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Hydrology and Earth System Sciences Discussions

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Interactive Comment

Interactive comment on "Topographic control of snow distribution in an alpine watershed of western Canada inferred from spatially-filtered MODIS snow products" *by* J. Tong et al.

J. Tong et al.

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Thank you for the constructive comments submitted on our manuscript. We have adjusted the text accordingly and provide below responses to the comments as well as details on the revisions performed in the manuscript. All the figures in this response are available at: http://nhg.unbc.ca/HESS

Response to Referee 1 (J. Parajka):

1. First, the scientific message of the paper is not clear. I would suggest the authors to carefully readdress and discuss the novelty of their own contribution. The presented work includes substantial computational effort; however the concepts, methods and

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datasets applied are not new. If the intention is to validate a spatial filter methodology, then the use of more extensive dataset of ground based measurements is needed. It will be interesting to see also the match between MODIS and station snow cover duration, but, again, using more dense ground data. Otherwise the conclusions about the spatial filter accuracy are not adequately robust.

Response: The primary goal of this paper is to understand topographic controls of snow cover fraction and snow cover duration in an area of mountainous terrain, rather than to rigorously evaluate the SF method. The validation of the SF method and its application to hydrometeorology are discussed in a separate paper (Tong et al., 2008). The reviewer is concerned that the primary focus of the paper is not clear, so we have modified the text in the introduction to more clearly emphasize the main goal of the present paper.

Owing to the sparseness of in-situ snow depth stations in northern BC, remotely sensed snow products are very useful to analyze the topographic control on snow distribution. Our spatial filter is a simplified method compared to others (e.g., Parajka and Blöschl, 2008) to improve the MODIS snow products but provides improved accuracy for this application.

2. Second, the motivation for the application of a spatial filter is not satisfactorily addressed. The results indicate that it helps to somewhat reduce clouds but it may have implications for the interpretation of results. The spatial filter mixes the snow cover information from neighboring cells and thus transposes the information from different aspects, slopes and altitude to the destination (cloud covered) pixel. I’m not convinced that methodologically is the spatial filter approach appropriate for the evaluation proposed in the title, and if so then it should be analyzed and discussed in more detail. The main question is if and how may this mixing affect the interpretations about the influence of selected topographic controls on the snow cover distribution. In this respect, I would suggest to test a simple temporal filter (e.g. 3-, 4- days) which offers a clouds reduction, good accuracy and does not affect (spatially) the relations between

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topography and snow cover characteristics.

Response: The SF method was applied to reduce cloud effects and improve the overall quality of the analysis. The reviewer is concerned that since the spatial filter uses information from neighboring pixels to reduce clouds, it is also potentially mixing snow cover information from cells with different slopes, aspects and elevations, therefore affecting the determination of the effect of these topographic variables on snow. While we agree with the reviewer that there may be some degradation in the relationship to topographic variables, we do not believe the SF affects the determination of trends in the topographic controls on snow cover fraction and snow cover duration. The SF only uses neighboring pixels so that there should not be on average large differences between the topographic variables in the neighboring pixels and the central pixel. Any differences that are introduced would cause increased variance in the results, but should not bias the average for a particular slope, aspect or elevation, especially when averaged over a very large number of pixels.

In this paper, we compare the snow cover fraction (SCF) and snow cover duration (SCD) distribution between MOD10A2 and SF (in Fig. 3, Fig. 6, and Fig. 7 in the paper). We also calculated the SCF distribution for different slopes and aspects from MOD10A2 and the difference of SCF between SF and MOD10A2 in the figures 1 and 2 below (in this response). The distribution trends of SCF and SCD controlled by topography are similar between MOD10A2 and the SF method, respectively (compare the figure below with Fig. 5 in the paper). Since SF is always higher than MOD10A2 the difference is positive. Furthermore, the fractions of points that are in-filled by the SF range from 0% to 10% at most (see Fig 3. in this response). Since every pixel in the snow product has the possibility to be spatially-filtered by the majority snow condition of the neighboring 3Œ3 cells, the standard deviations of the elevation for every 3Œ3 cells are shown in Fig. 4. (in this response). This indicates that the distribution of elevations of the neighboring 3Œ3 cells are relatively homogeneous compared to the elevation of the center pixel. Therefore, application of the SF method using information from neighboring cells did not seem to change the distribution trends of snow cover fraction and snow cover duration. Since MOD10A2 has more cloud cover than the SF (see Fig. 3a in the paper), it will have a bias toward lower snow cover fraction and snow cover duration. However, the SF products reduces this bias, obtaining larger snow cover fraction and longer snow cover duration than MOD10A2 owing to the decreased cloud amounts.

