Hydrol. Earth Syst. Sci. Discuss., 10, C1229–C1236, 2013
www.hydrol-earth-syst-sci-discuss.net/10/C1229/2013/

Hydrology and
Earth System
Sciences
Discussions

Interactive comment on "Spatial distribution of stable water isotopes in alpine snow cover" *by* N. Dietermann and M. Weiler

N. Dietermann and M. Weiler

markus.weiler@hydrology.uni-freiburg.de

Received and published: 28 April 2013

Dear Paul,

Thank you for considering our manuscript and the useful review comments. I very much appreciate your ideas and comments and I will incorporated most of them without reservation. I also would like to thank you for your support and your condolences.

General Comments Before I begin my review I want to convey my condolences to the family and friends of Nicolai Dietermann. This paper makes it clear that he was an insightful researcher and lover of snow covered mountains; I am pleased to see his thesis research published here and sorry that I won't have the opportunity to review more of his work. I commend his adviser for carrying this project forward in his memory. Dietermann and Weiler present data and analysis from a notably large snow isotope sampling effort performed shortly before and during the 2010 snowmelt season in four mountain catchments. Spanning over 1000m in elevation and including both Northerly and Southerly aspects, this is one of the largest spatial and temporal data sets on snow water isotopes in temperate mountain systems obtained to date. The authors demonstrate that the isotopic content varies along elevation gradients (presumably due to temperature effects on precipitation formation), by latitude (presumably due to distance from water source), by season (presumably due to differences in isotopic controls during accumulation and ablation season), and by aspect (presumably due to differential enrichment during ablation). When taken together, these relationships clearly demonstrate that 1) spatial variability in potential snowmelt water isotopes before melt is high, and that 2) the timing of melt water isotopic input varies with catchment morphology. The combination of spatial and temporal variability in water isotopes demonstrated by this work, the large spatial extent of sampling, and the relationships to putative controls on isotopic content make this a valuable addition to predictive catchment hydrology in seasonally snow covered systems. Given the importance of snow cover in montane catchments to downstream water resources for over 1 billion people worldwide, advances in placing variability in snow cover within catchment hydrological response is a critical area for research.

→ Thank you for the supportive comments and your nice summary of the main findings

This paper represents an advance in our understanding of the spatial variability snow water isotopic input, and I suggest that the authors say that this study is examining the spatial and temporal variability in potential meltwater isotopic signature rather than the processes contributing to spatial variability. Topographic and morphological data provide insight in how this variability may be distributed in space, and provides hints at processes, but without fresh snow samples, and detailed temperature, vapor pressure, or wind speed and pressure pumping profiles within the snowpack this variability cannot be attributed definitively to specific processes. The observed patterns in snow water isotopes and their relationship to variability in both topography and snow depth do suggest that spatial variability in energy balance controls on net snow water input also leaves a detectable signal in snow water isotopes.

→ I agree with this observation and the sections at the end of the introduction will be changed accordingly.

The attempt to combine samples before and after melt began is understandable given the focus is on meltwater inputs; more samples are likely to increase statistical power if they are sampled from the same population, or in other words representative of the same set of processes. In this case however, the processes that result in spatial variability in snow water isotopes before and after melt are quite different suggesting that these are two unique populations or sample sets and I suggest that they likely would be best analyzed independently. The processes occurring before melt contribute to the potential snowpack meltwater isotopic signature, while the processes occurring after melt reflect how this signature, developed during an extended period of net accumulation, evolves as snow water inputs are partitioned during the melt season. A reader unfamiliar with snow water isotopes may read the current paper and incorrectly assume that isotopic differences are only related to variability during snowfall and snowmelt and that these process will exhibit similar spatial patterns.

→ I will include the analysis of the two populations in addition to the whole population using a independent regression analysis for the two This should allow as pointed out by Paul Brooks to examined the two processes more independently.

