LiDAR~~ Lidar were first separated by either under canopy or in canopy gaps, and then were binned by elevation of the location where they were measured, with a bin size of 1-m elevation. As each elevation band had hundreds of snow-depth measurements after binning, the average of all snow depths was chosen as the representative snow depth, and the standard deviation calculated to represent the snow-depth variability within each elevation band. ~~Correlation c~~Coefficients of determination between snow depth and elevation of each site were calculated by linear regression. The fitted linear regression model of each site was applied to the DEM to estimate the snow depth. The residual of snow depth was calculated by subtracting the modeled snow depth from Lidar-measured snow depth. The slope, aspect and penetration fraction were binned into 1° slope, 1° aspect, and 1% penetration-fraction bins. In this study we treat penetration fraction as a physiographic variable and snow-depth residuals corresponding to each bin of each physiographic variable were averaged and visualized along the variable gradient to check the existence of these physiographic effects.~~Northness and slope were also averaged by elevation band for cross comparison. The differences of averaged snow depth between in canopy gaps and under-canopy areas were calculated for each elevation band and cross compared with the vegetation fraction, northness and slope.~~

~~To account for effects other than elevation in the snow depth, a linear regression model of snow depth and elevation was applied to the digital-elevation data to estimate snow depth. The differences between the estimated and LiDAR-measured snow depths were further investigated, with respect to slope, aspect and penetration fraction, by binning the snow-depth difference into 1° slope and aspect bins and 1% penetration-fraction bins. The difference values within each bin were averaged and the standard deviations were calculated.~~

For the variables found to correlate with the snow accumulation, the relative importance of each variable was calculated using the Random Forest algorithm (Breiman, 2001; Pedregosa and Varoquaux, 2011). A multivariate linear regression model was also fitted into all physiographic variables to calculate the regression coefficients, which could be used as the quantification of the effect on snowpack distribution from the variable.

To calculate the snow-depth difference between open and canopy-covered area along an elevation gradient, the 1-m resolution snow-depth data of the two conditions, open and canopy-covered, were smoothed separately against elevation using locally weighted scatterplot smoothing (LOESS) (Cleveland, 1979). The snow-depth difference was then calculated by subtracting the smoothed canopy-covered snow depth from that in open.

3. Results

The percentage of pixels that have snow-depth data measured is highly sensitive to the sampling resolution used in processing the Lidar point cloud, which is about 65 to 90% with 1-m resolution and gradually increases to 100% at 5-m resolution (Figure 4). Note that the percentage increases in going from the lower to higher elevation sites, consistent with local forest density decreasing with elevation.

The snow depth ~~estimated~~ in canopy gaps shows a ~~strong~~ consistent linear trend with elevation across all sites (Figure 5a). The variability (Figure 5b) is highest at about 1500 m, and gradually decreases within rain-snow transition until elevation reaches 2000 m. However, at above 2000 m, the trends of variability changing along elevation gradient vary across sites. ~~ey of distribution patterns and variability across the four sites (Figure 4a, 4b).~~ In general, snow depth is linearly correlated with elevation at all sites, both in the open area and under the canopy. ~~, snow depth under the canopy is consistently less than in the canopy gaps (Figure 5a).~~ Note that values at the upper or lower ends of elevation at each site have few pixels and maybe less representative of the value of physiographic attributes in the study areas (Figure 5~~4~~c). The forested area, of all four sites combined, spans the rain-snow transition zone in mixed conifer through subalpine forest to significant areas above treeline. ~~The snow-depth difference between canopy gaps and under-canopy varies with elevation, generally increasing from near zero at 1500 m, where there is little snow but dense canopy, to 40 cm in the range of 2000-2400 m, and varying from near zero to 60 cm at higher elevation where snow is deeper and canopy less dense.~~

For each individual site, ~~the~~ a least-squares linear regression~~s~~ of snow depth ~~and~~ versus elevation ~~were~~ was used to investigate the spatial variability of snow ~~-~~depth ~~across sites~~. The median elevation of the three sites increases ~~in going~~ from Providence to Bull to Shorthair. The lowest elevation at Providence Creek is less than ~~goes down to~~ 1400 m, and snow depth increases steeply in this region at a rate of 38 cm per 100 m in ~~canopy gaps~~open areas and 28 cm per 100 m under the canopy. Bull Creek has an elevation range of 2000-2400 meters, which is slightly higher than Providence, and has snow depth increasing at 21 cm per 100 m in ~~canopy gaps~~ open areas and 19 cm per 100 m under the canopy. For Shorthair Creek site, which is the highest of the three, the snow depth increases at 17 cm per 100 m in ~~canopy gaps~~open areas and 16 cm per 100 m under the canopy. Wolverton is 64 km further south and spans a wide elevation range, going from the rain-snow transition in mixed conifer, to subalpine forest, to some area above treeline. The average snow-depth increase is smallest among all four study sites, 15 cm per 100 m in canopy gaps and 13 cm per 100 m under the canopy. Unlike the other three lower-elevation sites, the snow depth at Wolverton site decreases ~~after~~ above 3300-m elevation. ~~However~~ The amount of area above this elevation is relatively small, and factors such as wind redistribution and the exhaustion of perceptible water can also affect snow depth at these elevations (Kirchner et al., 2014). ~~the amount of area above this elevation also drops off steeply.~~

The residuals for the snow in the open areas were further analyzed for effects of slope, aspect and penetration fraction. The snow-depth residual decreases about 10 to 40 cm as slope angle increases from 0° to 60°; and the residual decreases around 50 to 100 cm in going from north-facing to south-facing slopes (Figure 6a, 6b). More interestingly, the topographic effect can be seen from the color pattern of northness observed in the scatterplots (Figure 7a, 7b). The residual increases about 40 to 60 cm as penetration fraction increases from 0% to 80% (Figure

6C). Considering all of these variables together, elevation is the most important variable at all sites except for Shorthair, which has a relatively small elevation range (Figure 8). Aspect exerts a stronger influence than do slope and penetration fraction in open areas. However, for under-canopy areas, penetration is more dominant than aspect at two sites. The multivariate regression model was fitted to the data with aspect transformed into $0°$ to $180°$ range (north to south). Fitted models could be represented as the following two equations for open area and under canopy respectively,

$$SD = 0.0011 \times Elevation - 0.0112 \times Slope - 0.0057 \times Aspect + 0.1802 \times Penetration \quad (2)$$

$$SD = 0.0009 \times Elevation - 0.0128 \times Slope - 0.0046 \times Aspect + 0.9891 \times Penetration \quad (3)$$

where SD is snow depth and p-values of all regression coefficients of the two models are all smaller than 0.01.