Since we only used the SF on MODIS 8-day data (MOD10A2), the 3- or 4-day temporal filter can not be conducted based on the MODIS 8-day data. It would be possible to construct a 3-4 day temporal filter using MOD10A1 data, however it would not reduce the cloud as much as the MOD10A2 product, therefore it is not clear to us how this would improve accuracy except temporally.

Fig. 1. The average annual cycle of snow cover fraction distribution in different slope and aspect bands, 2000-2007 from MOD10A2.

Fig. 2. Difference of average annual cycle of SCF between SF and MOD10A2.

Fig. 3. The average annual cycle of fraction of points that are in-filled by the SF from 2001-2007.

Fig.4. Scatter plot illustrating the standard deviation of elevation of the neighboring 3Œ3 pixels around a center pixel.

3. Third, I wonder, if the application of 8-day MODIS product is of relevance for hydrologic applications. I would encourage the authors to provide the reasons why and where the 8-day MODIS product may be beneficial. In my opinion, the 8-day window is too large and together with the maximum snow cover assignment hides or shifts the information about important hydrological characteristics, e.g. the date when the snowmelt process starts. For many operational applications, the 8-day tolerance is simply not S1424 adequate. Again, I would suggest to focus on a shorter time window (e.g. 3-day) in the evaluations.

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Response: In a companion paper (Tong et al. 2008), we address the hydrological impacts of the SF products compared to the MOD10A2. The 8-day MODIS snow products are then used to assess the relationship between the SCF and river discharge in the Quesnel River Basin. To quote from this paper: "The correlation coefficient between normalized SCE of the SF and normalized streamflow is -0.84 ($p<0.001$) for snow melt seasons. This is 0.04 higher than that between normalized SCE of MOD10A2 and normalized streamflow owing to the effective reduction of cloud coverage by the SF." Yang et al. (2007) applied weekly snow products to analyze the relationships between snow distribution and hydrology. Zhou et al., (2005) also used the 8-day MODIS products to explore the hydrological application of the snow distribution. Furthermore, Immerzeel et al., (2008) use MOD10C2, which is a climate modeling grid product at a 0.05o resolution with global coverage and 8-day availability, to run a snowmelt runoff model to analyze the hydrometeorological impacts of the snow cover. All of these studies suggest that an 8-day window is suitable for the analysis of the relationship between snow distribution and hydrology in northern or alpine watersheds such as the QRB.

4. Finally, there is an open question, if the 1km grid resolution is adequate for the assessment of topographic controls on the snow cover distribution. There are studies (e.g. Trujillo et al. 2007), which explore in detail the effects of topography on snow cover distribution. Please provide a discussion, which will highlight the benefits, uncertainties and disadvantages linked with the use of coarse digital elevation model, MODIS datasets and outcomes and conclusions reached.

Response: The 1 km DEM is interpolated to the 500 m resolution of the MOD10A products by a nearest neighbor interpolation method in this paper. For the QRB, which is about 10000 km2, the 500 m resolution is highly suitable to analyze the topographic control of snow distribution. If we want to explore the benefits of a higher resolution DEM, the resolution of the snow products should improve too. See lines: 360-362. Future work may provide further details on the relationships between snow cover distribution, duration, and topography as the resolution of snow products and DEM improves.

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Specific comments: 1. p.2350: The V005 MODIS version uses exclusively a conservative cloud mask. Please correct.

Response: See lines: 86-88. The MODIS snow maps use a conservative cloud mask to determine clouds with the MODIS Cloud Mask data product (MOD35_L2) (Riggs et al. 2006).

2. p.2351-1353, Data and methods section: It is not clear how the accuracy index is calculated? Please provide more details.

Response: A relevant reference has been added. See lines: 161-163. The accuracy of the SF products over 2000-2007 is evaluated following the method used by Parajka and Blöschl (2008) with three fixed point snow depth observations in the QRB (Fig. 1, in the paper).

3. p.2352: What are the spatial patterns of clouds over the region? Do they differ seasonally? Where are the main differences in clouds frequency between daily and 8-day MODIS products?

Response: The following figures show the cloud coverage as a function of elevation.