For the processes during the net accumulation period, Dietermann and Weiler present a nice discussion on how elevation may affect the precipitation signal and how physical redistribution (avalanche and wind scour/ deposition) may subsequently modify those inputs. Processes associated with vapor exchanges between the snowpack and the atmosphere however, are less well represented and the data from the first ascents

in each catchment suggest that these exchanges vary in space. Although vapor exchange is bidirectional during the accumulation season, sublimation (and within pack evaporation from partial melt before the snowpack becomes ripe) typically is larger than condensation ranging from 10% - 20% of cumulative snowfall in sites with low vapor pressure deficits and/or stable boundary layers (Leydecker and Melack 1999, Link and Marks 1999, Hood et al. 1999) to 40% or more in drier, warmer, and/or more turbulent environments (Montesi et al 2004, Headstrom and Pomeroy 1998, Elder et al. 2004, Molotch et al. 2005, Harpold et al. 2013). More broadly, the resultant patterns in net snow accumulation are consistently and strongly related to local energy balance including shading and scattering of radiation from adjacent slopes and vegetation (Cline et al. 1998, Elder et al. 1991, Rinehart et al. 2009; Veatch et al. 2009).

→ I thank Paul Brooks for the nice summary and I will include a more detailed discussion about processes associated with vapour exchange in the discussion section as suggested.

Specific to this work, the large deviations in first ascent 2H values from the expected decrease with elevation suggest that there is significant enrichment in some locations. Barring melt, a likely explanation for this enrichment is water vapor losses from the snowpack. Snowpacks exposed to high solar radiation during the accumulation season exhibit kinetic fractionation of water isotopes (Gustafson et al. 2010; Biederman et al. 2012) although equilibrium fraction also could be expected to increase 2H values relative to fresh snow (Earman et al. 2006). Furthermore, Groot Zwaftink (2013) has suggested that sublimation of blowing snow is minimal in the region with most vapor fluxes occurring from a stable snow surface. Thus, one would expect that locations that exhibit more enriched values are subject to greater sublimation fluxes and thus delta snow should be larger and negative while those that are more depleted should represent protected environments, have positive delta snow values, and have minimal changes in isotopic content that follow the local meteoric water line. Although a distributed energy and mass balance model, including remote shading and scattering, would be helpful in confirming this interpretation of the data, the general enrichment of 2H with elevation on south facing slopes before melt is consistent with higher vapor fluxes in higher elevations that are less likely to be topographically shaded. These observations further highlight the importance of radiative forcing on snow pack mass and energy balance. Overall, the data in Figures 3, 4, and 5 on 2H and delta snow depth relationships with aspect and elevation before melt seem consistent with spatial distribution in vapor exchange with the atmosphere. → I will include a more specific discussion about the potential deviations from the expected decrease with elevation in the discussion section.

Once spatial variability in the meltwater isotopic signal has been set during accumulation, the isotopic content of the snowpack during the ablation season is affected by melt (e.g. Taylor et al. 2001), bi-directional vapor exchange with the atmosphere (Hood et al. 1999), and new snowfall (although this effect should be relatively small given the large volume of snow accumulated over the winter at these sites). In this data set, the similarity in elevation – 2H slopes during the accumulation and ablation seasons suggests that spatial variability in isotopic input is largely set during the accumulation season, while deviations from the slope set in winter suggest that temporal evolution of melt season processes plays an important role in isotopic input. Notable in the data however is the enrichment in 2H at mid elevations of northerly slopes in the Engstligen catchment and at higher elevations in the Laschadura catchment. The concurrence in spatial patterns in enrichment between accumulation and ablation samples in the Engstligen catchment suggests that this is a high energy environment subject to enrichment from sublimation and evaporation. Greater 2H enrichment in Laschadura similarly could be a function either of melt rate, evaporative enrichment in a high energy environment, or possibly condensation on to a cold snowpack underlying a warmer atmosphere with higher specific humidity (Hood et al. 1999).