The snow-depth difference between open and canopy-covered area was calculated with elevation from locally smoothed snow depth (Figure 7). It ~~The snow-depth difference between canopy gaps and under-canopy varies with elevation,~~ generally increas~~ing~~es from near zero at 1500 m, where there is little snow but dense canopy, to 40 cm in the range of 2000-2400 m, and varies~~ying~~ from near zero to 60 cm at higher elevations where snow is deeper and the canopy less ~~dense.~~dense. It is apparent that the snow-depth difference increases with elevation in the rain-snow transition zone, but lacks a clean pattern along either elevation gradient or penetration-fraction gradient when the elevation is higher.

~~A visual inspection of the pattern of snowpack distribution with elevation for all sites shows a consistent pattern (Figure 4). Especially for the elevation range where Providence and Wolverton overlap, the patterns of snow depth change are the same for both sites, with the only difference being Wolverton snow depth is consistently less than that in Providence, which is~~

~~likely due to a small amount of densification that occurred between the two acquisitions (Table 1) observed from depth sensors.~~

~~At higher elevations, vegetation coverage decreases consistent with lower temperature, and soil depth. By cross comparing the vegetation fraction and snow-depth difference (Figure 5a, 5b), similar patterns were observed at all sites along elevation gradient. Also, for most of the elevation range investigated, the snow-depth difference was either increasing or remaining constant, except for 2300 to 2500 m at Wolverton, where the snow-depth difference drops drastically, which may be explained by steeper and more southerly exposed slopes (Kirchner et al., 2014) (Figure 6).~~

~~The snow-depth residual deviation from a linear increase with elevation, investigated versus penetration fraction (Figure 7), indicates how the density of vegetation affects the snow-depth accumulation in canopy gaps. For all sites, the snow-depth residuals increase with penetration fraction, with bias across sites and fluctuations at higher penetration fractions.~~

4. Discussion

4.1 Sensitivity of measurements to sampling resolution

The results of the percentage of pixels with snow depth measured from Lidar data at different sampling resolutions illustrate that even high-density airborne Lidar measurements do not have 100% coverage of the surveyed area at 1-m resolution, especially in densely forested areas. According to the snow-depth difference between snowpack in open areas and under canopy, the trade-off between accuracy and coverage happens when adjusting the resolution; and lower sampling resolutions can introduce overestimation into the results. This is because upon averaging, sub-pixel area under the canopy that was not measured is represented by the open that is measured, introducing an overestimation error into the averaged snow depth of the pixel. Therefore, the sampling resolution for processing the Lidar point cloud needs to be chosen according to the objective and accuracy tolerance of the study.

~~The overall increasing trend of precipitation with elevation observed from airborne LiDAR data is consistent with the orographic effect on precipitation (Roe, 2005; Roe and Baker, 2006) and less snow accumulation was observed under vegetation at all sites. The decrease in under-canopy snow is consistent with previous work using ground-based data (Bales et al. 2011, Musselman et al. 2008, and Varhola et al. 2010). Finally, the penetration fraction explained part of the snow-depth residual of the linear model between snow depth and elevation.~~

~~4.1~~4.2 ~~Orographic~~ Physiographic effect on snow accumulation

Below 3300 m, the increasing trend of snow accumulation with elevation was observed for all sites (Figure 5~~4~~). Linear regression is applicable to model the relationship between snow depth and elevation when the study area has a broad elevation range. This holds true for all of our sites with the exception of Shorthair, where the elevation range is about 200 m and ~~As indicated in Table 3,~~ the ~~correlation~~ coefficient of determination for~~of~~ this linear model ~~used for Shorthair site~~ is much smaller than the other three sites, which have ranges greater than 500 m. ~~The other three sites all have elevation range larger than 500 m; however the elevation spans around 200 m at Shorthair site.~~ The bias of mean snow depth in the same elevation band between different sites is acceptable if the standard error is ~~being~~ added or subtracted from the mean (Figure 5~~4~~a, 5~~4~~b). The data-collection time, spatial variation and variations of other topographic features should introduce bias across sites. However, as data-collection time only differs a few days, *in situ* snow-depth sensor data suggest that the melting and densification effect ~~should be~~was under 2 cm (https://czo.ucmerced.edu/dataCatalog_sierra.html). Spatial variations at

1800-2000 m elevations between Providence and the further-south Wolverton site appear to have a consistent bias, with less precipitation falling in the southerly location. As for other topographic variables, the observation of a slope effect, shown as the trend lines in Figure 6a and the negative regression coefficients of the two linear models, could be explained by steeper slopes having higher avalanche potential, fewer trees and thus more wind; and thus some snow is more likely to be lost from these slopes. Snowpack located in south-facing slopes receives higher solar radiation, with the snowmelt being accelerated (Kirchner et al., 2014). This explains the trends observed in Figure 6b and the negative regression coefficients of the multivariate models. Although Lidar has measurement errors caused by slope and aspect (Baltsavias, 1999; Deems et al., 2013; Hodgson and Bresnahan, 2004), error is not able to be quantified and traced back to each variable and we assumed its influence on the trends could be neglected. As canopy interception results in reduced snow depth under canopy, the snow-depth residuals are found increasing with penetration fraction and the regression coefficients are positive (Figure 6c). The multivariate linear regression model built from the Lidar data is a significant improvement, as the variability of the snowpack distribution could explain 15 to 25% more than the univariate linear regression model with elevation as the only predictive variable (Table 4) and the estimation bias has a narrower distribution (Figure 9a, 9b). Also, fitting an individual linear model for each site is slightly better than using a general model with all sites' data involved (Figure 9c, d) and it might because that an individual model could capture regional micro-climate within the site better than a general model. The opposite trend of the relative importance of predictive variables observed in Shorthair is because it is a relatively flat site (Figure 1, Figure 8), which implies that topographic variables other than elevation need to be focused more when studying about areas with small elevation ranges in future works. ~~For other topographic features,~~

