**The Cryosphere
Discussions**

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Interactive comment on "Variability of snow depth at the plot scale: implications for mean depth estimation and sampling strategies" *by* J. I. López-Moreno et al.

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Response to "Variability of snow depth at the plot scale: implications for mean depth estimation and sampling strategies" by

J. I. López-Moreno et al. Anonymous Referee #3

We want to sincerely thank to reviewer 3 the interesting comments and suggestions which have helped to improve the quality of the work from a scientific and also formal point of view. As overall, the review point out the interest of the manuscript but suggest some possibilities to strength the manuscript. We think that the revised manuscript defines more clearly the scope of the manuscript and highlight the most interesting and

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novel points considered in this research. Below, we explain the changes introduced in the manuscript according to the comments of R.3 and justify why we have not followed a few of the suggestions.

1. This manuscript examines the variability of snow depth in 10 m by 10 m plots by measuring depths on 1-m grids, and demonstrates that errors in plot-scale average depth can be reduced by taking multiple measurements within a plot using appropriate sampling interval, rather than using a single data point. I can see a clear educational value in demonstrating this basic concept that natural processes, including snow accumulation, have spatial variability and multiple measurements provide a better estimate of population mean than a single measurement. However, I am not entirely sure if this manuscript in its present form contains significant new scientific knowledge that warrants publication in a refereed scientific journal. We all know that snow depth varies at all scales, and we make our sampling strategies that optimize the balance between required efforts and desired outcome (e.g. estimate of snow water equivalent distribution within a watershed).

We think that our paper provides much more information that simply snow varies and a single measurement is not adequate for representing the population. Using an important number of plots in two contrasted periods of the year we detected potential factors that may determine the need of more or less number of measurements and the sampling strategies which are the degree of variability and spatial autocorrelation. In a second part of the manuscript, we used thousands of simulated series to isolate and quantify the effect of snow variability and spatial autocorrelation of snowpack on estimation of snowpack at the plot scale. We think that the finding that any specific sampling strategy improves the estimation, but it is highly recommendable to space them at least 2 meters away each to the others is a result that can be useful for designing snow surveys. In addition, this paper underlines the necessity to improve in the understanding of the snowpack variability and spatial autocorrelation at the plot scale. Answers and modifications of the manuscript to points 1, 5 and 9 of reviewer 1;

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and points 1 and 2 of reviewer 2 address this concern and all of them have noticeably improved the original manuscript.

2. This requires consideration of topography, surface roughness (e.g. rocks, tree roots), vegetation, prevailing wind direction, and numerous other factors. The manuscript could be strengthened substantially by presenting the results in the broader context of snow depth measurement.

In our answer to point 2 of reviewer 1 we discuss this question in the following manner: The fact to not make reference to specific characteristics of terrain surface has been done intentionally, as it was not within the aim of our work. It is sure that terrain characteristics drive the spatial variability of snowpack at the scale in which we are working. However, when we go to measure snow, we do not know the characteristics of terrain surface beneath the snowpack, making impossible to take it into account in our sampling strategy. This is why we recommend conducting similar analyses in other areas, and we consider very interesting to reach "A better understanding of the factors that influence the spatial and temporal patterns of snowpack variability and spatial autocorrelation at the plot scale will aid efforts to obtain high quality snow datasets" (p. 1641, l-8-11 discussion manuscript)". We think that with the changes introduced in the abstract and introduction the scope of this research is much clearer in the revised manuscript.

3. For example, given the variability at a larger scale and limited resource, is it better to sample a larger number of points at a smaller number of plots, or smaller number of points at a larger number of plots within a study area?.

This is a very interesting research topic, but it cannot be adequately addressed with the experimental design that we followed for the conducted snow surveys. For this purpose, it would be necessary to have sampled more plots with less snow measurements (10-15 could be enough). However, as the field surveys were specifically designed to study the snow variability at the plot scale we took 121 measurements in each 100 m2

plot, which resulted in a rather unique dataset.

Specific comments

4. P1632, L3-5. Had there been snowmelt events between the two sampling dates? A graph showing daily average temperature over the accumulation and melt season willbe useful.

We have not available temperature series of this site, as the purpose of this research was to analyze the implications but not to identify the causes of the snow variability. In any case, in the revised manuscript it is stated that in April snowmelt events have occurred between the two sampling dates: "In April the intensity of the incoming solar radiation is much greater, and the aspect and forest canopy have a major influence on the spatial distribution of snow. The warmer temperatures at this time induce snowmelt at many locations, and reduce thermal gradients within the snowpack. In the latter period the snowpack is isothermal in most plots (Fassnacht et al., 2010)". Moreover in section 4.1 information of the overall evolution of the plots can be found "The mean snow depth among plots was more variable in April than in January, ranging from 65 to 253 cm. Snow accumulation increased in most of the plots, and the increase was substantial in 8 plots. Only in the two plots at the lowest altitudes (plots 1 and 2) did snow depth decrease slightly."

5. P1632, L12. How were the plots "randomly" selected? Please describe the procedure.

We marked in a map 15 points along the valley without assuming any prerequisite of the points. Afterwards, we went directly to those coordinates to sample 121 measurement of snow depth.

6. P1632, L13. What were the slope angle and aspect of these plots? What was the condition of the ground surface, e.g. exposed bedrock, grasses, understory shrubs, etc.? These are the important characteristics that influence snow depth variability.

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Given these factors, how did the authors ensure that plots were randomly selected?

