Reply to general comments of Reviewer 2:

Implementation of preferential flow process into one-dimensional model is challenging and important research. Accuracy of hydrological process will be enhanced by this improvement. Concepts and mechanisms of dual domain approach are described in more detail in the companion paper, Wever et al. (2016). Therefore, the main focus of this paper is the validation of the preferential flow model in terms of accuracy of runoff simulation. In this paper, authors performed the comparison with field data and showed the enhancement of accuracy in runoff by implementation of dual domain approach. The product of this study is appropriate to publish for HESS. On the other hand, although many contents of this paper described the success of this improvement, detailed analysis of the improved results are not sufficient. For example, information of snowpack was not shown and not considered in the discussion despite it affects significantly of the relationship between water supply and runoff. Information of snow stratigraphy helps to understand when and why PF model obtained better accuracy than RE model. In this study, authors used the SNOWPACK model. Therefore, it is not difficult to add the snowpack information. If there are observed data by snow pit observation, showing observed data is desirable. As well as showing snow stratigraphy, quantitative estimation of snowmelt amount is also necessary to discuss runoff as a response of the liquid water input. It can also be estimated from the output of the SNOWPACK model.

> We thank the Reviewer 2 for his constructive comments and ideas to improve the manuscript. Below, we give our response to the issues raised by the reviewer.
>
> We agree that the snow stratigraphy is a very important factor influencing liquid water transport in the snowpack. It certainly can help understanding when and why the PF model obtained better accuracy than RE model. Eiriksson et al. (2013) for example stated the importance of ice layers and stratigraphic boundaries for runoff formation at the slope scale. Considering findings of Wever et al. (2016), we think that even though considering preferential flow enabled to simulate ice layers, the probability of detection is still not sufficient to analyse the effect of ice layers on runoff generation. So far, we focused on bulk snow cover properties derived by the simulations and their effect on the model performance, as shown in the discussion section in the original manuscript for snow height and bulk density. Additionally, Wever et al. (2016) show the good representation of density observations of RE and PF model at WFJ. We therefore plan to investigate the existence of marked grain size and density changes, representing possible capillary barriers, on the performance of the different models. Also for the experiments and natural events, snow stratigraphy information will be discussed, as far as available.
>
> It is true that snowmelt is an important source of liquid water input for runoff generation. The total influx rate, consisting of both, rainfall and snowmelt can, besides snowpack stratigraphy, be an additional source of variability in the performance of the preferential model, since the area involved in preferential flow has been shown to be dependent on water influx rates for laboratory experiments in soil physics (DiCarlo, 2013). We will consider this in the updated manuscript.

Reply to specific comments of Reviewer 2:

P5 L18: This sentence describes Equation (1) is determined by Katsushima et al. (2013) and field observation data. Can you add the data used here (field observation data) in this paper? If it is already shown in previous paper, it should be referenced.

> Reply: The data used from Katsushima et al. (2013) is presented in a graph in Wever et al. (2016). The field observation data was actually not used for the fit in the end and we will delete that part of this sentence.

Fig 1 Please indicate the position of the sections of Fig. 1 (b) and (c) in the Fig. 1 (a)

> Reply: Apparently we caused confusion here, as all the figures show different experiments and don't relate to each other. We will revise the caption. (b) relates to Serneus 26.02.15 and (c) relates to the experiment in Klosters on 26.03.15.

P8 L16 Snowmelt amount should be considered in the analysis. It can be estimated from output data of the SNOWPACK.

> Reply: In general, liquid water input and therefore snowmelt represents a substantial amount of liquid water input and is a key factor influencing the water transport. We will estimate the snowmelt from the simulation output. As stated in our reply to the major comments, we also plan to extend the discussion in this sense.

Fig 3-5 Information of snow stratigraphy had better be added in these figures because it affects the relationship between input water supply and runoff. Although snow depth, averaged snow temperature and water content are shown in Table 2, it is not sufficient because water infiltration process is affected by more complicated snow conditions such as existence of ice layer, grain size contrast and ratio of wet snow to dry snow.

> Reply: As stated in the reply to major comments, we can extent the analysis by considering snowpack stratigraphy. In Fig. 1 of this reply letter, we provide the temperature and LWC profiles including identified crusts and ice layers for the sprinkling experiments. Unfortunately, no detailed information about grain size and shape is available for the snow profiles.

p9 L10-12 I guess that the reason of greater variability of snowpack runoff in highest located site is the existence of lateral flow due to ice layer or capillary barrier. In snowpack observation, are ice layer or capillary barrier existed?