~~Kirchner et al. (2014) proposed that northness and slope should have negative effects on snow accumulation. They noted that northness is positively correlated with solar radiation, and thus ablation, and northeastness deposition from prevailing winds. Steeper slopes also have has higher avalanche potential and snow is more likely to fall off from these slopes. Across the elevation range that we studied, the snow depth is globally smaller at Wolverton than all other sites; however the northness and slope are globally higher at Wolverton, which is consistent with the northness and slope effects on snow accumulation could exist. Also, the separate investigations on slope and aspect (Figure 6) show that smaller snow-depth residuals could be observed on steeper or more southerly exposed slopes, which further proved the existence of the northness effect. From Figure 2 we also need to notice that each site has about 10% to 24% of total surveyed area does not have point return because of canopy interception. Thus the statistical results are representative but not conclusive of surveyed sites.~~

~~4.2~~4.3 Vegetation effects on snow accumulation along elevation

Under-canopy snow distribution is governed by multiple factors that affect the energy environment, as observed by melting (Essery et al., 2008; Gelfan et al., 2004) and accumulation rates (Pomeroy et al., 1998; Schmidt and Gluns, 1991; Teti, 2003). Our results show different responses when comparing the snow-depth difference between open and canopy-covered areas between study sites (Figure 7c). In the rain-snow transition zone from 1500 to 2000 m of Providence we see a sharp linear increase between open and under-canopy accumulation that is likely governed by the under-canopy energy environment and the canopy-interception effect on precipitation, which accelerate snowmelt and prevent accumulation of under-canopy snow. Above 2000 m, the snow-depth difference observed at Bull and Shorthair stabilized around 40 cm and 20 cm respectively, with fluctuations less than 10 cm along elevation.~~The snow depth in open areas is increasing 2 cm / 100m to 12 cm / 100m steeper than snow depth in under-canopy areas (Table 3). Schmidt and Gluns, (1991) found that the snow intercepted by canopy increases with cumulative snowfall and the interception would saturate when the precipitation is heavy enough. Therefore, in our study sites, with more snow intercepted at higher elevation, the snow-depth increasing slope of under-canopy observations is gentler than open areas.~~ Breaking from this pattern, the large dip in snow-depth difference, down to 10 cm, observed at Wolverton at elevations of 2250 - 2750 m deviates from the 35-40 cm plateau. Also, the snow-depth difference at Shorthair stabilizes around 20 cm, which is 20 cm lower than the stabilized value at Bull. Based on the scatterplot in Figure 7a and 7b that color coded by northness, at elevation range of 2300 m to 2700 m, there are a lot more data points with both low snow depth and extremely negative northness in the open area than under the canopy, which implies that anisotropic distribution of other topographic variables is affecting the snow-depth difference. This is further shown by filtering out the data points not within a small certain range (-0.1 to 0.1) of northness, and then reproducing Figure 7c using the filtered data. As presented in Figure 10, it is apparent that the large dip at Wolverton is flattened out to a canopy effect of around 25-45 cm as the topographic effect is filtered out. Thus a sigmoidal function was used to characterize the snow-depth difference changes with elevation excluding topographic interactions. The interactions between topographic variables and vegetation is most likely attributable to the under-canopy snowpack being less sensitive to solar radiation versus snowpack in the open area (Courbaud et al., 2003; Dubayah, 1994; Essery et al., 2008; Musselman et al., 2008, 2012).

In spite of filtering the topographic effect, there is still about a 20-cm magnitude of fluctuation in the snow-depth difference, which might be attributed to various clearing sizes of open area at different locations and various vegetation types in the forests (Hedstrom and Pomeroy, 1998; Pomeroy et al., 2002; Schmidt and Gluns, 1991), however, these features of the sites are not able to be explored from this Lidar data set.

~~The difference of averaged snow depth between open and under-canopy areas increases with elevation as vegetation coverage decreases (Figure 5a, 5b). We found that a high density of vegetation exerts a negative influence on snow accumulation in canopy gaps, which makes the snow-depth difference less significant at lower elevations. With precipitation increasing along the elevation gradient, the difference of snow depth between open and canopy-covered areas also increases; and in more densely forested areas, even though the open area does not have canopy right above the ground (Hedstrom and Pomeroy, 1998; Pomeroy et al., 2002; Schmidt and Gluns, 1991) they can still be influenced by the canopies around them. Golding and Swanson (1986) found that the difference increased with clearing size, caused by snow ablation as well as direct solar radiation reaching the snowpack. Another cause of this effect could be traced back to how precipitation drops on the ground. As precipitation has both horizontal and vertical velocities, in a densely forested area a small fraction of snowflakes or raindrops would be intercepted by the vegetation, not only vertically, but also horizontally. Therefore, the snow accumulated in the open area that is surrounded by dense vegetation would actually be smaller than the snow accumulated in a wide-open area. This is also consistent with the finding that areas at the drip edge have snow-depth values, intermediate between under canopy and in the open (Bales et al., 2011). Thus in the more-open forests at higher elevation, the under-canopy and in-canopy-gap allow for greater snow-depth differences. Since the differences could change in different forest conditions and also under the effect of drip-edge transitions, binary classification of in canopy gaps and under-canopy does not work for quantifying differences in snow accumulation.~~

~~Furthermore, the pattern could be altered as some other topographic feature varies. We observed a sudden drop of snow-depth difference in the elevation range of 2300-2500 m at Wolverton from Figure 5a. By visually inspecting the vegetation-pixel percentage, northness, and slope along the elevation gradient (Figure 4d, 5b, 5c), it is observed that the vegetation pixel percentage decreases constantly at a low rate and northness decreases from positive to negative (north dominant to south dominant); while the slope kept increasing significantly in this elevation range. Dubayah (1994), Courbaud et al. (2003), and Essery et al. (2008) found that slope is a dominant factor in modeling the solar radiation received by the soil when canopy structures remain constant, and more solar radiation would be received on steeper south facing slopes, which could be the cause of the snow-depth difference decrease that we observed.~~

