Response to Reviewer 1

Implementation of the preferential flow process into one-dimensional numerical snowpack model is valuable effort. Reproduction of ice layers in numerical snowpack model is also valuable. Furthermore, the dual domain approach is interesting idea. I appreciate the development of the new schemes to consider the preferential flow effect. On the other hand, considering the heterogeneous process in one dimensional model needs the various assumption, and it leads to the discrepancy between simulations and field observations. In the present state, this model still have the limitation of accuracy. In my opinion, achievement in this paper is new development of the concept to implement the preferential flow process in one-dimensional model with the purpose of reproduction of ice layers. The accuracy of this model is expected to be enhanced by cooperation with multi-dimensional model and laboratory experiment. In that context, the suggestion in the discussion section, laboratory experiment with small water input rates and heat process simulation with multi-dimensional models, are important messages from this study. In my opinion, this paper is acceptable in the Cryosphere. I made lists following minor comments to make better contents of the paper.
We thank the reviewer for his constructive comments and ideas to improve the manuscript. We agree that our approach is rather a starting point than a complete description of preferential flow and ice layer formation. Nevertheless, we also would like to stress that we think that the discrepancies between model and observation should not be attributed to model representation errors alone. Also inconsistencies and subjectiveness in snow pit observations, as well as inaccuracies in meteorological and snow lysimeter measurements to drive and verify the SNOWPACK model play an important role. Please find our detailed response to the issues raised by the reviewer below.

minor comments

1. Introduction: Attempt to consider the effect of preferential flow in the numerical snowpack model is also tried by Katsushima et al. (2009). The preferential flow process in their model is not physical base, but it is the start point of their experiment in Katsushima et al. (2013). I recommend to include following reference. Katsushima, T., Kumakura, T., Takeuchi, Y., 2009. A multiple snow layer model including a parameterization of vertical water channel process in snowpack. Cold Regions Science Technology 59(2-3), 143-151.
   We thank the reviewer for pointing our attention to this study, which certainly deserves citation in our manuscript. They used a similar concept to initiate preferential flow when ponding is occurring in the model domain. We will make appropriate references to this study when revising the manuscript.

2. P3 l22: In the present state, Equation (1) seems reasonable method to estimate the ratio of preferential flow area. However, this equation is too simplified and needs the improvement in the future. For example, considering only grain size is not sufficient. If author has any ideas of the experiment to improve this equation, I recommend to add the suggestion in this manuscript. It will be informative message for other researcher.
   We agree with the reviewer that Eq. 1 should be considered a preliminary result. Given the analogy between the ice matrix and soil, results from experiments with soil suggest that the preferential flow area in snow should most likely become a function of system influx rate. We think that repeating the experiments at low water input rates is an important step, although achieving low infilitration rates in a laboratory setting is generally challenging. We also think that confirmation of the absence of preferential flow for fine grains, as reported by Katsushima et al. (2013), needs to be acquired by increasing the sample size to exclude the possibility that the finger width is larger than the snow sample. This may

lead to the erroneous conclusion that the wetting of the complete snow sample shows the absence of preferential flow and only matrix flow is active. Please see also the major comment from Reviewer 2. We will amend the manuscript at this point.

3. P3 l25 Usually, preferential flow path area get wider with time. Therefore, decrease in preferential flow area due to grain growth seems distant from actual process. However, in the dual domain simulation, if the decrease in preferential flow area due to grain growth leads the movement of water to matrix flow area, it can be considered as indirect expression for expansion of preferential flow area.
The situation described in P3L25 is not happening often. However, we wanted to describe our decision to limit the preferential flow area, instead of moving additional water from preferential flow to matrix flow if the preferential flow area decreases below the necessary area to accomodate all preferential flow water. While individual paths may increase with grain size, the data we used to establish the fit is showing that the total preferential flow area decreases with increasing grain size. We will amend the manuscript to report that the situation described in P3L25 happens seldom. We therefore also think that it should not be considered that this represents "an indirect expression for the expansion of the preferential flow area", as Reviewer 1 suggests. During the formation of preferential flow paths, paths indeed not only grow in length, but also in width. This is for example reported in Hirashima et al. (2014). However, this process is occurring on short time scales (typically within minutes/hours) when the preferential flow is developing towards a steady state. This widening is then likely not driven by grain growth, but by the non steady preferential flow path formation process. In the simulations, we aim to represent the steady state, particularly as SNOWPACK simulations are used to assess snow cover development on time scales from hours to a full season. Still, possible future revisions of Eq. 1 may be constructed for these kind of effects. On the other hand, it should maybe not be aimed for that 1-dimensional snowpack models with a dual domain descritpion describe the full dynamics of preferential flow paths, as long as the net effect is properly described. Such tasks may be more suited for full 3-dimensional snowpack models.

