Response to reviews

Please find below our point-by-point response to all issues raised by both reviewers. The responses are the same as we uploaded to the online discussion. However, we amended here in which line numbers of the revised manuscript changes have been made.

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 made appropriate references to this study when revising the manuscript, see P2, L21,28 and P4, L21.

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 infiltration 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 amended the manuscript at this point: on P4, L2-3 and on P12, L17-21, we discuss now that preferential flow was not observed for fine grains and that larger snow samples may be required to confirm the absence of preferential flow for fine grained snow. Our suggestion that experiments at low input rates are probably needed to refine Eq. 1 was already mentioned in the original manuscript and can be found back in the revised manuscript on P12, L12-17.

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 P3, L25 in the original manuscript 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 accommodate 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 amended the manuscript to report that this situation happens seldom, see P4, L6. 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 description 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 included an additional figure, Fig. 6 in the revised manuscript, showing in more detail how snow density, grain size, snow temperature and liquid water flow interplay to form ice layers. This 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 in the original manuscript 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 in the original manuscript 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 was causing confusion at this point and we revised the manuscript, see P10, L18-23, as well as the figure caption (see Fig. 7 in the revised manuscript).

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, which is now Fig. 8 in the revised manuscript. 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 amended the manuscript to discuss the results for simulations using Richards equation only, see P11, L4-8.

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 provide a discussion now in the revised manuscript, see P11, L30 to P12, L3.

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 amended the manuscript at this point, see P12, L30 to P13, L5.

Response to Reviewer 2

The authors have chosen to address a challenging topic and the results of this effort reflect the difficulty of simulating a heterogeneous, three dimensional, multi-process phenomenon in a 1-dimensional framework. While there is certainly much progress and future work to come in this area, the authors have presented a valuable analysis and initial framework that can be adapted and built upon in the future. As such, I am recommending that this work be accepted for publication in The Cryosphere, following some minor revisions that I believe will improve the quality and usefulness of the work.
We thank the reviewer for his constructive comments on the manuscript. Please find our detailed response to the issues raised by the reviewer below.

Major comment

Much of the framework relies on the interpretation of the results of Katsushima et al. (2013) as interpreted by Hirashima et al. (2014). They found that when water had reached the bottom of the profiles in their laboratory experiments, that the fractional area at 4 cm depth was smaller with larger snow grain size. The wetted fraction was interpreted here as the preferential flow fraction. As grain size decreased the wetted fraction increased and this was interpreted as the preferential flow fraction being larger. However, as this extends to the finest grain size, it is stated that no preferential flow was observed, and indeed if slower matric flow was happening, the deepest wetted area would be larger and more uniform. If that is what happened, and matric flow had extended beyond the 4 cm depth, then we have no clear transition defined between the two flow regimes. I would like the authors to discuss the interpretation of the experiment on which Figure 2 is based.
We partly agree with the interpretation of the experiments by the reviewer. We think that at some point, it may become not possible anymore to clearly define matrix flow and preferential flow regimes. If one observes that 90% of the snowpack is wetted during infiltration, could you still call it preferential flow and flow fingering, or is it just matrix flow where 10% of the snowpack is somehow not involved in matrix flow? However, we should also consider the possibility that the observations in the studies by Katsushima et al. (2013) and Hirashima et al. (2014) are not sufficient to conclude that both regimes cannot be clearly defined. It may happen that the finger width exceeds the size of the container used in the experiments such that the preferential flow finger is not identifiable as such anymore DiCarlo (2013). The diameter of the rings used in the experiments by Katsushima et al. (2013) was 5 cm and larger rings may be required to study water flow for small grains. On the other hand, in soil science, experiments also have demonstrated that for certain flow regimes and small grain size, no preferential flow forms and the flow is considered stable DiCarlo (2013). This was also found for larger grain sizes at low infiltration rates. We think that at this point, it is uncertain whether for fine snow grains, a regime exists were no preferential flow forms, or that preferential flow in snow forms under any circumstance for infiltration in snow. We hope that future experimental studies will address these issues. We did not explicitly

mention in the manuscript the absence of preferential flow for fine grains in the observations by Katsushima et al. (2013) when discussing Fig. 2. We now report this on P4, L2-3. However, more importantly, the smallest grain size class used in the experiments by Katsushima et al. (2013) is not often found in the SNOWPACK simulations. This grain size class is mostly associated with new snow fall and subsequent metamorphism generally quickly increases the grain size. We amended the manuscript with an extra figure (see Fig. 6 in the revised manuscript). In subfigure 6(e), the grain radius from the simulations is shown. Here, we coloured the grain radius black when it is below 0.16 mm, which corresponds to the lowest grain size class used by Katsushima et al. (2013). As can be seen, the important parts of the snowpack involved in preferential flow have a grain radius larger than the specific grain size class for which no preferential flow was observed.

Specific Comments:

- P2 line 15: Although I would not expect a through presentation of the work of Colbeck (1979) or Marsh and Woo (1985), the authors have stated that these works were not widely adopted. A couple of sentences summarizing the main concepts presented in these studies, and any weaknesses that may have resulted in their lack of adoption, would help to inform the readers about the need for progress in this area of research.
  We revised the manuscript as follows (see P2, L14-21 of the revised manuscript):
  "In early attempts by Colbeck (1979) and Marsh and Woo (1985) to describe preferential flow in snowpack models, the water flow in snow is described as a flow in multiple flow paths. In Colbeck (1979), flow paths are defined that differ in size and snowpack properties, which results in different percolation speeds in the individual snow paths when applying Darcy's law. In Marsh and Woo (1985), the snowpack is divided in flow paths of equal size and snowpack properties, but based on comparted lysimeter measurements, it is determined how much of the total flux is transported in each of the individual flow paths. Both approaches never found widespread adoption, probably because they require a-priori specification of the flow path variability (Marsh, 1999)."
  Why exactly the adoption of those approaches was limited is difficult to assess. It may be related to the uncertainty of the additional parameters needed for those descriptions. It may also be that most model developments focussed on processes that required more urgent attention. When taking the SNOWPACK model as an example: the model was originally developed for avalanche warning purposes and was later developed to study other areas, like snow hydrology, catchment hydrology, Antarctic snow covers, the Greenland ice sheet, etc. Furthermore, there seems to be a strong increase in interest in liquid water flow in snow in the recent years. The availability of high quality laboratory experiments, new modelling techniques, etc., turned the attention again to preferential flow. We therefore do not want to interpret too much why the early modelling attempts did not find widespread adoption.