~~4.3 Quantify vegetation effects on snow accumulation~~

~~In the previous section, we reasoned that vegetation reduces snow accumulation in canopy gaps by blocking the snow that in a less-dense forest would fall to the ground. Vegetation density is a significant factor (Teti, 2003), as we observed that snow-depth difference increases when vegetation fraction decreases. Figure 7 shows the quantification of the vegetation-density effects on the snow-depth accumulation. Considering the blocking of snow from vegetation (Pomeroy et al., 1998; Schmidt and Gluns, 1991), the vegetation density should be transformed into open fraction that one could see from the given pixel. In this case, penetration fraction was applied to represent percentage opening. As is shown in Figure 7a, the snow-depth residual differed from the linear increase with elevation is highly correlated with penetration fraction, which implies that penetration fraction is a good indicator of vegetation effects on snow accumulation. Moreover, the ranges of the snow-depth residual are similar and the patterns of snow-depth residual changing against penetration fraction are consistent across sites, as the~~

~~studied sites share similar vegetation structures and climate conditions (Fites-Kaufman et al., 1970). The consistency of changing patterns supports the idea of modeling the relationship between vegetation density and snow depth so that the effects from vegetation on open area snow accumulation could be quantified.~~

5. Conclusions

As an advanced and promising remote-sensing technology, Lidar is able to measure snow depth of 100% survey area at 5-m sampling resolution however the accuracy is still left to be evaluated because of lacking enough representative measurements under the canopy. A 1-m resolution processed Lidar data set is more accurate but the percentage of pixels with measurements is much less than 100%.

Using processed Lidar data sampled at 1-m resolution, averaged snow depth within each 1-m elevation band shows a strong correlation with elevation at all sites, indicating that snow accumulation in the southern Sierra Nevada is primarily affected by orographic lift. Snow-depth residuals calculated by de-trending the elevation dependency are correlated with slope, aspect and penetration fraction, which shows the effect of additional physiographic variables on snow accumulation other than elevation. The relative importance of these variables in predicting snow depth implies that other than elevation, aspect affects snow-accumulation and retention more in open areas, while penetration fraction is as important as aspect for snow under the canopy. More significantly, a multivariate linear regression model fitted with variables for slope, aspect and canopy penetration fraction explains 15 to 25% more snow-depth variability than using elevation as the only predictive variable, suggesting multiple predictive variables will be more effective for quantifying the water equivalent in the Sierra Nevada at peak snow accumulation.

The snow-depth difference between open and canopy-covered areas increases in the rain-snow transition elevation range and then stabilized around 25 to 45 cm at high elevation. Large magnitude of fluctuations are presented at certain elevation ranges in Wolverton and Shorthair, which is partially due to interactions from other topographic variables, evidence of which is found by filtering the northness into a narrow band and which causes the fluctuations flattening out.~~The regression analysis of snow depth versus terrain and vegetation attributes that are extracted from LiDAR show that snow accumulation in the southern Sierra Nevada is strongly affected by both the orographic effect and vegetation factors, and are consistent across the four sites studied. Comparing these results across sites reveals that the altitudinal effects on snow accumulation are consistent and globally linear, with a lapse rate of approximately 15 cm per 100 m. By cross comparing between snow depth and other topographic features along the elevation gradient, we confirmed that the variability of snow depth, after de-trending the altitudinal effect, could be further explained by attributes such as slope and aspect. The characterization of snow-depth difference between open and canopy-covered area, together with vegetation fraction, not only suggests that the snow-depth-difference increase along the elevation gradient is because of vegetation density decreasing, it also suggests that, penetration fraction can be used to quantitatively study vegetation effects on snow accumulation. Moreover, the analysis of the snow-depth residual from the altitudinal trend and penetration fraction reveals that the vegetation effects on snow accumulation are consistent across the four study-sites, implying that the effects could be quantified and modeled mathematically.~~

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Table 1. LiDAR data collection information

	Snow-off flight date	Snow-on flight date	Area, km^2
Bull	August 15, 2010	March 24, 2010	22.3
Shorthair	August 13, 2010	March 23, 2010	6.8
Providence	August 5, 2010	March 23, 2010	18.4
Wolverton	August 13-15, 2010	March 21-22, 2010	58.9

Table 2. Flight parameters and sensor settings

Flight parameters		Equipment settings	
flight altitude	600 m	wavelength	1047 nm
flight speed	65 m s^{-1}	beam divergence	0.25 mrad
swath width	233.26 m	laser PRF	100 kHz
Swath overlap	50%	scan frequency	55 Hz
point density	10.27 p m^{-2}	scan angle	±14°
Cross track res	0.233 m	scan cutoff	3°
Down track res	0.418 m	scan offset	0°

Table 3. Linear regression of averaged snow depth vs. elevation in four sites

	Bull	Shorthair	Providence	Wolverton
Open R^2	0.968	0.797	0.931	0.914
Vegetated R^2	0.978	0.737	0.921	0.972
Open slope, cm per 100 m	21.6	16.1	37.8	15.3
Vegetated slope, cm per 100 m	19.9	13.1	26.0	13.4

Table 4. Coefficients of determination of univariate and multivariate linear models

	Univariate model R^2	Multivariate model R^2
Bull	0.23	0.37
Shorthair	0.06	0.32
Providence	0.39	0.53
Wolverton	0.16	0.38
All sites	0.43	0.57

