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Hydrology and
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Discussions

Interactive comment on "Controls on the temporal and spatial variability of soil moisture in a mountainous landscape: the signatures of snow and complex terrain." *by* C. J. Williams et al.

C. J. Williams et al.

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Final response of authors to anonymous Referee #2 major comments on "Controls on the temporal and spatial variability of soil moisture in a mountainous landscape: the signatures of snow and complex terrain" - C. Jason Williams, James P. McNamara, and David G. Chandler

(Reviewer comments in italics, author responses in normal text with text changes noted in bold, all referenced page numbers and figures are to the on-line version of the discussion paper)

1) *Page 1942, Line 9: You attribute these patterns to snow accumulation and snow*

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melt. Yet, there is only a weak correlation to the snow variables. Thus the visual comparison of the maps is more convincing than the correlation analyses. You should state this explicitly in the text and discuss this difference as well. Is this because of the problems related to the measurement scales (i.e. that you are comparing point measurements rather than patterns)? The correlation with distance to the divide is stronger than the correlation with snow. Doesn't this suggest that it is mainly flow controlled rather than input controlled? This is currently not discussed in the discussion section.

The primary difference in the two analyses discussed in this comment are: 1) the correlation analysis is partially static, soil moisture by sample date versus snow variables at the time of maximum snow depth, and 2) spatial maps capture soil moisture patterns that are dictated by processes (lateral flow in this case). We will first explain the distinct patterns in soil moisture that develop and then discuss these developments in the context of the comment. The reader should refer to Fig. 1 for the geography discussed below and to Fig. 5 for the spatial maps.

Two distinct soil moisture patterns develop in the course of the hydrologic year (Fig. 5). Wetter than average soil moisture conditions form first in the central portion of the catchment and form a source area for streamflow near sample locations 23-26. In late winter, soil moisture contents rise above mean levels in the southwestern portion of the catchment (sample locations 1, 4, 5-9, and 12-15) and form a link between the centrally located source area and catchment outlet. This pattern persists into the plant growing season. The timing of its development is dependent first on lateral flow early in winter in the northern part of the catchment and delayed water input from a deep snowpack in the southwestern portion of the catchment.

Autumn rains in the wet-up period raise soil moisture contents to $\sim$0.20 m^3 m^{-3} at depths of 75 cm throughout most of the catchment (Table B). Field capacity at the site is reached at soil moisture contents of 0.18 m^3 m^{-3} (McNamara et al., 2005). The onset of lateral flow occurs during the autumn wet-up season in shallow soil locations as field capacity is reached throughout the soil profile (McNamara et al., 2005). Precipitation shifts from rain to snow as the air temperatures drop with the onset of winter. Southerly exposures in the northern portion of the catchment facilitate oscillating snowmelt and snowpack formation events in these locations. Therefore, soil water input remains high in early winter in the northern portion of the catchment while soil water in the remainder of the catchment is reduced by storage in the developing snowpack. Snowmelt events in the northern portion of the catchment delay formation of the persistent snowpack. More easterly exposures in the southwestern portion of the catchment accumulate snow, delaying soil water input. High soil water input early in the winter season into shallow soils (Fig. 2a) in the northern portion of the catchment exceeds field capacity and lateral flow continues beyond the wet-up period. Early winter lateral flow in the northern portion of the catchment fuels a downslope growing source area in the central portion of the catchment and streamflow initiation begins above the upper weir (McNamara et al., 2005). As air temperatures continue to cool, the snow pack development begins in the northern portion and continues in the southwestern portion of the catchment. Soil moisture contents in the central portion of the catchment remain above mean conditions due to the formation of the streamflow source area. As snowmelt begins, the central portion of the catchment gets wetter with additional soil water input from upslope snowmelt (lateral flow) and the southwestern portion, with the greater snowpack, begins to wet-up above catchment mean soil moisture levels due to late-season high soil water input (snowmelt). The shallower snowpack in the northern portion of the catchment disappears first, leaving drier spring season conditions in the northern portion of the catchment and wetter conditions in the central and southwestern portions of the catchment.

The above described patterns are more easily observed with the spatial maps (Fig. 5) than the correlations (Table 1) for several reasons. First, the correlations of soil moisture with snow variables are based on one snow measurement date, time of maximum snow accumulation. Snow accumulation is greatest in the southwestern portion of the catchment (Fig. 2b) and soil moisture contents are greater there late in the wet season

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(Fig. 5). Therefore, the strongest correlations in soil moisture and snow variables appear late in the wet season. The central portion of the catchment receives the average snowfall, but soil moisture contents there early in winter are the result of early season melt water delivered from upslope contributing areas. Therefore, early winter soil moisture contents in the central portion of the catchment are lateral flow driven. This explains the stronger correlations in soil moisture with distance to the divide rather than snow variables early in the winter. The suggestion of lateral flow formation is based on field observations of streamflow initiation, soil moisture patterns, and soil moisture simulations of the study site presented in McNamara et al. (2005).