> Reply: Unfortunately, no detailed information about snow microstructure stratigraphy is available for the natural events. However, ice layers and the position of layer transitions were qualitatively assessed before the onset of rainfall. For the Event of Jan 03, no distinct ice layers were observed. The snow cover built up within the previous week with mostly very cold temperatures and just a light melt refreeze crust at the top. For the Jan 09 event, the previous event lead to distinct ice layers. But apparently, these differences in the snowpack layering for both events are not expressed by different behaviour of the lysimeter. They are in both cases very heterogeneous in runoff.

P10 L20 This sentence indicated that snowmelt affected runoff significantly. Therefore, snowmelt amount should be estimated. Analysis considering snowmelt amount will make better discussion.

> Reply: As stated in our reply to the major comments, we plan to extend the discussion in this sense and provide information about snowmelt. We plan on analysing snowmelt as an important part of system input rates and analysing their implication on the performance of the water transport models.

P11 L4 RMSE(d,e) -> RMSE (b,e)

> Reply: This will be changed in the updated manuscript. Thanks!

P11 L10 R2 value in WFJ was improved by PF model more significant than that in CDP. This result implies preferential flow predominated more in WFJ. Does the ratio of dry snow in WFJ was larger than that in CDP?

> Reply: By applying a bulk threshold of 1 vol% LWC to separate between dry and wet initial snow conditions, 30% of events at CDP had a dry initial snow cover, whereas this was the case for just 1 event at WFJ. If looking at the ratio of wet layers to dry layers within the snowpack, this single event had 15% of the layers wet, whereas for all other events at least 99% of layers had a LWC of at least 1 vol%.

P12 In the discussion section, success of PF model was discussed mainly. However, discussions about shortcomings of the model and suggestion of required improvement are also important for future research.

> Reply: Thanks for the advice. We will answer this with the last comment (P14, L30) in detail.

P14L1 This sentence indicated that snow densities were spread from below 200kg m-3 up to 500 kg m-3 in CDP. But the accuracy of hydrological parameters (e.g. suction and hydraulic conductivity) of low-density snow in numerical snowpack model are insufficient because measurement of them is difficult. They are estimated using equations formulated based on the measured results using high-density snow. For this reason, inadequate accuracy is anticipated when low-density snow comprises a portion of snowpack. Can you add the discussion about the accuracy of runoff simulation in the case of snowpack with low-density snow? It may provide the information whether hydrological parameters of low-density snow should be measured in some way or is not important for runoff estimation.

> Reply: Thanks for this comment and advice. This topic was also raised by Reviewer 1. The laboratory experiments from Yamaguchi et al. (2012) and Katsushima et al. (2013) were conducted on snow with densities of 380 kg m^{-3} and above (typically 400-600 kg m^{-3}), therefore much more in range of the densities at WFJ (around 450-500 kg m-3). This could explain the higher variance in R^2 values for runoff at CDP (including densities below 200 kg m-3). We will adapt the discussion accordingly. This suggests that the variable performance of RE and PF models at CDP may be associated with the existence of lower snowpack densities. Fig. 2 in this reply letter shows R^2 values for the CDP-events, split in two samples with initial densities below and above 350 kg m^{-3}, respectively. The PF model shows better performance for lower densities when compared to the RE model. In general, the low-density parameters need more experimental backing – as the reviewer suggested - and we will discuss this adequately.

P14 L30 Do you have any suggestion to improve the model? The companion paper, Wever et al., suggested some ideas to enhance the accuracy of ice layer formation. Suggestion to enhance the accuracy of runoff is welcome in this paper. Discussions considering snow stratigraphy help to provide idea for further improvement.

> Reply: The suggestions provided in Wever et al. (2016) for improving the preferential flow model apply also for this study. This concerns especially the two parameters which have been calibrated: the threshold for saturation (Θ_{th}) and the number of preferential flow paths for refreeze (N). Laboratory experiments or detailed simulations using multi-dimensional snowpack models might be able to determine the number and size of preferential flow paths for lower input intensities and snow densities. Additionally, we think that very limited data of high temporal and spatial resolution snowpack runoff measurements are available, limiting validation possibilities. CDP and WFJ provide long-term measurements on an adequate temporal resolution; however, this data gives little information about spatial variability of snowpack runoff. Large area multi-compartment lysimeter setups might help improving estimating size, amount and spatial heterogeneity of flow fingers. The lysimeters should be at least 10 m^2 in total area to minimize the effect of preferential flow for the total lysimeter area (Kattelmann, 2000). Sprinkling experiments with low sprinkling intensities on such a device could fill a knowledge gap about water transport in snow under conditions naturally occurring, but under controlled conditions. Also the role of ice layers for vertical water transport is not yet resolved. During the sprinkling experiments in this study, the dry and cold snowpack showed highest lateral flows, but also clearly dominating vertical preferential flow. Our experiments for a ripe snowpack did not show pronounced lateral flow but distinct matrix flow, while Eiriksson et al. (2013) observed lateral flow in saturated layers during wet conditions on a slope. The implications of preferential flow or distinct lateral flow on ice layers or structural transitions can also be observed on the catchment scale. Rössler et al. (2014) had to adjust parameters, leading to very fast overland flow to be able to model the hydrological implications of a major ROS event in October 2011 in Switzerland. It is quite likely that this parameter had to be set that high to compensate for neglecting lateral flow within the snowpack or vertical preferential flow. To be able to better forecast such events, research has to be promoted from experimental lab and field studies over sophisticated multi-dimensional water transport models to simplified but operationally applicable 1D water transport models. We will amend the discussion in the manuscript regarding this point.