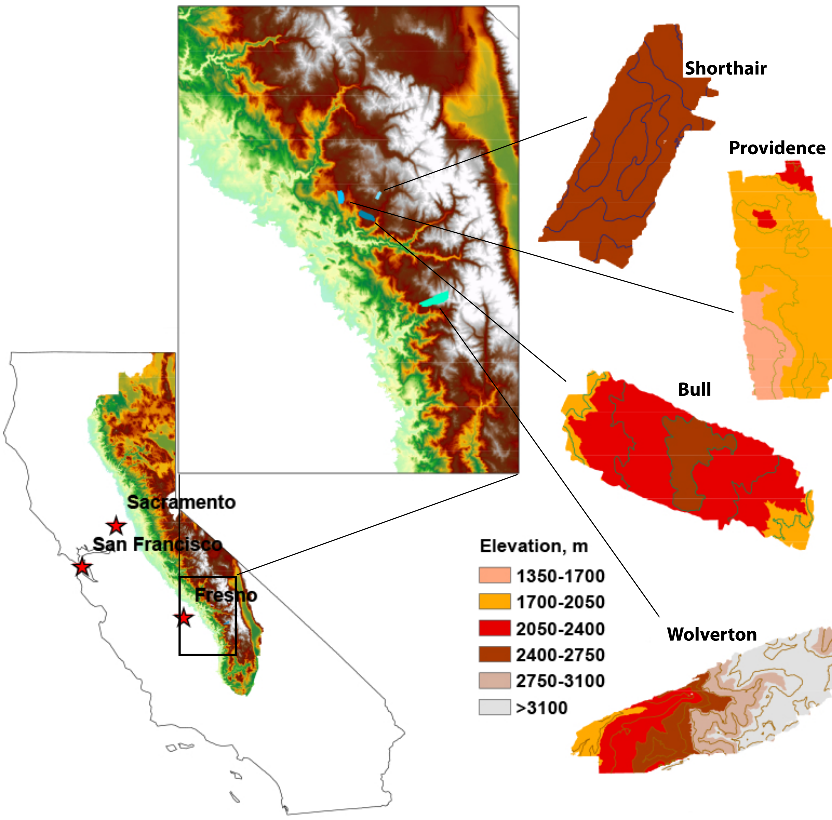

Figure 1. Study area and Lidar footprints. (Left) California with Sierra Nevada. (Center) Zoomed view to show the locations of Lidar footprints. (Right) Elevation and 200-m contour map (100-m for Bull) of LiDAR footprints

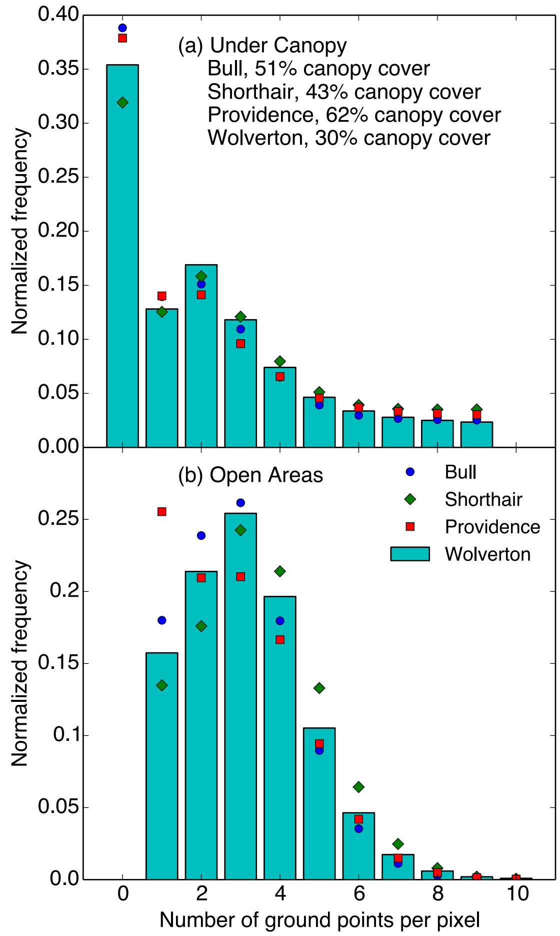

Figure 2. (a) Normalized histogram of the number of ground points for under canopy pixels. (b) Normalized histogram of the number of ground points in open pixels.