- P2 lines 19-21: I suspect that the specific application suggested in the example would require at least a 2-d model. The dual-domain approach is a good starting place. Given that the authors point to three flow regimes (matric flow, flow fingering and macropore flow), it would seem appropriate to include multiple flow domains in the future; one step at a time.
  Thank you for the comments. We actually think that the application for wet snow avalanche prediction may already benefit from the dual domain approach, not necessarily requiring a full 2-dimensional model. Here, acquiring accurate snow depth and meteorological forcing in avalanche slopes is probably a more important source of uncertainty than the liquid water flow modelling. We agree that potentially, the dual domain could be extended with additional domains for other water transport processes. However, we think that validation and calibration of the model will become increasingly difficult given the

typical inaccuracies in forcing data (meteorological measurements) and validation data (snow lysimeter data) for snow models as well as deficiencies in model process descriptions.

- P7: I suspect that there would be an interaction between the layer thicknesses (resolution) and the threshold of defining ice lenses / layers. A thicker layer would require more water equivalent to reach a given threshold density, and this would be harder to achieve in terms of water and energy transfer. A higher resolution or finer layers should enable higher threshold density values for defining ice layers.
  Indeed, this is illustrated in Fig. 7 in the original manuscript, Fig. 8 in the revised one. For a specific threshold, the probability of detection is higher using thinner layers, which also means that for the same probability of detection, the threshold can be set higher for thin layers than for thicker layers. However, our interpretation of this figure is still that the difference between high and normal resolution simulations is much smaller than the difference between observations and simulations. Many discrepancies between observed and simulated snow profiles in terms of layering are probably not caused by the initial layer thickness, but also by errors in meteorological forcing as well as model simplifications and model process representation errors.

- P8 lines 7-17: This is an honest discussion of the performance issues but also shows that this methodology may be useful for future development.
  Thank you.

- P9 lines 1-5: Was the precipitation type generally known in the observations or was this 2003 event a specific example of a known case in which the model misclassified the precipitation type? In any event, if it was known that the precipitation was rain, the model's diagnosis could be overwritten for this event, and if precipitation type was generally known, the model could be fed rainfall and snowfall separately. It would remove a source of uncertainty from the results. If the precipitation type was not generally known, but merely appeared to follow expected patterns save for the 2003 example, then it is not necessary to make any changes, given the size of the dataset.
  Precipitation type is generally not known for the Weissfluhjoch measurement series, and the separation in rain and snow is done on the basis of air temperature. However, this particular event is a known case where rain on cold snow formed an ice layer which sustained throughout the snow season. We did experiments to force the model with rainfall for this period, but still the ice layer did not form. Probably the following reasons play a role: the SNOWPACK model is mostly run in 15 minute time steps and processes are solved sequentially. This means that at the beginning of the time step, new snow is added to the domain. Then the heat equation is solved to describe the temperature change over the 15 minute time step. Excess energy present after 15 min. is converted into snow melt, or, vice versa, in refreeze. Then, water flow is calculated over these 15 minutes. The fact that the equations are currently not solved in a coupled way but in a sequential way leads to the situation where water from rainfall can percolate out of the surface layer before there is time to refreeze the water. Furthermore, the water from rainfall is put in a layer of about 1.5 cm. In reality, one can imagine that rain drops hitting a snow surface below freezing will freeze directly at the surface, thereby creating an ice layer. It may even be the case that the ice layer thickens because the pore space at the surface vanishes, creating ponding conditions. Radiative cooling or rain with near surface air temperatures slightly below 0 °C may cause this ponding water to refreeze. If one really wants to force the model to form an ice layer when rain falls on a cold snowpack, we can think of a mechanism where the upper most layer of the snowpack is split and the upper part of the splitted layer is forced to take ice density. On P9, L30 to P10, L3 of the revised manuscript, we report and discuss now that even forcing the precipitation to be rainfall did not create an ice layer in the

simulations.

- P9 lines 7-13: I would expect the spread in simulated snow density to be somewhat smaller than observed with such a model, based on the fact that snow pits sample small spatial areas, and the presence of discontinuous ice layers and fingering may increase the number of samples necessary to obtain a reliable estimate of the mean density and its variability at a given depth. The PFP simulations in Figure 6 appears to capture the density distribution slightly better than the Richards equation alone. Have other statistical measures been explored as alternatives or in addition to r2? A comparison of the mean and variance may show closer agreement with the PFP simulations. There is Willmot's index of agreement or one of the revised formulations. The objective is not to choose the statistic that makes the model appear better, but r2 has been criticized as being insensitive to important factors of model performance.
As snow density in the field is generally measured in sections of about 20-30cm depth, the presence of ice layers, with typical vertical extents of less than 2 cm, is hardly detectable in the measurements. We think that simulations with preferential flow do have a slightly lower performance in reproducing snow density in the simulations, for the reasons mentioned in P10L14-18 in the revised manuscript. We now also tested using Willmott's index and also with this index, simulations with preferential flow perform slightly worse on overall density distribution (the index decreases from 0.84 *for simulations with Richards equation only to 0.83 for simulations with preferential flow). However, it seems that when changing from the 20-30 cm thick snow segments with measured density to high resolution vertical spacing, the simulations with preferential flow may better capture the variability by reproducing the ice layers. Measuring ice layer density is complicated (Watts et al., 2016) and we currently lack a good dataset of high resolution snow density measurements to validate the density distribution at the vertical resolution of the simulations (ca. 2 cm). Currently ongoing field campaigns using snow micro penetrometry (SMP, Schneebeli and Johnson (1998)) may change this situation soon and offers future potential to more in-depth verify the snow microstructure and snow density in the simulations in high detail. We report the results from the statistical test of Willmott's index in the revised manuscript on P10, L11-13. Additional discussion about this point is provided on P10, L13-20. Potential future measurements are discussed now on P10, L21-24 of the revised manuscript.*

- In looking at Figures 8 and 9, there are differences in the performance of the REQ and REQ+PF models from year to year. It would be interesting to compare the conditions against a ranking of differences in r2 (Fig. 8) and arrival date (Fig. 9). Are there specific snowpack or meteorological conditions that are correlated with the differences in performance between years? Knowledge of this may be useful for future model development.
We provide here the same response as to Reviewer 1, 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 provide a discussion now in the revised manuscript, see P11, L30 to P12, L3.

Technical Comments:

- P1 line 18: Change 'extend' to 'extent'
  Changed, see P1, L18. Thank you.

- P1 line 20-23: Change 'Water may flow... instead (Eiriksson et al., 2013)' to 'Water may flow laterally over ice layers or crusts, which reduces travel times and has a significant impact on catchment scale hydrology; alternatively, preferential flow in snow may promote vertical percolation instead (Eiriksson et al., 2013)'.
  Changed, see P1, L20-23, thank you.

- P1 line 23: This reads as if the reader is familiar with the increased melt on the Greenland Ice Sheet, which is likely to be true but, I would add a word or two to indicate the time frame.
  The reference we used to support this claim investigated a period of about 2 decades to relate changes in firn structure to warming trends, although the process may be occurring over longer time scales. This is revised in the manuscript, see P1, L23.