Extensive discussion regarding the correlation data and the soil moisture patterns exists in the original manuscript on Page 1944, Lines 10-28. There, we explain distance to the divide captures water availability, the early winter flow contributions of lateral flow to downslope locations in the central portion of the catchment and the late season higher soil water contents in the southwestern catchment locations associated with late season snow water input and lateral flow sources. We have added the following sentence to that above referenced discussion section for clarity on this issue:

Page 1944, Line 27, following "...due to intense solar radiation." - **The ability of the distance to divide variable in this study to represent available water input throughout the year, both the early season lateral flow and the late season snow water input, storage, and lateral flow, explains its more significant correlation with overall soil moisture trends as compared with snow and soil variables.**

2) *Page 1942, Line 27: During the early December period soil moisture at depth (thus above the bedrock layer) has not increased yet (see your Figure 3 and discussion related to Figure 3). Thus the hypothesis about bedrock flow or subsurface stormflow over the bedrock seems to make little sense for this period. There thus is a contradiction in the story that needs to be discussed better. Do you have evidence for lateral flow while the soil is still wetting up?*

Figure 3b depicts soil moisture measured in 15-min intervals at a deep soil location in the southwestern portion of the catchment, near surface soil moisture sample location 9 (see Page 1934, Lines 7-9). The figure also shows mean, maximum, and minimum soil moisture contents measured in the near-surface (0-30 cm depth) along the study grid (see Fig. 1). The figure illustrates that soil moisture contents from 0 to 75 cm depth in fact increase above 0.20 m^3 m^{-3} during the wet-up period. In a previous study, McNamara et al. (2005) determined field capacity for soils at the site was reached at 0.18 m^3 m^{-3} volumetric moisture content. McNamara et al. (2005) determined lateral flow occurred once soil moisture contents were near field capacity throughout the soil profile. In this study, soil moisture contents at depths of 0-75 cm were at or near field capacity halfway through the wet-up period (Fig. 3b, Table B). This would indicate the presence of lateral flow in soil locations with shallow soils. Soil depths in the northern portion of the catchment typically range from 24 to 35 cm (Table A1) and measured near-surface (0-30 cm) soil moisture content in mid-December was at or near field capacity in most of these locations (Table B). Additionally, field observations found streamflow initiation began in the wet-up periods synchronous with field capacity soil moisture contents. This too is consistent with streamflow initiation reported by McNamara et al. (2005). Therefore, there is no contradiction to what is presented in the manuscript. See response to Referee #2 comment #1 for additional description regarding the development of lateral flow. The evidence for lateral flow exists by way of the previous work in McNamara et al. (2005) and the observed soil moisture contents in the northern portion of the catchment during the wet-up period.

The authors have added the following text to add supportive evidence for lateral flow:

To establish field capacity - on Page 1933, Line 6, inserted following "...and more gradually and delayed at depth." - **Field capacity at the site is approximately 0.18 m^3 m^{-3} volumetric soil moisture content (McNamara et al., 2005).**

To establish exceeding field capacity in wet-up - on Page 1938, Line 17, changed text, "...soil moisture increased to approximately 0.21 m^3 m^{-3}..." to **"...soil moisture**

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increased above field capacity to approximately 0.21 m^3 m^{-3}..."

To support discussion on the lateral flow in the northern portion of the catchment in early winter - on Page 1942, Lines 11-12 - changed text "...Water input upslope from this location is high during the wet-up period due to early winter rainfall and oscillating snowmelt events on these south facing slopes." to **"...Water input upslope from this location exceeds field capacity in autumn and early winter (Table B) due to rainfall and oscillating snowmelt events on these south facing slopes."**

On Page 1942, Line 19, changed text "...the Treeline catchment due to high water input into sloping terrain over shallow soils..." to **"...the Treeline catchment due to water input in excess of field capacity into shallow soils on sloping terrain."**

On Page 1942, Line 22 - After "...(Fig. 5)." inserted **"...that initiates streamflow generation above the upper weir (McNamara et al., 2005)."**

On Page 1944, Line 18 - Changed "...soils, steeply sloped terrain, and high water input..." to **"...soils, steeply sloped terrain, and water input in excess of field capacity..."**

3) *Sections 5.1 and 5.2. Subsurface flow is invoked as a partial reason for the observed soil moisture patterns. I think that this section needs to be written more as a possible hypothesis. I agree in part that this is plausible and likely but you do not provide any data or measurements in this paper that show that subsurface flow actually took place during these periods. If there is (better) evidence regarding the importance of subsurface flow, these sources need to be referenced better. While lateral flow seems very plausible, there is no description or explanation for why lateral flow at depth would lead to increased shallow soil moisture. Or do you expect the lateral flow to take place in the top soil layers? The description in section 5.1 seems to suggest that you assume that lateral flow takes place at depth. Please clarify.*

The authors do propose that the lateral flow occurs at depth and the proposition is

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based in part on a previous study in the catchment (see McNamara et al., 2005) as noted in response to Referee #2 major comments #1 and #2. We suggest the evidence of lateral flow exist in the study from McNamara et al. (2005) and is supported in this study by early winter soil moisture contents and field observations of streamflow initiation in the northern portion of the catchment early in the winter season. The explanation for lateral flow is presented in response to Referee #2 major comment #1. The authors propose the text changes noted in response to Referee #2 major comment #2.