Fig. 5. Average annual daily cloudy days at different 100 m elevation bands.

Fig. 6. Average annual 8-day cloudy days at different 100 m elevation bands from MOD10A2.

Figures 5 and 6 (in this response) show that the number of cloudy days increases along the elevation gradient in the QRB and that these are similar for both daily and 8-day MODIS products. However, the number of cloudy days in the latter is significantly less than in the daily products. From Fig. 3 in the paper, there is no significant seasonal change of cloud coverage fraction in the QRB. Since there is a general increase in cloudiness with elevation, and the QRB generally increases in elevation from west to east, it follows that the eastern part of the basin is cloudier.

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4. p.2353: Please justify the application of the 10m elevation bands in the calculations.

Response: To obtain more accurate topographic controls on snow cover, we employ 10 m elevation bands for this calculation. However, the SCD and standard deviation of 100 m elevation bands are shown in Fig. 7 (in this response). As Fig. 7 (in the paper, shown here as Fig. 8) indicates, the trends in snow cover duration and the standard deviation of snow cover duration with elevation are consistent and not "noisy" indicating that the use of 10 m bands is acceptable to show these trends. Larger elevation bands could have been used, but would have shown the same trend and have masked this variability. Some of the standard deviation is likely due to inaccuracy in the DEM, as the reviewer notes. Comparison of Figs. 7 in the paper and 8 (in this response) show that the use of 10 m and 100 m elevation bands show the same trends.

Fig. 7. The mean (left) and standard deviations (right) of snow cover durations for 100-m elevation bands for 3 seasons based on the MOD10A2 and spatial filtered products, 2001-2007.

5. and 6. p.2354: the term snowmelt is confusing. The snowmelt may start even if there is no change in the snow cover fraction. Please consider this in your interpretations. p.2358. The term melt rate usually refers to the amount of water (in mm) melted within a given time period. Please consider to use another term for the depletion of snow covered area.

Response: "melt" is changed to "ablation of SCF" in the text.

Tables and Figures: 1. Tables and Figures: Please do not use the abbreviations (without an explanation) in the table and figure captions and keep in mind that the captions should be "self-standing"

Response: We have added text describing the (previously used) abbreviations.

2. and 3. Tab.2. I would suggest to omit this table; it may be described in the text. Tab.3. The same as for Tab.2., the regression line may be plotted in Fig.7.

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Response: Since Table 2 is the percentage of 12 combinations of slopes and aspects in the area, it is difficult to describe them clearly only with text. Fig.7. already contains much information. We experimented with adding regression and correlation information to this figure, but it became too cluttered in our opinion as the following figure 8 (in response). Therefore, we suggest keeping table 2 and table 3.

Fig 8. The mean (left) and standard deviations (right) of SCDs snow cover durations for 10-m elevation bands for 3 seasons based on the MOD10A2 and SF Spatial filtered products, 2001-2007. The correlation coefficients ($p<0.001$) between Snow cover durations and elevations within different periods and the corresponding d(SCD)/dz (days (100 m)-1) are shown too.

4. Fig.1 Please consider to add geographic coordinates (e.g. as a cross) to the plot. The watershed is not delineated to the marked gauge, why?

Response: We added latitude/longitude lines to the revised figure as suggested by the reviewer. The outline of the watershed and the gauge position are as defined by the Canadian Hydrology Network, and represent the entire drainage of the Quesnel River to the point where it enters the Fraser River. The gauge station is located slightly upstream from the mouth of the river – this is why the watershed is not delineated to the gauge station.

5. Fig.2. Are the topographic attributes derived from the 1km grid? If so, please add this information to the figure caption.

Response: Fig. 2. The distribution of terrain in the Quesnel River Basin by (a) elevation, (b) slope and (c) aspect calculated from the Global Land One-kilometer Base Elevation (GLOBE) digital elevation model.

6. 7. and 8. Fig.3,4 5 and 7. Difficult to read. Please consider to use colors. Fig.4. The term melt rate is misleading. Fig.6. Please consider to make the maps larger. There is a lot of black-space in the figure, please minimize it. I would also suggest to change

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the first three colors in the palette, to be more intuitive.

Response: As recommended by the referee, we have enlarged the figures and deleted the black-space in figure 6. Fig. 3, 4, 5, 7 are changed into colors. We have changed "melt rate" to "ablation rate of snow cover fraction".

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 5, 2347, 2008.

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