- P1 line 24: Change 'extends in' to 'extents, on'.
  Changed, see P1, L24 to P2, L1, thank you.

- P2 line 6 (possibly elsewhere): I find the use of the term 'snow covers' to be awkward. I suggest the use of the term 'snowpack' or 'snowpacks'.
  Changed throughout the manuscript, thank you.

- P2 line 15: I would change 'deployment' to 'adoption'.
  Changed, see P2, L20, thank you.

- P7 line 5: Change '... given the suspicion of problems...' to '... due to suspected problems...'.
  Changed, see P7, L22, thank you.

- P9 lines 8-9: Change '.... is well reproduced...' to '... is reproduced well...'
  Changed, see P10, L6-7, thank you.

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Simulating ice layer formation under the presence of preferential flow in layered snowpacks

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Abstract. For physics based snow cover models, simulating the formation of dense ice layers inside the snowpack has been a long time challenge. Their formation is considered to be tightly coupled to the presence of preferential flow, which is assumed to happen through flow fingering. Recent laboratory experiments and modelling techniques of liquid water flow in snow have advanced the understanding of conditions under which preferential flow paths or flow fingers form. We propose a modelling approach in the one-dimensional, multi-layer snow cover model SNOWPACK for preferential flow that is based on a dual-domain approach. The pore space is divided into a part that represents matrix flow and a part that represents preferential flow. Richards equation is then solved for both domains and only water in matrix flow is subjected to phase changes. We found that preferential flow paths arriving at a layer transition in the snowpack may lead to ponding conditions, which we used to trigger a water flow from the preferential flow domain to the matrix domain. Subsequent refreezing then can form dense layers in the snowpack, that regularly exceed 700 kg m^{-3}. A comparison of simulated density profiles with bi-weekly snow profiles made at the Weissfluhjoch measurement site at 2536 m altitude in the Eastern Swiss Alps for 16 snow seasons showed that several ice layers that were observed in the field could be reproduced. However many profiles remain challenging to simulate. The prediction of the early snowpack runoff also improved under the consideration of preferential flow. Our study suggests that a dual domain approach is able to describe the net effect of preferential flow on ice layer formation and liquid water flow in snow in one-dimensional, detailed, physics based snowpack models, without the need for a full multi-dimensional model.

1 Introduction

Ice layers form a marked microstructural transition inside the snowpack (*Fierz et al.*, 2009). Their formation is generally considered to be tightly coupled to the presence of preferential flow in snow (*Marsh and Woo*, 1984; *Pfeffer and Humphrey*, 1998; *Fierz et al.*, 2009). Despite their often small vertical ~~extend~~extent, (thin) ice layers may have a profound impact on large scale processes in a snowpack, such as liquid water, heat and vapour flow (*Colbeck*, 1991; *Hammonds et al.*, 2015). Many fields of study have addressed the issue of ice layers in snowpacks. Water may flow laterally over ice layers or crusts, ~~reducing travel times and significantly impact~~ which reduces travel times in catchments and has a significant impact on catchment scale hydrology~~, although on the other hand~~; alternatively, preferential flow in snow may promote vertical percolation instead (*Eiriksson et al.*, 2013). Recent studies have demonstrated that the increased melt on the Greenland Ice Sheet during the last few decades lead to changes in the firn structure, particularly through the formation of ice layers by percolating water in sub-freezing snow (*de la Peña et al.*, 2015). These ice layers can reach considerable vertical ~~extends in~~ extents on the order of 1 m (*Machguth et al.*, 2016) and may reduce the storage capacity of melt water in the firn by making access to deeper firn layers more difficult. Subsequent melt events may thus be accompanied by much more efficient runoff, due to lateral flow over these ice layers (*Pfeffer et al.*, 1991). Ice layers can also have a profound impact on microwave emission from ~~snow covers~~the snowpack, which is used in remote sensing retrieval algorithms (*Rees et al.*, 2010; *Roy et al.*, 2016). For rock stability of permafrost affected regions, the presence of ice layers near the base of the snowpack as well as inside the snowpack was found to prevent liquid water from reaching joints in the rocks, thereby improving rock stability (*Phillips et al.*, 2016). Ice layers in ~~snow covers~~ snowpacks also impact the access to food resources for wild life in snow covered areas (e.g., *Vikhamar-Schuler et al.* (2013)). Climate change projections of future increases in rain-on-snow events in high latitudes (*Ye et al.*, 2008), increased snow melt on ice sheets (*de la Peña et al.*, 2015) as well as more frequent melt events in alpine snowpacks (*Surfleet and Tullos*, 2013) show urgency to be able to determine how these changes affect the snowpack microstructure in the future.

For 1D snow cover models, whether they are physics based or simple, it is notoriously difficult to simulate the formation of ice layers. This can be understood as most models do not consider preferential flow, which is a crucial transport mechanism to allow downward propagating water flow in sub-freezing snow. Liquid water can thereby reach areas in the snowpack where the cold content is large enough to refreeze the percolating melt water and form ice layers (*Humphrey et al.*, 2012). ~~Early~~ In early attempts by *Colbeck* (1979) and *Marsh and Woo* (1985) to describe preferential flow in ~~snowpacks~~ snowpack models, the water flow in snow is considered as a flow in multiple flow paths. In *Colbeck* (1979) , flow paths are defined that differ in size and snowpack properties, which results in different percolation speeds in the individual snow paths when applying Darcy's law. In *Marsh and Woo* (1985) , the snowpack is divided in flow paths of equal size and snowpack properties, but based on comparted lysimeter measurements, it is determined how much of the total flux is transported in each of the individual flow paths. Both approaches never found widespread ~~deployment. When considering~~ adoption, probably because they require a-priori specification of the flow path variability (*Marsh*, 1999) . In *Katsushima et al.* (2009) , a description of preferential flow for snowpack models is proposed where water in excess of a threshold in saturation (for example in ponding conditions inside the snowpack) is directly routed to the soil below the snowpack. This approach improved the prediction of snowpack runoff, ~~neglecting preferential flow~~but is not able to simulate the formation of ice layers due to percolating melt water in preferential flow channels, as the water in preferential flow is considered to have left the snow domain of the model. The fact that many snow models neglect preferential flow, even when they are used for hydrological studies where snowpack runoff is a primary process, may be justified for describing seasonal runoff characteristics (*Wever et al.*, 2014a). However preferential flow may be crucial for understanding the response of a snow cover on short, sub-daily time scales, for example during rain-on-snow events ~~(*Rössler et al.*, 2014; *Wever et al.*, 2014b; *Würzer et al.*, 2016a)~~ (*Katsushima et al.*, 2009; *Rössler et al.*, 2014; *Wever et al.*, 2014b; *Würzer* Also for wet snow avalanche formation, the exact location at which liquid water starts ponding can influence snow stability (*Wever et al.*, 2016) and considering preferential flow may be important for the exact timing of when weak layers are reached by water. Snowpack models developed for avalanche warning purposes (*Brun et al.*, 1992; *Lehning et al.*, 1999) may therefore also benefit from a description of preferential flow processes in snow.