See point 3 of this review. We have not analyzed the surface characteristics of the plots beneath the snowpack because the paper focuses on the impact of the snow variability and we do not analyze the causes of such variability. As, we did not know about the characteristics of the plots we did not assume any prerequisite to sample a given point. In any case, the main results of the paper are derived from the simulated series, which allowed to isolate the effect of variability and spatial autocorrelation and these results are not dependent of the location of the sampled plots.

7. P1632, L14-16. I do not understand this sentence. Please be more specific. Following also the recommendation of reviewer 1 the phrase has been deleted

8. P1632, L20. How tall were the trees, and what kind?

We have added: "Eight of the plots were located in forest openings where the size of the open area was less than twice the height of the surrounding trees (Pinus uncinata and silvestris of 5-15 m in height)"

9. P1632, L25. Did the field data support that snow depth indeed had a Gaussian semivariogram?

Yes, it is the reason why we used this type of semivariogram

10. P1633, L16. What model of semivariogram was used, and why?

A circular semivariogram model was used. Inspection of the fit provided by different semivariogram models revealed that the circular model was a good choice for the data. Other semivariogram models provided a similar fit and could be used as well, but the results of the analysis did not change significantly as a function of the semivariogram model. This information was incorporated to the manuscript, and a new figure was added to illustrate the concepts of the semivariogram: 'The existence of spatial correlation at the plot scale was determined at each sampling plot by means of the empirical semivariogram. The semivariogram plots the average semivariance between pairs of

points as a function of the distance among them. Relevant parameters of the semivariogram are the sill (limit of the variogram tending to infinity lag distances.), the nugget (The height of the jump of the semivariogram at the discontinuity at the origin.) and the range (The distance in which the difference of the variogram from the sill becomes negligible. In models with a fixed sill, it is the distance at which this is first reached; for models with an asymptotic sill, it is conventionally taken to be the distance when the semivariance first reaches 95% of the sill). HERE A CIRCULAR SEMIVARIOGRAM MODEL WAS USED (FIGURE 3).'

11. P1633, L21. How is standard error (SE) defined? By Eq. (1)?

The term SE was not well used in this context. We have changed the phrase as follows: "Subsets of different sample sizes (from n = 1 to n = 121) were randomly extracted from each plot to assess the relationship between the error of the estimate mean snow depth and the sample size".

12. P1634, L12. What criteria were used to classify the distribution as leptokurtic? Can the sample distribution be approximated by a Gaussian distribution? A normal plot of the data will be useful.

Figure 1 shows that most of the plots exhibit a normal distribution (a Kolgomorov-Smirnov test confirms it) and the kurtosis coefficients indicate that in some cases may exist a tendency to leptokurtic distributions (also confirmed with the kurtosis coefficients). We think that a visual inspection of Figure 1 may be enough and we should not enlarge the manuscript with a very detailed analysis of this question

13. P1634, L20-23. Discussion of semivariogram without semivariogram shown in figures is hard to follow. A few sample semivariograms will be very useful.

We have added a new Figure (Figure 3) to illustrate two different semivariograms and their main parameters which are discussed in the manuscript (sill, range and nugget).

14. P1635, L5-6. Negative correlation between average depth and the coefficient of

variation (CV) suggest that the standard deviation is uncorrelated with depth. I would find it more meaningful to present mean and standard deviation, rather than the derived parameter (i.e. CV).

Standard deviation is dependent on the magnitude of the variable, this is the reason why we use the coefficient of variation and, consequently, it tends to show a positive correlation. Using CV, we can demonstrate that the relative variability of snow depth is negatively correlated with depth.

15. P1636, L21-23. In real-world studies, observers always examine the numerous factors affecting snow depth distribution (see my general comment), and place sampling points in most effective locations to minimize errors while optimizing the balance between the amount of work and desired outcome. I do not think that the design of numerical experiment effectively address the relevant issues. It is highly desirable to re-design the numerical experiment in such a way that the results provide significant new insights into optimal sampling strategy in real-world conditions.

We think that the experimental design was appropriate for the objectives of this work. We think that the revised version of the manuscript explains clearly that the objective of the manuscript is to quantify the effect of snow variability and its spatial autocorrelation on estimation of snow depth at the plot scale. For this purpose, the combination of random observations with simulated series is a robust approach. We have insisted in our answers that in real snow surveys we have not always a previous idea of the surface beneath the snowpack. Other studies with specific experimental designs must address your very interesting proposed question.

16. P1638, L20-21. What are the sources of variability? This needs to be examined using the field data (e.g. ground surface roughness, slope angle and aspect, meteorological conditions), rather than referring to the literature from different regions.

Please, see answers to general comments and point 6. Basically, the purpose of this work is to analyze the effect of the snow variability, not the causes of such variability.

17. P1649, L15-16. It is no surprise that a single measurement does not give the Accurate estimate of average. The important issue is whether or not errors in plotscale measurements lead to "highly biased" estimates of snow depth when depths measurements are taken in numerous plots in a study area. This needs to be clearly discussed using the field data.

This point has been addressed in the response to the general comments. We think that our study goes beyond this obvious statement (a single measurement may be inaccurate). The question that you propose is very interesting, but it does not mean that the error in the estimation at the plot scale and the definition of sampling strategies at this scale is also very interesting. For instance, if snow measurements are used to validate a snow model or an estimation done from LIDAR, it is necessary to know which part of the error may be due to the measurement itself. Other experimental designs (more plots with less measurements than 121) would help to get information to define the optimum sampling strategy at the catchment or slope scale.

Thanks a lot for your helpful comments

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/5/C802/2011/tcd-5-C802-2011-supplement.pdf

Interactive comment on The Cryosphere Discuss., 5, 1627, 2011.