4. P8 L26 Fig.5 Can you add the detailed figures of snow temperature, density and water content focusing the beginning of March during the formation of ice layers? It helps the understanding why ice layer formed only the simulation with preferential flow.
It is an interesting suggestion by the reviewer to show more of the processes occurring during the formation of ice layers. We will therefore include an additional figure in the manuscript, showing in more detail how snow density, grain size, snow temperature and liquid water flow interplay to form ice layers. This figure is shown in Fig. 1 in this document. The figure shows how preferential flow water (b) is percolating faster than matrix flow water (a), thereby reaching parts of the snowpack where the temperature is well below freezing (c). In (e) it can be seen that water accumulates on grain size differences between layers. By refreezing, melt-freeze crusts form (f) and when the density increases above 700 kg/m^3 (d), the model interprets the layer as an ice layer (f).

5. p9L7 When the density data was counted, was the layer thickness considered? Also, Fig.6 show two figures, left one seems for all layers and right one seems data in specific condition. However, in PFP simulation, the data near 900 kg/m3 existed in right figure despite it did not exist in left figure. It seems strange.
The left hand side of Fig. 6 shows density for the segments as measured by the observer. These segments sample vertically about 30 cm of the snow cover at a time. The simulated snow profiles are aggregated to the same segments as measured by the observer, and then we show the average density over this segment. So indeed, we considered the layer thickness when the density data was processed. This is a comparison

of how the simulated density distribution agrees with the observed one. The problem with this analysis is that ice layers are thinner than the typical segments used by the observer, and are not sampled as such. Sampling the density of the actual ice layers is rather complicated (e.g., Watts et al. (2016)) and this is not done during the regular snow profiles at WFJ. Therefore, the right hand side of Fig. 6 shows the highest modelled density in a model layer, which was found within 20 cm of an observed ice layer. A model layer has a typical vertical extent of less than 2 cm. In this case, no density information is available from the observation at this level of detail, and the simulated snow density cannot be verified by the measurements. Apparently, our presentation of the analysis is causing confusion at this point and we will revise the manuscript and the figure caption to provide a better description of what is depicted in Fig. 6.

6. P9 L20 Figure 7 does not include the result of REQ. Ice layer may form even if the preferential flow is not considered depending on temperature and liquid water condition. Result of REQ had better be included in Fig. 7 to show the advantage of the consideration of preferential flow.
   We revised the figure. Please see Fig. 2 in this document. For clarity, we only show the two most important statistics for simulations with Richards equation only. The statistics for the probability of detection shows that using Richards equation only, no ice layers with a dry snow density above 600-700 kg/m^3 are reproduced by the model. The prediction bias shows that high density layers are predicted much less frequent compared to how often they are found in the observations. Including preferential flow in the model, is clearly improving both the probability of detection as well as the prediction bias. We will amend the manuscript to include the revised figure.

7. P10 6-7 No consist difference of r2 values considering preferential flow indicates that the matrix flow is predominant in this period. Thus, I guess most of snow was wet in this period. When enhancement in accuracy of runoff by considering preferential flow is discussed, information of snow stratigraphy should be included to show the ratio of dry snow, existence of ice layer and difference of grain size at layer boundary. Results of runoff simulation is discussed mainly in Würzer et al. So if their paper shows the snow stratigraphy as well as runoff simulation, it is not necessarily required in this paper.
   The manuscript by Würzer et al. (2016) shows the effect of preferential flow on short time scales during rain-on-snow events, which is a specific type of event. We also felt the need to show how the preferential flow formulation simulates snowpack runoff on seasonal time scales, not only during specific events. Therefore, we decided to include snowpack runoff analysis in the manuscript and we prefer to keep it here. Concerning the explanation of the year-to-year variability, we provide here the same response as to Reviewer 2, who raises a similar issue: it certainly is an interesting suggestion to try to explain year-to-year differences in performance of snowpack runoff simulations. However, we did not find a statistically significant correlation between, for example, the r^2 value or arrival date and the number of ice layers or the number of jumps in grain size or hardness observed in the profiles. We tested both linear correlation using Pearson correlation as well as rank correlation coefficients (Spearman, Kendall). One issue is that, as Reviewer 2 points out, meteorological conditions also vary from year to year. In some melt seasons, percolation speeds through the snowpack are high, in others it takes a few weeks for the whole snowpack to become wet. These differences arise from weather patterns: in some years warm weather prevails for several weeks in the melt season, leading to a quick wetting of the snowpack, whereas in other years, snow melt periods are interrupted by periods with colder weather and new snowfall amounts. We therefore also analyzed the maximum difference in the relative part of the snowpack that consists of melt forms in the observed profiles, between two subsequent snow profiles. This is an indication of the progress of the melt water front inside the snowpack. However, also this did not reveal any