~~Recently, multi-dimensional~~ Multi-dimensional snow cover models have been developed to simulate preferential flow ~~(*Hirashima et al.*, 2~~ but those models simplified and neglected several snowpack processes (i.e., snow settling, snow microstructure evolution), meaning that they are not yet applicable to natural ~~snow covers~~snowpacks. Furthermore, multi-dimensional snow cover models generally require more computational power, making them unsuitable for large scale deployment. However, those multi-dimensional model developments provide crucial insights that allowed for a parametrisation of a dual domain approach for preferential flow for the 1D, physics based, detailed SNOWPACK model (*Bartelt and Lehning*, 2002; *Lehning et al.*, 2002a, b), which we present in this study.

2 Dual Domain Implementation

To simulate preferential flow, we apply a dual domain approach as schematically shown in Fig. 1. The pore space is subdivided into a part that is involved in preferential flow, and a part that is representing matrix flow (labelled 1 in Fig. 1). For the construction of the domains and the exchange processes between both domains, we exploit recent results from laboratory and model experiments as well as applying concepts from hydrological modelling. The water flow in the model is described for both the matrix and preferential flow domain by solving Richards equation for both domains sequentially at the commonly used SNOWPACK time step of 15 min. After solving Richards equation for the matrix domain, the exchange of water between the matrix and preferential flow domain is determined and vice versa. If the pressure head exceeds the water entry pressure head of the layer below (labelled 2 in Fig. 1) water moves from matrix to preferential flow (labelled 3 in Fig. 1). If the saturation in the preferential flow path exceeds a threshold (labelled 4 in Fig. 1), water moves back to the matrix domain (labelled 5 in Fig. 1). Only the matrix part is allowed to undergo phase changes and ice layers form when water moves back from preferential flow to matrix flow and refreezes. Preferential flow remains always in the liquid phase. Refreezing of preferential flow water is mimicked by moving water from preferential flow to the matrix flow domain (labelled 6 in Fig. 1). Below, the water exchange processes are described in more detail.

2.1 Defining the Dual Domains

For the dual domain approach, the pore space is subdivided in a matrix and preferential flow domain (denoted with 1 in Fig. 1). For soils, the relative area involved in preferential flow is often found to be a function of the ratio of system influx rate over saturated hydraulic conductivity (*Glass et al.*, 1989a, b) for a given soil texture. In the experimental data on snow presented by *Katsushima et al.* (2013), a more pronounced dependence of the preferential flow area with grain size is found, rather than with the system influx rate. We illustrate their experimental results graphically in Fig. 2. Whereas the grain size shows a distinct pattern of smaller preferential flow area for larger grain sizes, the system influx rate showed a rather ambiguous pattern, where ~~not always increased influx leads~~ increased influx did not always lead to a larger preferential flow area. The grain sizes used in their experiments span over typical ranges found in natural ~~snow covers~~ snowpacks and this dependence is important to take into account. It also has to be noted that the infiltration rates in their experiments exceed typical values in natural conditions. We therefore decided to determine the dependence of preferential flow area on grain size using the lowest experimental infiltration rate only. A fit to this selection of the data (see Fig. 2) provides the following expression for the preferential flow area (F):

$$F = 0.0584 r_{\mathrm{g}}^{-1.109}, \tag{1}$$

where F is the preferential flow area fraction (-), and r_{g} is the grain radius (mm). The matrix flow domain is accordingly defined as $(1-F)$. For fine grained snow ($r_{\mathrm{g}} \approx 0.12$ mm), *Katsushima et al.* (2013) did not observe preferential flow, in contrast with the snow samples with $r_{\mathrm{g}} \approx 0.21$ mm and larger. However, typically most parts of the snowpack consist of larger grains than the smallest grain size used in the experiments. Thus, to provide a continuum description of the matrix and preferential flow regime, Equation 1 is used for all grain sizes. For numerical stability, F is limited between 0.01 and 0.90. Generally grain size increases over time in snow, and this may occasionally lead to a situation where the preferential flow area in the next SNOWPACK time step is reduced below the required one to accommodate for the liquid water present in the preferential flow domain. We therefore additionally ensure that F is large enough to contain all present preferential flow water.

For both domains, the relationship between pressure head and liquid water content (LWC) is described by the van Genuchten parametrisation for snow as experimentally determined by *Yamaguchi et al.* (2012). For the matrix flow domain, the saturated LWC is scaled by $(1-F)$ and for the preferential flow domain by F. Furthermore, we determine the residual water content for the matrix flow domain using the approach described in *Wever et al.* (2014a), while setting it to 0 for the preferential flow domain. Saturated hydraulic conductivity is parametrised using the parametrisation for permeability proposed by *Calonne et al.* (2012).

2.2 Water Exchange Between Matrix and Preferential Flow Domain

All liquid water input (snow melt, rainfall, condensation) is added to the matrix flow domain. A prerequisite for the formation of an unstable wetting front (i.e., flow fingering) is that the system influx rate is below the saturated hydraulic conductivity of the medium (*DiCarlo*, 2013), which is generally fulfilled in snow (*Katsushima et al.*, 2013). In order to initiate preferential flow, we use the concept that preferential flow paths form when the pressure head in the matrix flow domain exceeds the water entry pressure of the layer below. This was found to be the case in laboratory experiments (*Katsushima et al.*, 2013; *Avanzi et al.*, 2015) and was successfully exploited in numerical modelling to initiate preferential flow ~~(*Hirashima et al.*, 2014)~~ (*Katsushima et al.*, 2009; *Hirashima et al.*, 2014) . The water entry pressure h_{we} (m) can be expressed as a function of grain ~~size~~ radius according to *Katsushima et al.* (2013):