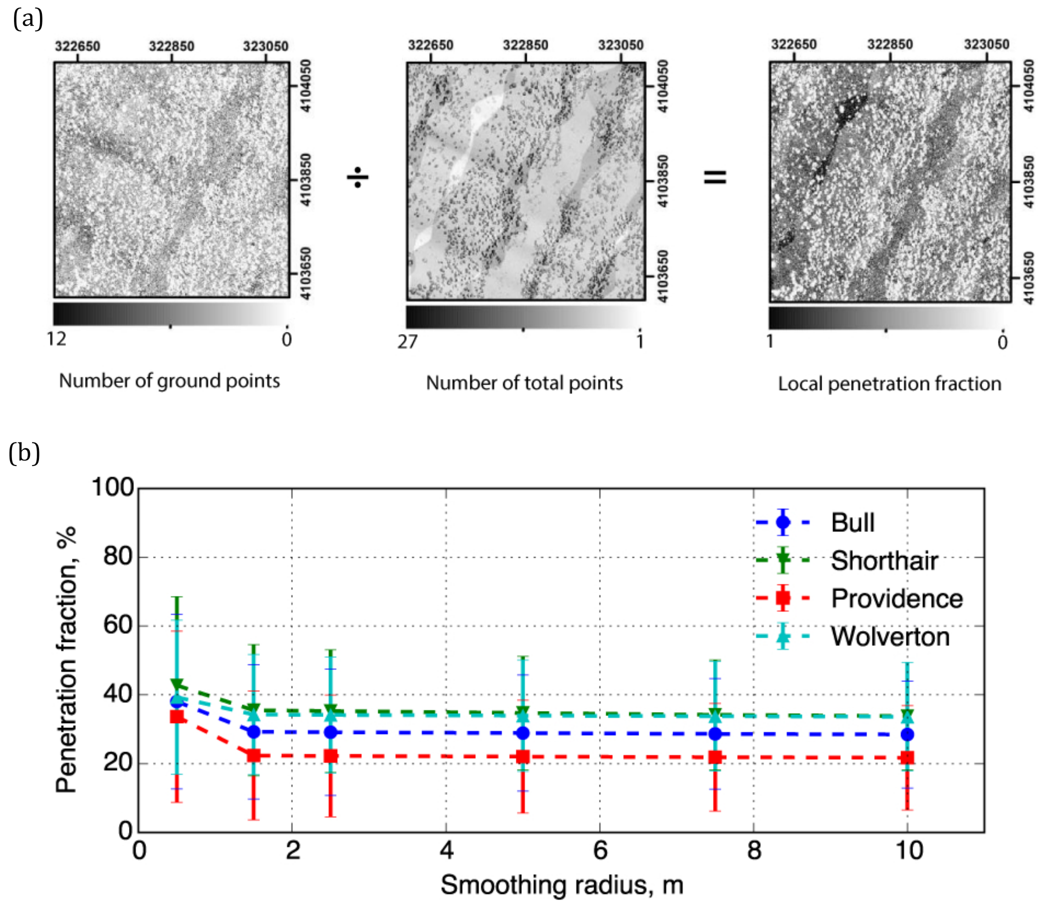

Figure 3. (a) Dividing the number of ground points of each 1-m pixel by the total number of points in the pixel will result the penetration fraction of the local pixel. (b) Sensitivity of the smoothed penetration fraction to the smoothing radius, showing that the result is not sensitivity as the radius is larger than 1.5 m.

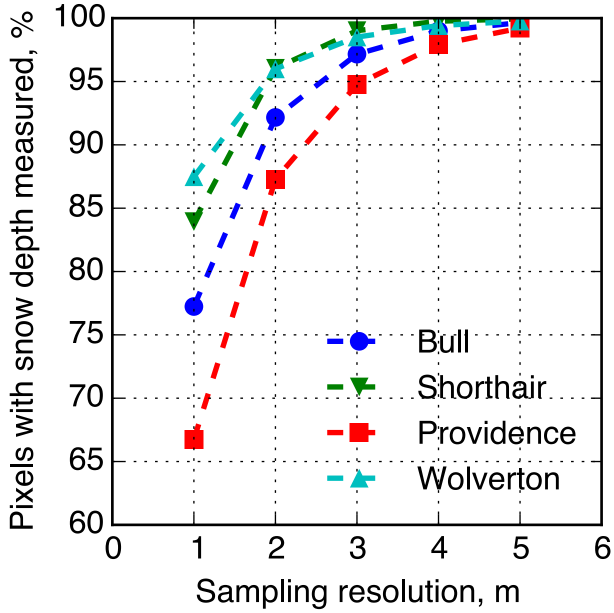

Figure 4. Sensitivity of the percentage of pixels with snow depth measured to the sampling resolution used in processing the Lidar point cloud at each site.

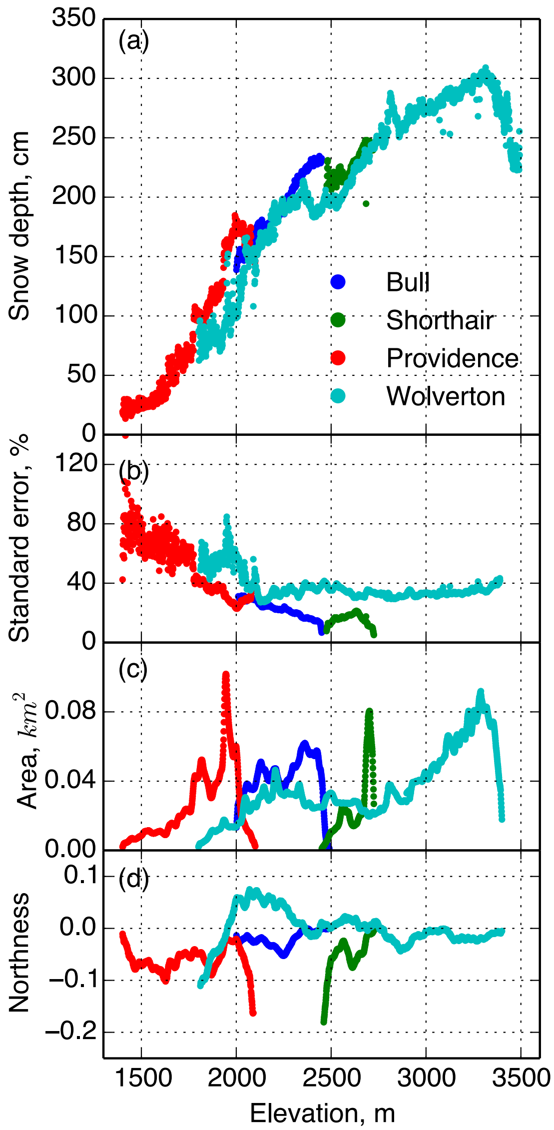

Figure 5. (a) Averaged snow depth from snow-on and snow-off Lidar data versus elevation for pixels in the open at the four sites. (b) Standard error of the snow depth within each 1-m elevation band. Values above 3400 m not shown, where there are few data. (c) Total area of averaged data within each elevation band. (d) Averaged northness of each elevation band from four sites.