statistically significant information. We think that ultimately, there are many factors contributing to high or low r^2 values or good or poor estimates of the arrival date: warming rate of the snowpack, presence of capillary barriers and ice layers that may trigger preferential flow, errors in meteorological measurements and errors in snow lysimeter measurements. The snow lysimeter at the Weissfluhjoch measurement site has a surface area of 5 m^2. As an illustration, Fig. 2 in Kattelmann (2000) shows that with this size, the variation coefficient is still quite large, and that an area of at least 10 m^2 may be required to more accurately capture snowpack runoff. Furthermore, inconsistencies in the bi-weekly profiles are present due to the subjective component of judging grain size and shape, as well as the fact that multiple observers are responsible for the snow profiles. All these factors make the analysis of factors contributing to high or low model performance difficult. We will discuss this in the revised manuscript.

8. P10-11 In the discussion section, descriptions '(1) P10L27-31, the absence of studies at low input rates makes the general validity of condition 1 we implemented uncertain (2) P10L6-9 Muti-dimensional snowpack models may help here to develop better understanding of the heat exchange processes between preferential flow paths and surrounding snow matrix, as a function of the number density of active preferential flow paths' are important messages. These suggestions provide the idea for valuable laboratory experiment and analysis using other model. If authors have other idea (e.g. the experiment to parameterize the process of transition from preferential flow to matrix flow.) and added in the manuscript, it will be welcomed as valuable information for reader studying wet snow.
We think the most crucial step is to investigate and quantify the heat exchange between preferential flow paths and the surrounding ice matrix, as a function of preferential flow area and the number of preferential flow paths. We expect that the vertical percolation speed of the preferential flow fingers is slowed down when percolating cold snow where considerable refreeze may take place. We think that a deeper investigation requires laboratory experiments with low water input rates (this may be difficult to achieve), high resolution temperature measurements (probably using infra-red photography) as well as dye-tracer to follow the wetting of the snowpack. Related to point 2, larger sample sizes may be required to prevent preferential flow finger width exceeding the sample size. We additionally think that using multi-dimensional models to simulate laboratory experiments helps to quantify the heat and water flow and to verify to what extent formulations of the heat and water exchange between preferential flow paths and the surrounding matrix reproduce the observations in laboratory experiments. For example, when a preferential flow path hits a microstructural transition, it starts spreading over the interface at some point. This is often explained via the water entry suction, yet the exceedance of the water entry suction in the preferential flow path in our simulations was not occurring often enough to successfully reproduce ice layers. Detailed laboratory and numerical studies using multi-dimensional models may assess the liquid water content distribution inside a preferential flow path. However, here it is important to note that some studies suggest that the water flow and wetness distribution inside a preferential flow path can probably not be described by Richards equation (DiCarlo, 2013). Ultimately, formulations for heat and water exchange between preferential flow paths and the surrounding matrix can then be incorporated in a model framework for 1-dimensional snowpack models, such as the one which we propose in this study. We will amend the manuscript at this point.