4) *Page 1943, Line 13: Because the soils there are shallower the volumetric moisture content will decrease faster, even if the evapotranspiration loss and initial moisture content are the same.*

The authors are not sure of the intent of this comment and therefore do not address it in the manuscript.

5) *Page 1941, Lines 16-18: It is interesting that individual points occasionally experience large changes in rank. But this is not discussed in the discussion section. It would greatly add to the paper, if this was discussed in more detail. Why is this the case? Is this because the measurements were made manually and thus inserted in a slightly different plot each time so that one time it can be close to a rock but next time it is not? Or because each location has a slightly different bulk density? Or is this mainly because the spatial pattern/spatial variability in soil moisture changes so quickly?*

We agree that local variability of soil properties can cause different moisture content measurements within close proximity. Unfortunately, we do not have appropriate data to investigate this issue. However, single locations rarely experienced dramatic rank changes when others did not. More commonly, there were quiescent periods when minimal rank changes occurred and active periods when groups of points fluctuated widely. This suggested that the rank changes are driven by hydrologic variables.

6) *Page 1946, Line 15: Point 3 is only valid from the wet through the dry down period.*

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You show on P1939L21 that there are only 2 points consistently wet and that there is only 1 point consistently dry. Thus statements 1-3 on P1946 are only valid from the wet-dry down period.

We state, relative to this comment, variable snow distribution coupled with high relief and variable soil depths in small mountain watersheds imparts a signature of variability on soil moisture during snowmelt that persists even through dry periods. We offer three supportive points (these points are what the comment refers to): 1) standard deviation of moisture content scales linearly with the mean while the coefficient of variation remains relatively stable (true, see Fig. 4), 2) SWE at maximum snow depth, distance to the divide, and soil depth all have strong correlations with moisture content during wet-up and snowmelt that diminish, but persist through drydown (needs amendment, significantly correlated in wet - dry periods, Table 1), and 3) with few exceptions points within the watershed tend to maintain their wetness position (true for wet - dry periods based on rank change index).

The original leading statement remains true, however, the supportive points need clarification and amendment as noted above. Point 1 is true as currently presented in the text. Point 2 should indicate the correlations are significant for the wet through dry periods (not wet-up), but the significance should not be noted as strong for all variables. Point 3 should indicate wetness position is maintained for the wet - dry periods. During these periods, wet points remain wet and dry points remain dry with a few exceptions. Most positional changes in actual wetness rank occur during wet-up in the presence of the autumn rainfall regime (see Fig. 5).

The authors present the following amendments to the text:

On Page 1946, Lines 12-15, Points 2 and 3 should read, **"2. SWEmax, distance to divide, and soil depth are all significantly correlated with soil moisture content from the early winter wet through the dry periods of the year." "3. overall, points within the watershed tend to maintain their wetness position with exception of**

autumn rainfall period (wet-up)."

7) *Page 1947, Line 27: I appreciate the link to climate change and think that this is an important one. It would greatly add to the paper if you could speculate (based on your results) how the soil moisture patterns would change. Would it look more like the wetting up stage?*

It is difficult to speculate on this issue, as any consistent alteration to the precipitation regime would potentially alter vegetation. That would then alter soil moisture patterns. We would expect streamflow to begin at nearly the same time. However, the duration of streamflow would likely be shorter given the current delay in water input imparted by storage in the pack (McNamara et al., 2005). Given the uncertainty in any such predictions, the authors suggest such speculation should not be included in the manuscript. We offer the following inclusion at the request of the referee:

Page 1948, Lines 1-3: Change lines after "...of soil moisture for other ecosystem processes." to read, **"Conversion of the precipitation regime at the site studied here would likely facilitate a change in the structure of the vegetative community, a resultant different seasonal organization of soil moisture, and a reduced duration of streamflow through the catchment. Predictive models of such responses will need to incorporate the requisite influences of static and dynamic variables on catchment processes."**

8) *Figure 5: It would be much better to show more maps (e.g. 2 dates for each state) so that the patterns are clearer and it is easier for the reader to follow the text. Now the reader does not get a sense of the variability within each state.*

We have added two additional maps to the Fig. 5. The additional maps are for 11 July 2003 (dry period) and 11 Nov 2003 (wet-up period). The addition of these maps assists in following the progression from the dry to wet periods and through drydown.

The Fig. 5 caption changes to **"Fig. 5. Mean relative difference (MRD) in soil**

moisture content by sampling location for representative dates during dry (11 Jul 2003), wet-up (11 Nov 2003, 19 Dec 2003), wet-high flux (11 Mar 2004, 23 Apr 2004), initial drydown (4 May 2004), following spring rain (2 Jun 2004), and final drydown (30 Jun 2004) periods. Points having positive MRD are indicated in blue, negative MRD in red. Relative differences from the mean greater than 0.10 are indicated by open circles, greater than 0.20 indicated by filled circles."

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 5, 1927, 2008.

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