$$h_{\mathrm{we}} = 0.0437\,(2r_{\mathrm{g}}) + 0.01074\cancel{,}. \tag{2}$$

One important condition to reach the water entry pressure is water ponding on a microstructural transition inside the snowpack (*Hirashima et al.*, 2014; *Avanzi et al.*, 2015). This is denoted with 2 in Fig. 1. To achieve the high LWC value observed in experiments (*Avanzi et al.*, 2015), we use the geometric average to calculate the hydraulic conductivity between snow layers (*Wever et al.*, 2015). In our implementation, the amount of water in the matrix part in excess of the threshold corresponding to the water entry pressure of the layer below, is moved to the preferential flow domain in the layer below (denoted with 3 in Fig. 1). ~~If afterwards~~ A capillary overshoot condition was found in snow (*Katsushima et al.*, 2013) , which means that the capillary pressure in the ponding layer decreases again after preferential flow forms. This increases the liquid water content in the preferential flow paths and to mimic this effect, we allow more water to flow from matrix flow to preferential flow once the threshold is exceeded than only the amount of water above the threshold. If after the water in excess of the threshold is moved and the saturation (i.e., ratio of water volume to pore volume) in the layer in the matrix domain is still higher than the saturation in the layer below in the preferential flow domain, the saturation is equalized by an equivalent water flow with the following approach. Equal saturation in a specific layer with index i in the matrix domain and a layer with index j in the preferential flow domain can be expressed as:

$$\cancel{\frac{\theta_{\mathrm{m}}-\theta_{\mathrm{r,m}}}{\theta_{\mathrm{s,m}}-\theta_{\mathrm{r,m}}}}\frac{\theta^i_{\mathrm{m}}-\theta^i_{\mathrm{r,m}}}{\theta^i_{\mathrm{s,m}}-\theta^i_{\mathrm{r,m}}}=\cancel{\frac{\theta_{\mathrm{p}}-\theta_{\mathrm{r,p}}}{\theta_{\mathrm{s,p}}-\theta_{\mathrm{r,p}}}}\frac{\theta^j_{\mathrm{p}}-\theta^j_{\mathrm{r,p}}}{\theta^j_{\mathrm{s,p}}-\theta^j_{\mathrm{r,p}}}, \tag{3}$$

Where the subscripts m and p denote the matrix and preferential flow domain, respectively, θ is the LWC ($\mathrm{m^3\ m^{-3}}$), θ_{r} is the residual LWC ($\mathrm{m^3\ m^{-3}}$) and θ_{s} is the saturated LWC ($\mathrm{m^3\ m^{-3}}$). In the model, layers are counted from below, such that equalizing saturation between the matrix domain in the layer above and the preferential flow domain in the layer below corresponds to $j = i-1$.

Given layer thicknesses ~~L_{m} and L_{p}~~ L^i_{m} and L^j_{p} for the layers in the matrix flow and preferential flow domain, respectively, the total LWC in the matrix and preferential flow layer is defined as:

$$\theta_{\mathrm{tot}} = {\theta^i}_{\mathrm{m}}{L^i}_{\mathrm{m}} + {\theta^j}_{\mathrm{p}}{L^j}_{\mathrm{p}} \tag{4}$$

Under the requirement of an equal degree of saturation for a given total LWC, we can solve Eq. 3 for ~~θ_{m}:~~ θ^i_{m}:

$${\theta^i}_{\mathrm{m}} = -\cancel{\frac{(\theta_{\mathrm{r,m}}\theta_{\mathrm{s,p}}-\theta_{\mathrm{r,p}}\theta_{\mathrm{s,m}})L_{\mathrm{m}}+(\theta_{\mathrm{r,p}}-\theta_{\mathrm{s,p}})\theta_{\mathrm{tot}}}{(\theta_{\mathrm{s,m}}-\theta_{\mathrm{r,m}})L_{\mathrm{m}}+(\theta_{\mathrm{s,p}}-\theta_{\mathrm{r,p}})L_{\mathrm{p}}}}\frac{\left(\theta^i_{\mathrm{r,m}}\theta^j_{\mathrm{s,p}}-\theta^j_{\mathrm{r,p}}\theta^i_{\mathrm{s,m}}\right)L^i_{\mathrm{m}}+\left(\theta^j_{\mathrm{r,p}}-\theta^j_{\mathrm{s,p}}\right)\theta_{\mathrm{tot}}}{\left(\theta^i_{\mathrm{s,m}}-\theta^i_{\mathrm{r,m}}\right)L^i_{\mathrm{m}}+\left(\theta^j_{\mathrm{s,p}}-\theta^j_{\mathrm{r,p}}\right)L^j_{\mathrm{p}}}, \tag{5}$$

after which ~~θ_{p}~~ θ^j_{p} can be found by applying Eq. 4.

Additionally, if the saturation in the matrix domain ~~exceeded~~ exceeds the saturation of the preferential flow domain in a snowpack layer, saturation is equalized using Eq. 5, with ~~$L_{\mathrm{m}} = L_{\mathrm{p}}$~~ $i = j$ and consequently $L^i_{\mathrm{m}} = L^j_{\mathrm{p}}$. This is motivated by the fact that once snow is wet, no horizontal gradients in pressure head are expected to be present in a snow layer, and thus, following the Van Genuchten water retention curve, the saturation of the matrix domain is equal to the saturation of the preferential flow domain.

Conceptually, water will leave the preferential flow domain and enter the matrix domain if the pressure head inside the preferential flow domain exceeds the water entry pressure of the dry snow around the preferential flow path. This procedure was able to simulate water spreading on microstructural transitions in the multi-dimensional snow model by *Hirashima et al.* (2014). However, in our study, this approach rarely succeeded in forming ice layers, as the condition is rather seldom met. This fact can be interpreted in light of the physics behind preferential flow. It was demonstrated that an overshoot condition exists in flow fingers, which means that the tip of a flow finger shows marked higher saturation than the tail. This flow behaviour cannot be described by Richards equation (*DiCarlo*, 2013), although Richards equation continues to provide a correct description above and below the wetting front. The reason why the condition worked in *Hirashima et al.* (2014) may be due to the fact that the simulations involved high water influx rates, much higher than experienced in natural ~~snow covers~~snowpacks. This would increase the amount of water accumulating on the capillary barrier when liquid water flow over the transition is slower than the water flux arriving from above. In the absence of a solution for this problem (*DiCarlo*, 2013), we simply apply a threshold in saturation (Θ_{th}) of the preferential flow domain (denoted with 4 in Fig. 1). Once this threshold is exceeded, water will flow back to the matrix domain (denoted with 5 in Fig. 1). In our approach, we first move as much water as freezing capacity is available in the matrix domain. If after this approach the threshold is still exceeded, we additionally equalize the saturation in the specific layer in the matrix and preferential flow domain, using Eq. 5. For the lowest snow layer above the soil, the saturation is always equalized between the matrix and preferential flow domain, regardless of whether the saturation threshold is exceeded or not. This suppressed spiky snowpack runoff behaviour. In soil layers, preferential flow is ignored by setting the hydraulic conductivity for the preferential flow domain to 0 and the preferential flow area to 2 %.