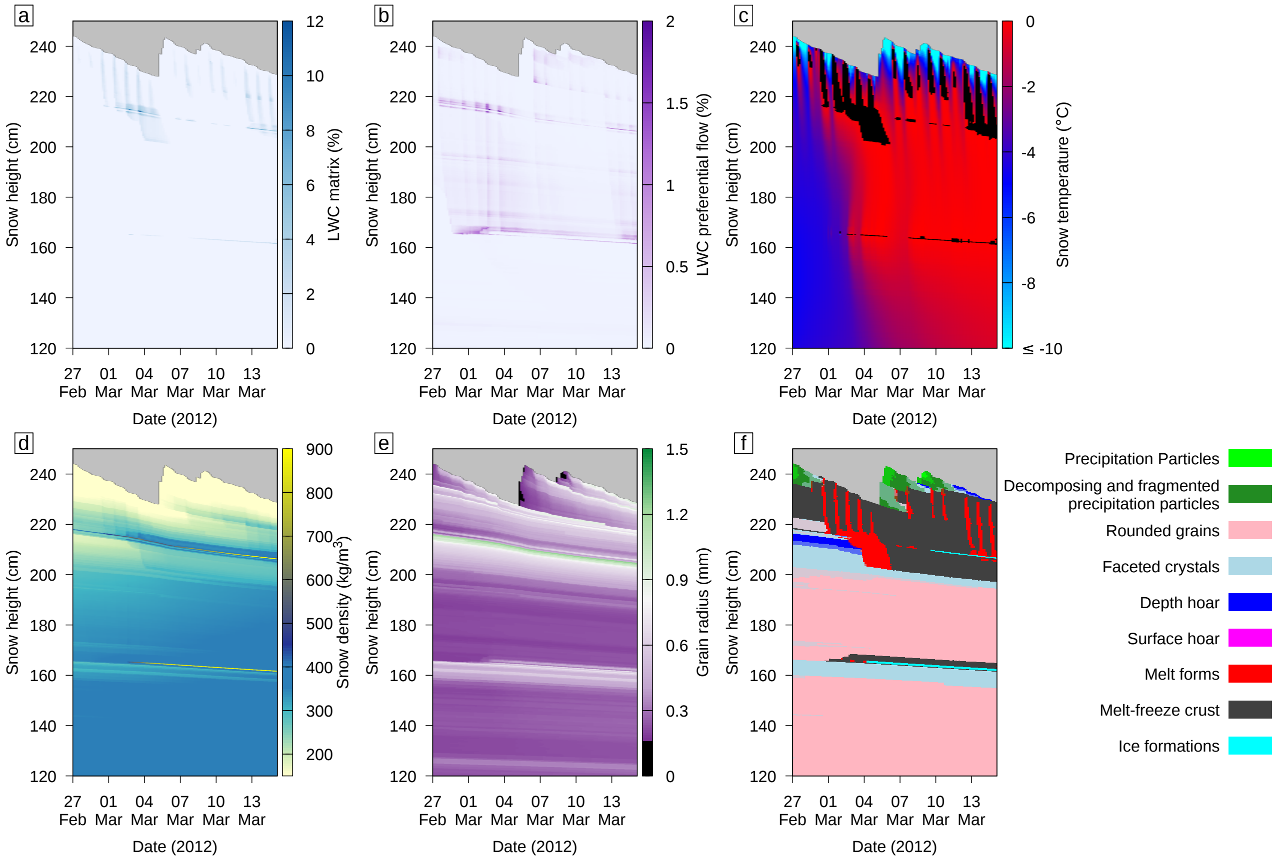

Figure 1: LWC in matrix flow (a), LWC in preferential flow (b), snow temperature (c), snow density (d), grain radius (e) and grain shape (f), depicting a detail of Fig. 5 in the original manuscript. Only the upper part of the snowpack is shown for the period 27 February to 15 March. In (c), snow at melting temperature is coloured black to highlight wet parts and in (f), ice formations are defined as modelled dry snow density exceeding 700 kg/m^3.

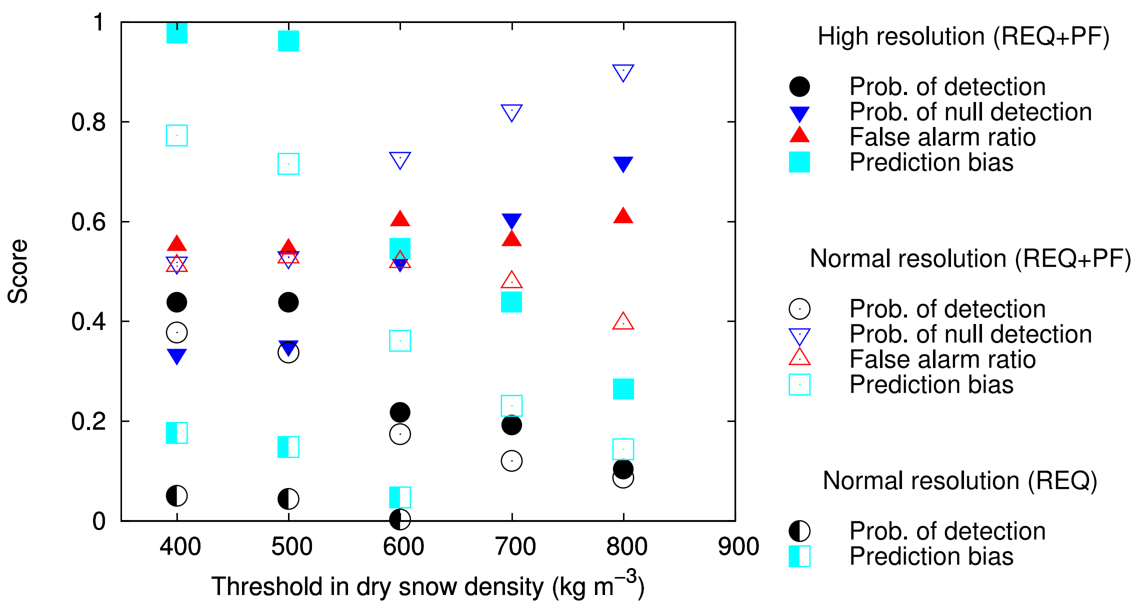

Figure 2: Contingency statistics as a function of threshold in dry snow density that defines an ice layer in the simulations, for both normal and high resolution simulations including preferential flow (REQ+PF) and normal resolution simulations using Richards equation only (REQ).

References

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