→ There are certainly different effects more or less dominant in the different regions. However, without fresh snow samples, and detailed temperature, vapor pressure, or

wind speed and pressure pumping profiles within the snowpack, these differences cannot be explained satisfactory. I will include some possible effects in the discussion section, but I will keep this quite vague since the differences cannot be proven.

Technical and editorial comments The paper would be considerably strengthened through the inclusion of a local meteoric water line with symbols for individual values for each snow sample. This probably would be a two part figure with one panel for accumulation and one for ablation. You also need one line for the western catchment and one for the three eastern catchments given differences in inputs. These figures place the work in a much broader context by showing actual values along with any indication of equilibrium and possible kinetic fractionation. → As also suggested by the other reviewers I will add a 2H-18O diagram including LMWL in the revised paper showing all samples and referring to the different watersheds and maybe splitting the data between accumulation and ablation period – however, this may not be as clear since ablation may have already started on the south facing slopes before the first ascent.

Similarly, any information on snowpack isotopic variability or physical structure with depth would be very helpful in interpreting these results. The development of faceted crystals at depth and ice layers throughout can be used to assess the likelihood of meltwater loss. If the snowpack structure reflects long-term metamorphism throughout the winter, then causes of isotopic variability can be limited to precipitation, physical redistribution, or vapor loss, greatly increasing the strength of inferences drawn about processes affecting spatial variability.

→ We did not sample all these detailed information in this study. However, we started a new study where detailed isotope profiles and physical snow properties were sampled, unfortunately, Nico was unable to finish this study due to the accident.

The methods describe two sampling events per catchment/ slope, but the data in figure 3 present from one to three ascents per catchment/ slope. Clarifying the number of observations would be helpful.

→ I will provide the information in the method section that in the Engstligen catchment samples from a total of three ascents of the northern slopes were taken beginning of April, end of April and end of May, respectively

Line 1. Consider revising to "The stable water isotopes 18O and 2H have been used for over 40 years to. . ."

→ It is not clear to me what changes the reviewer is suggesting. Does he dislike the wording or the general statement about the 40 years?

Line 5. Consider changing "they have become" to "they are a commonly used tracer. . ."

→ will be changed as suggested

Lines 17-20 and 21 – 23. It is not correct that snowpacks preserve the isotopic content of each snowfall except due to snow mass transfer. The initial isotopic content of snowfall contributes to the integrated snowpack signal, but both equilibrium and kinetic fractionation modify snow water isotopic content. This is a function of temperature and resultant vapor pressure gradients both within the snowpack and between the snowpack and atmosphere. One should not expect complete sublimation of entire snow crystals and enrichment as you discuss at the end of this paragraph occurs due to both equilibrium processes (your current references) as well as kinetic fractionation (Gustafson et al. 2010; Biederman et al. 2012)

→ I agree with the reviewer and the paragraph in question will be changed to: "The initial isotopic content of snowfall contributes to the integrated snowpack signal, but mass transport through wind drift and avalanches and equilibrium and kinetic fractionation modify snow water isotopic content. During precipitation-free periods the snow is removed layer by layer through sublimation. The resulting fractionation is a function of temperature and resultant vapor pressure gradients both within the snowpack and between the snowpack and atmosphere. Unlike the evaporation from the surface of a

water body in which the remaining water accumulates steadily in heavy isotopes, one would expect that no isotopic change occur in the remaining snow cover due to complete sublimation of individual snow crystals. In practice, however, an enrichment of heavy isotopes in the upper snow layers takes place, which happens due to diffusion of water vapor in the pores of the snow pack and also due to partial melting which causes evaporation and percolation of melt water in the remaining snow (Gat, 1996; Stichler et al., 2001) as well as kinetic fractionation (Gustafson et al. 2010; Biederman et al. 2012)."

Page 11 "proof" could be changed to "demonstrate"

→ As also suggested by the other reviewers this will be changed to "prove"

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 2641, 2013.