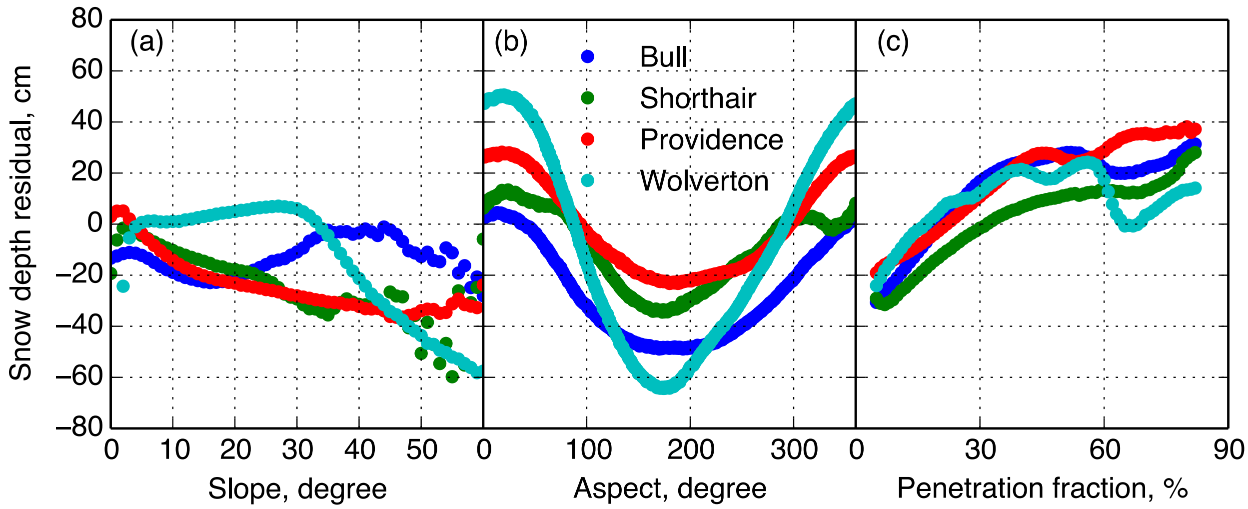

Figure 6. (a) Averaged snow-depth residual along slope. Raw snow-depth residual was calculated from Lidar measured snow depth and estimated snow depth from the linear regression model (open areas). (b) Averaged snow-depth residual along aspect. (c) Averaged snow-depth residual along penetration fraction.

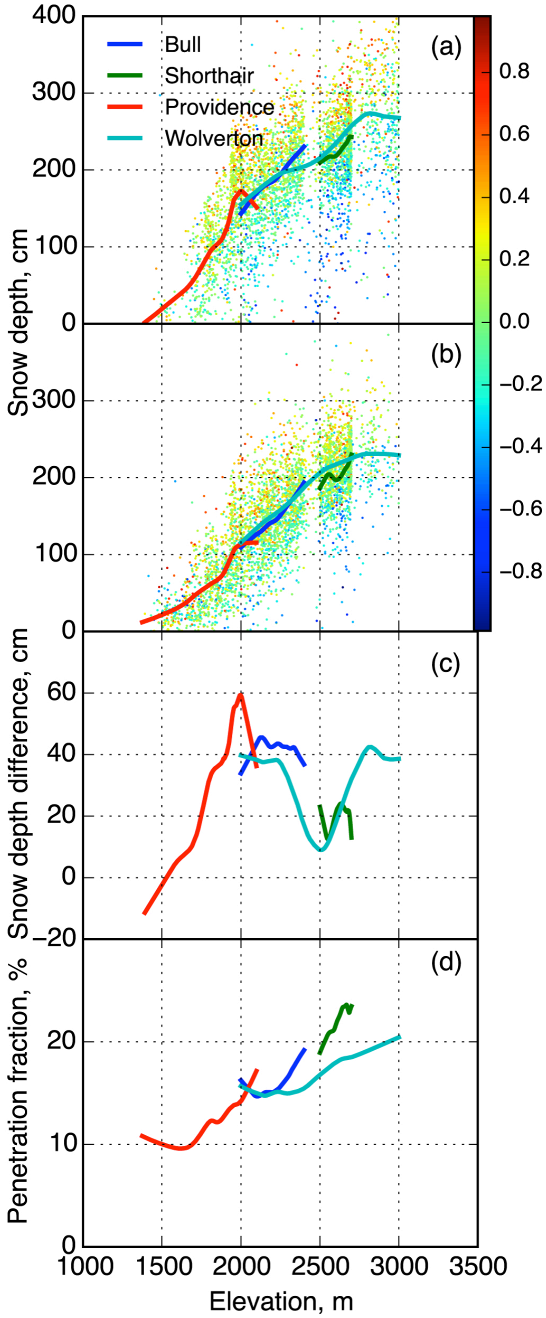

Figure 7. LOESS smoothed snow depth with northness color coded scatterplot of raw-pixel snow depth against elevation for (a) open area (b) canopy-covered area. (c) Snow-depth difference along elevation calculated from the LOESS smoothed snow depth. (d) Averaged penetration fraction.

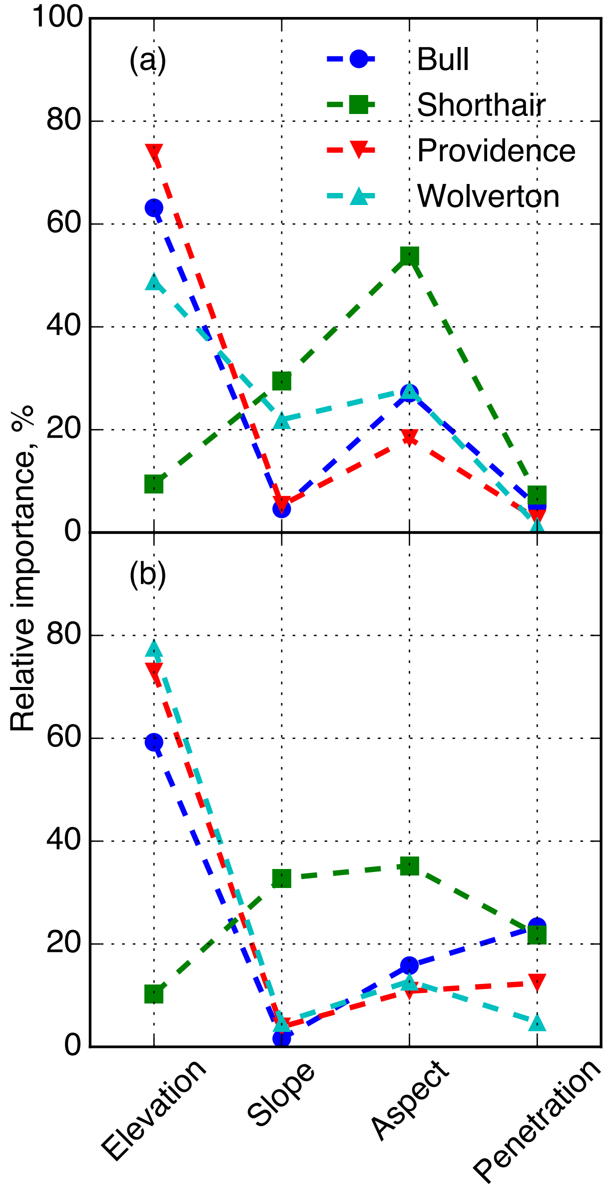

Figure 8. Relative importance of each physiographic variable in predicting the snow depth from each site for (a) open area (b) canopy-covered area