2.3 Refreezing Preferential Flow

In our approach, water in the preferential flow domain is not considered for phase changes. However, in reality preferential flow is known to refreeze, even forming ice structures in the shape of flow fingers inside the snowpack (*Kattelmann*, 1985; *Marsh*, 1988; *Fierz et al.*, 2009; *Williams et al.*, 2000). For simplicity, we currently do not consider microstructural changes due to preferential flow, although they may have a strong effect on the water flow in snow. Grain growth and subsequent reduction of capillary forces as well as ice columns may increase the efficiency of the preferential flow paths considerably.

For the thermal effects, we first describe the heat flux between the preferential flow part and the matrix part by assuming a pipe with radius r (m) at melting temperature T_0 (K) in the middle of a 1 m^2 snowpack at temperature T_{e} (K) (see Fig. 3). If we assume that the horizontal temperature gradient inside the snowpack is linear, then the temperature T_{e} is found at a radius R^* (m) such that surface areas A_1 (m^2) and A_2 (m^2) are equal. We can then approximate Fourier's law for heat flow for the heat flux between the preferential flow and matrix domain ($Q_{H,\mathrm{p}\rightarrow\mathrm{m}}$, J m^{-1} s^{-1}) as:

$$Q_{H,\mathrm{p}\rightarrow\mathrm{m}} = \kappa \frac{\partial T}{\partial x} \approx \kappa \frac{(T_{\mathrm{e}} - T_0)}{\left(\sqrt{\frac{1+F}{2\pi}} - \sqrt{\frac{F}{\pi}}\right)} \tag{6}$$

The volumetric content that needs to be transferred from the preferential domain to the matrix domain (denoted with 6 in Fig. 1), in order to satisfy the refreezing capacity provided by the heat flux $Q_{H,\mathrm{p}\rightarrow\mathrm{m}}$ over the outer area of the preferential flow path can be subsequently expressed as:

$$\Delta\theta_{\mathrm{w,p}\rightarrow\mathrm{m}} = N\pi F L_{\mathrm{e}} Q_{H,\mathrm{p}\rightarrow\mathrm{m}} \Delta t \tag{7}$$

where L_{e} is the latent heat associated with freezing ($3.34 \cdot 10^5$ J kg^{-1}) and N is a factor describing the effect of multiple flow paths forming area F. Often, numerous flow paths can be identified per square meter of snowpack, as for example found in a field study by *McGurk and Marsh* (1995). They report a flow path density between roughly 100 to 300 per m^2. However, this number is not necessarily representative for the number of flow paths actively and concurrently transporting water, as often new preferential flow paths form in subsequent melt cycles (*Schneebeli*, 1995). *Albert et al.* (1999) found only 3 preferential flow paths per m^2 during the first wetting of a previously sub-freezing snowpack. When more flow paths are present, the energy exchange will be more efficient. Additionally, the gradients with the surrounding snow will be larger. We ~~interpret~~ use N as a tuning parameter in the model related to the number of flow paths per m^2.

3 Data and Methods

3.1 Data

We simulate 16 subsequent snow seasons (2000-2015) for the Weissfluhjoch (WFJ) measurement site, located at 2536 m altitude in the Eastern Swiss Alps. For this site, a dataset of bi-weekly snow-profiles made in close vicinity (<25m) of the meteorological station used to drive the SNOWPACK model in this study is available (*WSL Institute for Snow and Avalanche Research SLF*, 2015; *Wever et al.*, 2015). The snow profiles contain information about grain size and type, judged by the observer using a magnifying glass, as well as snow density in sections of typically 20-50 cm height and snow temperature. Melt-freeze crusts (i.e., parts of the snowpack that have been wet and froze again), as well as ice layers are explicitly marked as such in the profiles. Ice lenses (i.e., non continuous ice layers) are not marked as an ice layer, but are reported in a separate remark. As subsequent snow profiles need to be made in undisturbed snow, they also sample spatial variability in addition to the temporal evolution. Furthermore, judging whether a specific layer is a crust or an ice layer is also partly subjective. This is also indicated in the data: sometimes the same layer is not identified similarly in subsequent snow profiles, although this may also indicate spatial variability. To account for spatial variability at the measurement site, we select the highest modelled dry snow density within a range of 20 cm above or below an observed ice layer, when comparing simulated and observed ice layers.

For validating the snowpack runoff simulated by the model, we use the snow lysimeter data from a 5 m^2 lysimeter, as described in *Wever et al.* (2014a). In that paper, it was discussed that a discrepancy between measured and modelled runoff is particularly present at the beginning of the melt season, and involves the first ca. 5 % of seasonal snowpack runoff. Here, we consider the measured snowpack runoff for the period March 1 to May 31 only, and particularly focus on the first 20 mm w.e. runoff from the snowpack. This period corresponds to the onset of snowpack runoff, while preventing that the statistics are dominated by the main melt period. We additionally exclude lysimeter data from snow season 2000 and 2005 from the analysis, ~~given the suspicion of~~ due to suspected problems with the lysimeter in these seasons (*Wever et al.*, 2014a).

3.2 Methods

3.2.1 Model Setup

The simulation setup of the SNOWPACK model for WFJ is equal to the snow-height driven simulations in *Wever et al.* (2015), in which new snow fall amounts are determined from increases in measured snow height. This ensures a simulation that closely follows the measured snow height, which will enable a correct comparison of simulated and observed snow profiles. Ice layers observed in the field can range from a few mm to a few cm and up to 1 m in firn on the Greenland Ice Sheet (*Fierz et al.*, 2009; *Machguth et al.*, 2016). To reduce computational costs, the SNOWPACK model applies an algorithm to merge elements when they exhibit similar properties. In default setting, this procedure typically maintains the layer spacing around 1.5 to 3 cm, except for certain special cases, like buried surface hoar or ice layers inside the snowpack, which should be maintained irrespective of their thickness. This means that in default setup, with a typical layer spacing of 1.6 cm, the formation of ice layers is coupled to relatively thick layers compared to ice layers found in natural alpine snowpacks. Forming thinner ice layers requires less water and energy to refreeze. We therefore performed high resolution simulations where we lower the threshold above which no merge is allowed from 1.5 cm to 0.25 cm. Further, for the high resolution simulations, we initialize new snow layers during snowfall in steps of 0.5 cm, instead of the default value of 2 cm. This lead to a typical layer spacing of 0.45 cm. Results presented here are with the high resolution simulations, although we discuss the performance of the default resolution as well. Simulations with matrix flow only took on average 2.3 min per simulated year to complete on a typical desktop PC, using the default SNOWPACK settings. The dual domain approach, which requires solving Richards equation twice, increased the computation time to 8.0 min per year. The high resolution simulations, which we show here, took 71 min per year to complete.