References:

Eiriksson, D., Whitson, M., Luce, C. H., Marshall, H. P., Bradford, J., Benner, S. G., Black, T., Hetrick, H., and McNamara, J. P.: An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales, Hydrol. Process., 27, 640-654, doi: 10.1002/hyp.9666, 2013.

Katsushima, T., Yamaguchi, S., Kumakura, T., and Sato, A.: Experimental analysis of preferential flow in dry snowpack, Cold Reg. Sci. Technol., 85, 206-216, doi:10.1016/j.coldregions.2012.09.012, 2013.

Kattelmann, R.: Snowmelt lysimeters in evaluation of snowmelt models, Ann Glaciol, 31, 406-410, Doi 10.3189/172756400781820048, 2000.

Rössler, O., Froidevaux, P., Börst, U., Rickli, R., Martius, O., and Weingartner, R.: Retrospective analysis of a nonforecasted rain-on-snow flood in the Alps-a matter of model limitations or unpredictable nature?, Hydrol. Earth Syst. Sci., 18, 2265-2285, doi:10.5194/hess-18-2265-2014, 2014.

Yamaguchi, S., Watanabe, K., Katsushima, T., Sato, A., and Kumakura, T.: Dependence of the water retention curve of snow on snow characteristics, Ann. Glaciol., 53, 6-12, doi: https://doi.org/10.3189/2012AoG61A001, 2012.

Figures:

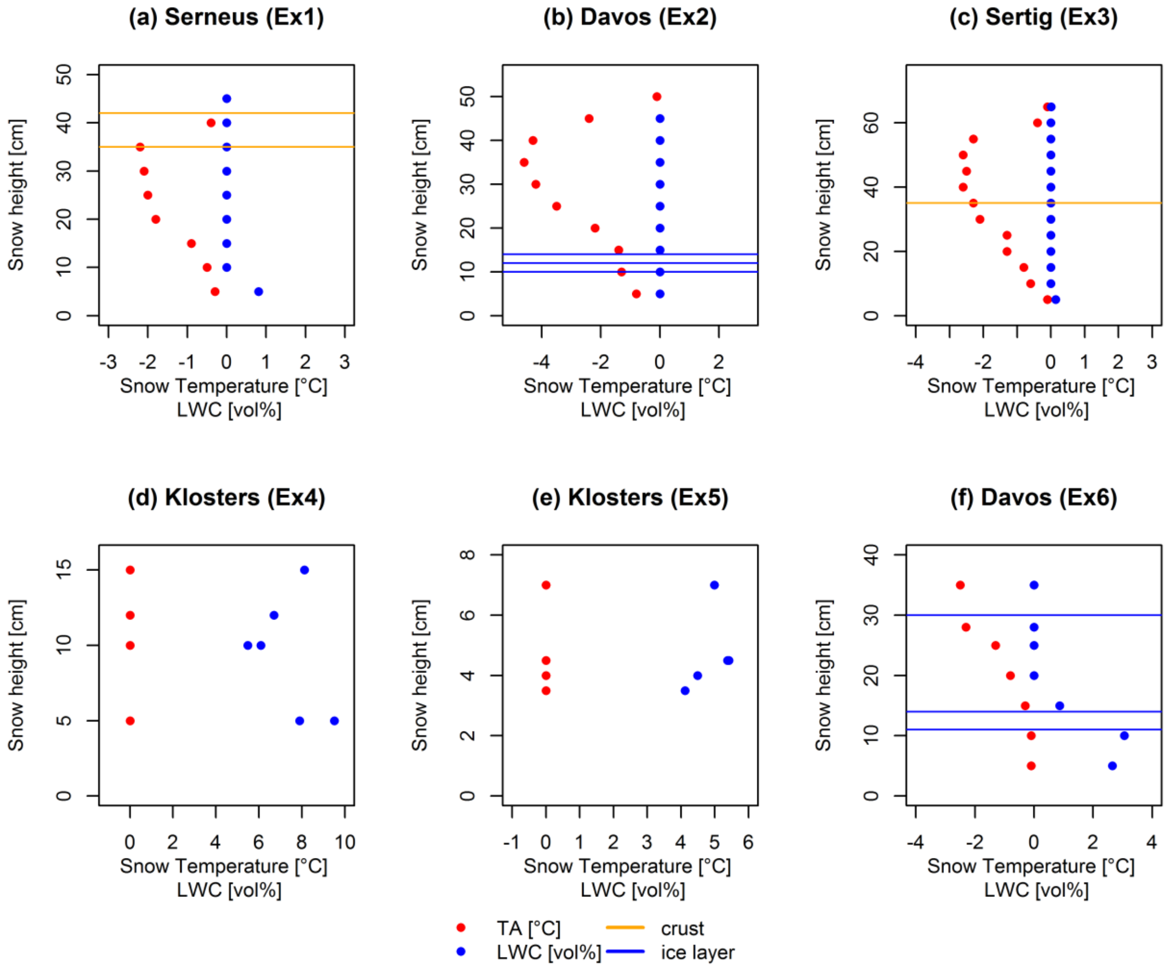

Figure 1: Snow temperature and LWC profiles representing the sprinkling experiment pre-conditions. The lines represent observed ice layers (blue) and crusts (orange).

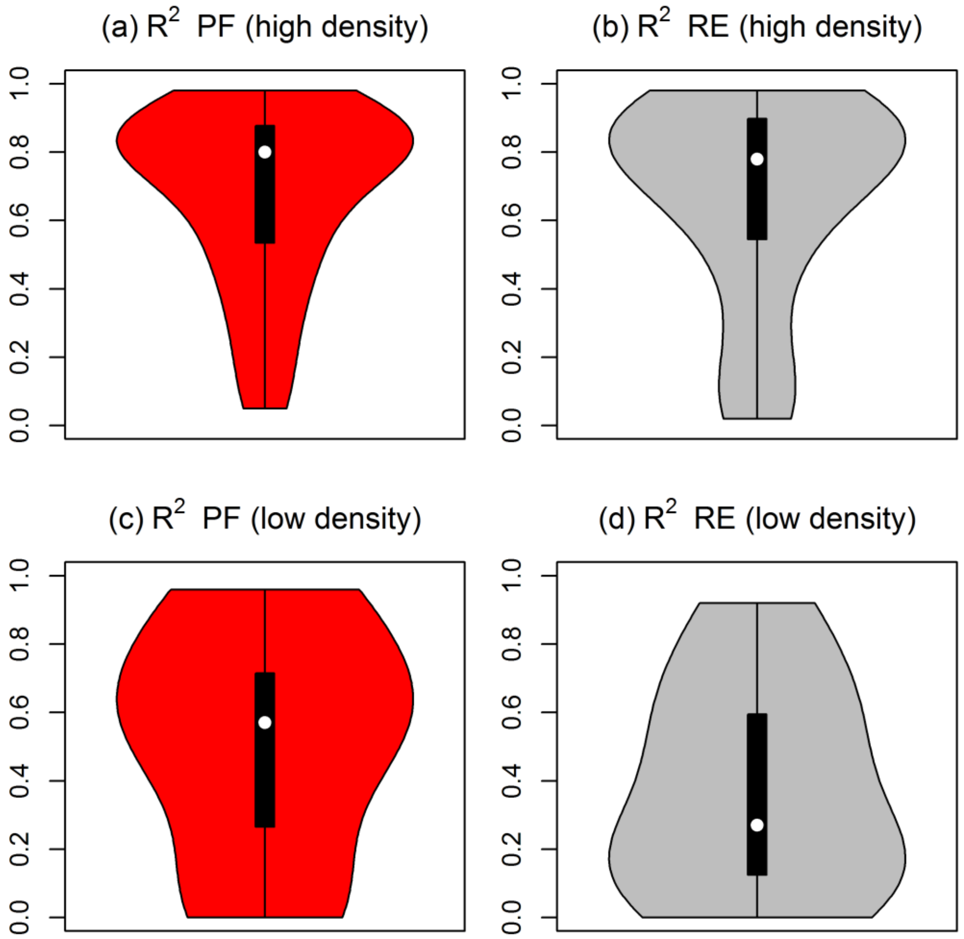

Figure 2: R^2 values for CDP events for the PF (a,c) and RE (b,d) model. The sample is split for bulk densities above 350 kg m^{-3} (a,b) and below 350 kg m^{-3} (c,d). The x-axis describes the density function of the data.