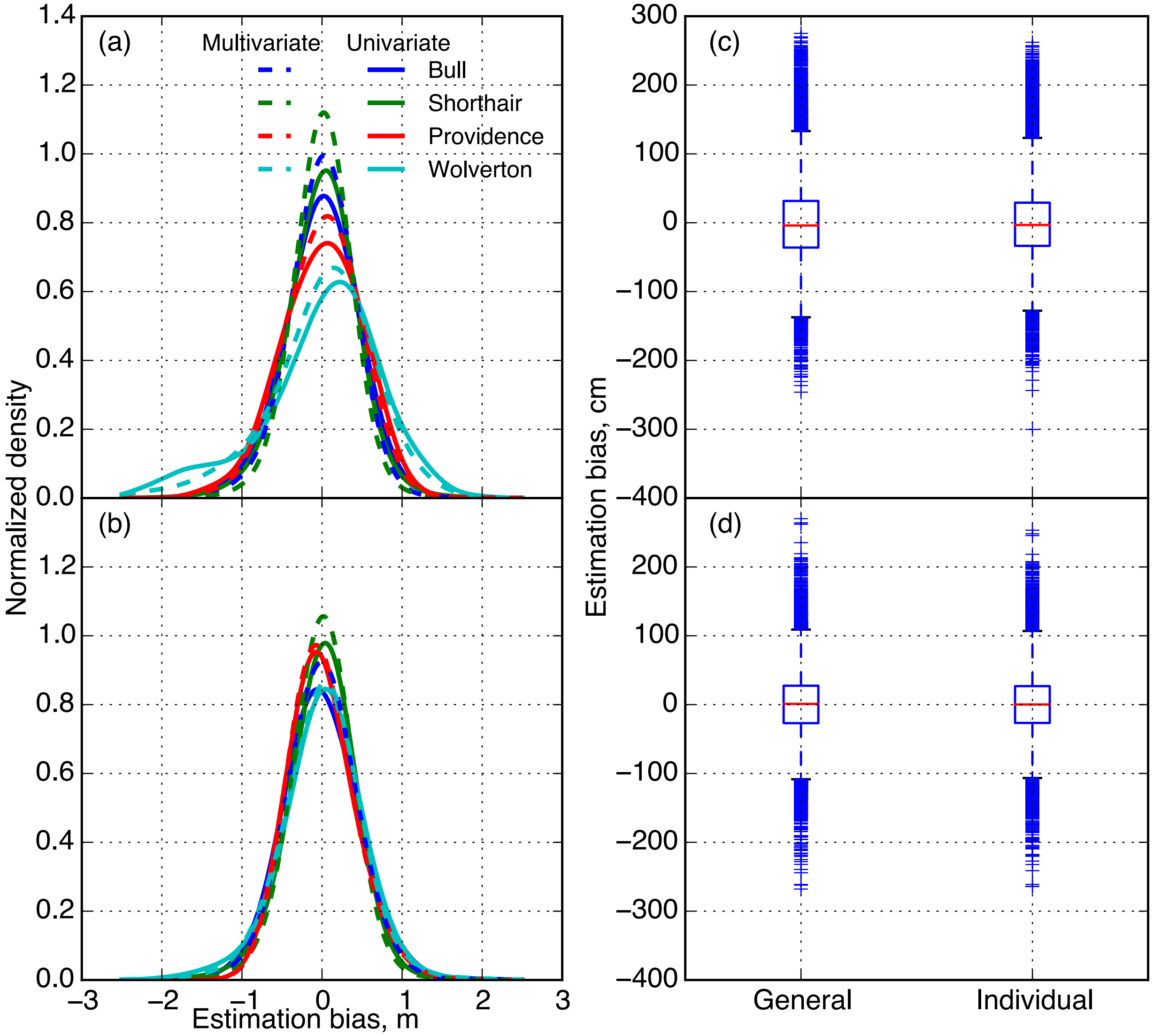

Figure 9. Normalized density of estimation bias for (a) open area (b) canopy-covered area; Estimation bias boxplots of using one general linear model with all sites' data combined and four linear models of each individual site for (c) open area (d) canopy-covered area.

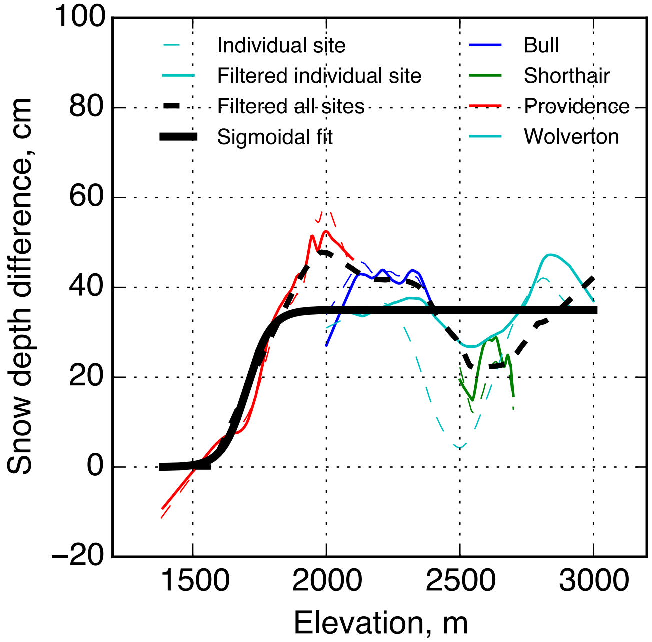

Figure 10. Snow-depth difference between open and canopy-covered area: comparison between using raw 1-m pixel snow depth and northness-filtered 1-m pixel snow depth, together with the sigmoidal fit of the snow-depth difference changing with elevation