Densities of ice layers in the field can vary over a wide range. For example, *Marsh and Woo* (1984) reports a range from 630 to 950 kg m^{-3}, which makes it ambiguous to determine above which threshold of modelled dry snow density a layer should be considered an ice layer. In the default setup, a layer with a dry snow density exceeding 700 kg m^{-3} is considered an ice layer by the SNOWPACK model. However, we apply different thresholds here to verify the sensitivity of the choice of threshold on the results. Indeed, it may be that simulated layers cannot reach the density of observed, thin, ice layers due to their larger vertical extent in the model.

4 Results

4.1 Parameter Estimation

In the preferential flow formulation we propose, two tuning parameters are left: the threshold in saturation of the preferential flow domain (Θ_{th}), above which water will flow back to the matrix part, and a parameter related to the number of flow paths per m^2 (N). To determine an optimal set of parameters, a sensitivity study was carried out. For Θ_{th}, values from 0.02 to 0.16 in steps of 0.02 were used and for N, values 0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 5.0 were used.

Fig. 4 shows the probability of detection POD (i.e., the ratio of observed ice layers that are reproduced by the model over the total number of observed ice layers) for different thresholds that define a modelled ice layer, as a function of both tuning parameters. When ice layers are defined by higher densities, the POD decreases. Highest POD is achieved for no or minor freezing (i.e., small values for N), and a saturation in the preferential flow path around 0.1. The non-linear relationship in Fig. 4 arises from the delicate balance of refreezing water that is not able to percolate deeper and ~~ponding~~ the amount of ponding possible at microstructural transitions, required for water to move back to the matrix domain in order to freeze as an ice layer or lens. For snowpack runoff, highest scores in terms of r^2, RMSE or the arrival date of the first 20 mm w.e. are generally achieved with refreezing and low thresholds in saturation of the preferential flow domain (see Fig. 4). Both slow down the progression of preferential flow water. It seems difficult to find a set of parameters that will maximize both the reproduction of ice layers, as well as snowpack runoff simulations. Nevertheless, even with optimal settings for the formation of ice layers, the early stage of snowpack runoff (i.e., the passage time of the first 20 mm w.e. of runoff) is better reproduced than without considering preferential flow.

After executing all 80 SNOWPACK simulations for the sensitivity study, ranks were determined for the POD of ice layers, using 700 kg m^{-3} as density threshold for ice layers, and the r^2 value for hourly snowpack runoff. The combination of both parameters that provides the lowest sum of the ranks for ice layer detection and snowpack runoff was considered the optimal combination of coefficients. This procedure gave $\Theta_{\mathrm{th}} = 0.1$ and $N = 0$ and $\Theta_{\mathrm{th}} = 0.08$ and $N = 0$ for the normal and high resolution simulations, respectively, as optimal combination of tuning parameters and this set of parameters will be used for the results. Interestingly, it implies that for ice layer formation, refreezing of preferential flow should be ignored (i.e., $N = 0$).

4.2 Example Snow Season

Fig. 5 illustrates the difference in simulated snow density between a simulation with only Richards equation and Richards equation including preferential flow at high resolution for snow season 2012. Similar figures for the other simulated snow seasons are shown in the Online Supplement. The overall density distribution is similar in both simulations, but only with preferential flow, ice layers are formed. The location is in good agreement with observations of ice layers and crusts observed in the snow profiles in the field. Fig. 6 shows detailed simulation output for the period in the beginning of March 2012 and the upper part of the snowpack only. The distribution of liquid water is showing that the preferential flow (Fig. 6b) is percolating ahead of the matrix flow (Fig. 6a). This partly is due to the absence of phase changes for water in preferential flow, but also ~~that~~ due to the lower area, and thereby lower value for θ_{s}, such that hydraulic conductivity increases faster with increasing LWC. In contrast to matrix flow, preferential flow reaches areas where the snowpack is still below freezing (Fig. 6c).

Ponding at microstructural interfaces is occurring in both the matrix and the preferential flow domain~~and it marks the layers were water~~. In the example, a jump in snow density (Fig. 6d) and grain radius (Fig. 6e) around 165 cm and 210 cm in the snowpack mark the layers where water accumulates, refreezes and forms ice layers (Fig. 6d,f). Solving Richards equation twice (for both domains) appears to be able to identify those layers. Refreezing locally increases the snow temperature to melting temperature (Fig. 6c). Initially, the model identifies refreeze inside the snow layer and marks the layer as a melt-freeze crust. Once dry snow density exceeds 700 kg/m^3, the layer is marked as an ice layer (Fig. 6f). Note that Fig. 6e shows that most of the snowpack consists of grain sizes for which preferential flow was observed in the experiments by *Katsushima et al.* (2013) . The smallest grain size class from those experiments, for which no preferential flow was observed, is only found in the new snow layers during snowfall (black coloured areas), after which metamorphism rapidly increases grain size to regimes for which preferential flow was observed. This justifies the application of Eq. 1 for the full range of grain size in the model.

In addition to preferential flow, ice layers can also form by surface processes. For example, rainfall in November 2003 in a sub-freezing snow cover formed an ice layer at the surface and this ice layer was subsequently observed during the rest of the 2004 snow season (see Fig. S5 in the Online Supplement). This layer is not reproduced in the SNOWPACK model~~, as~~. Firstly, the model did not recognize the precipitation as rainfall due to the low air temperature during the event. ~~This layer~~ Second, even when the model was forced to interpret the precipitation as rainfall, the ice layer did not form at the surface. The model solves for the heat and water flow sequentially in a 15 min. time step, whereas the formation of an ice layer during rainfall is occurring on shorter time scales. Furthermore, we hypothesize that rain droplets probably freeze directly upon contact with the snow surface, creating an ice layer locally at the surface, whereas the SNOWPACK model considers the rainfall as an incoming flux in the top layer. When the available energy for freezing is not sufficient to freeze the full depth of the top layer in the model, an ice layer is not formed. In reality, the surface ice layer is possibly even hindering water entry to deeper layers, which may thicken the surface ice layer. This particular ice layer in 2004 has been excluded in further analysis.

4.3 Density Profiles

Fig. 7 shows the observed snow density distribution in all snow profiles from snow seasons 2000-2015, typically representing vertical sections of 20-50 cm and sometimes smaller sections. The distribution of snow density for ~~in~~ these sections is ~~well reproduced~~ reproduced well by the simulations, although the spread in simulated snow density is lower than the observed spread. All simulations provide very similar snow density distributions. The r^2 value between observed and simulated density in the measurement sections is highest (r^2=0.74) for the simulations with Richards equation only and in *Wever et al.* (2015), it is shown that the temporal evolution and vertical distribution of snow density is in good agreement with measured snow density. With preferential flow, the r^2 value reduces to 0.71. This reduction in model performance when using preferential flow is also confirmed when using Willmott's index of agreement (*Zambrano-Bigiarini*, 2014; *Willmott*, 1981) , which was determined to be 0.84 and 0.83 for simulations with Richards equation only and simulations with preferential flow, respectively. Nevertheless, the simulations with preferential flow are maintaining the overall snowpack density profile generally well and the reduction in r^2 value may be attributed to the fact that calibration of snow settling functions was not performed considering the preferential flow model. Another reason may be that with preferential flow, more water is moved downward and less water can refreeze in matrix flow in the upper snow layers. It may be argued that an underestimation of snow settling can be compensated for by an overestimation of refreezing water. In any case, the simulations with preferential flow stand out when looking at the highest snow density simulated in a layer within ±20 cm of an observed ice layer. In this case, much higher snow densities are found in individual layers under consideration of preferential flow.

As the manual snow density measurements in the field represent much larger vertical sections (20-30 cm), these measurements cannot be used to verify the much higher resolution (1-2 cm or less) simulated densities on that scale. Time series using other measurement techniques, as for example snow micro penetrometry (*Schneebeli and Johnson*, 1998) or measuring volume and mass of excavated ice layers (*Watts et al.*, 2016) , may assist in a more in-depth model verification in the future.

Fig. 8 shows the POD for different dry snow density thresholds that define an ice layer in the simulations. The POD decreases with increasing threshold from 0.44 for 400 and 500 kg m^{-3} to 0.10 for a threshold of 800 kg m^{-3} for the high resolution simulations. When comparing with field observations, it is important to note that it is not clear which density should be assigned to a layer that an observer would denote as an ice layer. The probability of null detection, which in this case is defined as the percentage of simulated profiles correctly simulating the absence of ice layers in the full profile is above $50\ \%$ for an ice layer definition threshold of 600 kg m^{-3} in high resolution simulations. In normal resolution simulations, the probability of null detection is higher. The bias, which is the ratio of the number of simulated ice layers over the number of observed ice layers, is generally below 1. This indicates a slight underestimation of the frequency of ice layers in both high and normal resolution simulations. It shows that our approach is neither largely overestimating nor underestimating the presence of ice layers inside the snowpack. The false alarm rate indicates that around half of the ice layers that are simulated do not find a correspondence in the observed snow pits. The results illustrate the general difficulty of observing ice layers with often small vertical extent in the field and reproducing those ice layers in the model due to a delicate interaction between water flow and the ice matrix. However, the results also indicate that the model is able to capture a significant proportion of ice layers that formed in natural snowpacks, while maintaining the overall snowpack structure well. In contrast, simulations with Richards equation only generally do not reproduce any layer with a dry snow density exceeding 600 kg m^{-3}. The prediction bias is correspondingly below 0.20 even for low thresholds of 400 kg m^{-3} for defining an ice layer. This indicates that the failure of reproducing ice layers in those type of simulations cannot be resolved by choosing low thresholds, but that preferential flow seems to be a crucial process to simulate the formation of ice layers.

4.4 Snowpack Runoff

In addition to ice layer formation, snowpack runoff is also strongly impacted by preferential flow. For rain-on-snow events at the WFJ measurement site, *Würzer et al.* (2016b) found an improvement in r^2 from 0.52 for Richards equation only to 0.68 for the dual domain approach. Interestingly, Fig. 9 shows that for the melt period, there is no consistent difference between r^2 values for daily and hourly snowpack runoff whether or not preferential flow is considered. On average both simulations have equal r^2 ~~value~~ values of 0.81 and 0.90 for hourly and daily snowpack runoff, respectively. However, as already noted in *Wever et al.* (2014b), the effect of neglecting preferential flow on seasonal time scales may be very limited. In that study, particularly the first arrival of melt water was noticeably underestimated when only considering matrix flow with Richards equation. As illustrated in Fig. 10, the arrival time of the first 20 mm w.e. in the melt season is much better reproduced by the dual domain approach. The time difference between the arrival date of the first 20 mm w.e. changes from 7.7 days too late for the Richards equation model to 2.9 days too early in the dual domain approach. Generally, the average time difference between modelled and measured first 10 mm w.e. cumulative snowpack runoff is even more negative than the average time difference for 20 mm w.e. cumulative runoff. This suggests that particularly earliest season snowpack runoff from preferential flow is overestimated in the simulations. The standard deviation ~~is also~~ of the time difference for 20 mm w.e. is slightly smaller for the preferential flow formulation than for the matrix flow only. The fact that the standard deviation is smaller indicates that yearly variability between observed and simulated runoff is smaller and that the model is apparently able to better explain yearly variability. ~~Generally, the absolute time difference between modelled and measured first 10 mm w.e. cumulative snowpack runoff is less than the absolute time difference for 20 mm w. e. cumulative runoff . This suggests that early season snowpack runoff from preferential flow is overestimated in the simulations. In *Würzer et al.* (2016b) additional confirmation is provided that the onset of snowpack runoff during~~ In *Würzer et al.* (2016b) additional analysis of the role of preferential flow in producing snowpack runoff during rain-on-snow ~~events is better reproduced by the dual domain approach~~events shows that for these events, snowpack runoff is better reproduced using the dual domain approach.

Altough considering preferential flow improved the snowpack runoff simulation, year-to-year variability in model performance is still large. The difference between simulations with or without preferential flow are often smaller than the year-to-year variability. For example, in melt season 2001 and 2010, r^2 values are low in both simulations and the difference between the simulations is smaller than the difference in r^2 values with other years. Explanatory factors for the year-to-year variability in model performance for reproducing snowpack runoff were not found. Snowpack characterizing statistics, for example the observed number of ice layers or observed number of jumps in grain size and hardness, did not correlate significantly with r^2 for snowpack runoff or the arrival date. This is probably due to a combination of errors in meteorological forcing conditions, observer bias in the bi-weekly snow profiles, and the limited representativeness of the snow lysimeter. Its surface area of 5 m^2 may be considered too small to capture a representative area for snowpack runoff, such that randomness in the exact location where preferential flow paths form may influence the measurements (*Kattelmann*, 2000) . Separating the individual errors appears to be difficult.

5 Discussion

In the implementation of the dual domain approach, we attempted to stay close to a physics based process description. Laboratory experiments and multi-dimensional snowpack models have provided crucial insights in the preferential flow and water ponding processes. However, the number of quantitative experimental studies is still limited and many aspects may be refined in further studies. The model uses four criteria to specify the dual domain approach: (1) the area involved in preferential flow, (2) a condition to move water from matrix flow to preferential flow, (3) a condition to move water from preferential flow to matrix flow, (4) a condition describing the refreezing process of preferential flow. Two calibrating coefficients, related to criterion 3 and 4 were used to optimize the simulations.

The area involved in preferential flow (condition 1) is currently parametrised with grain size only. Given observations from soil physics (e.g., *Glass et al.* (1989b)), a dependence on the water influx rate is to be expected. Currently, laboratory settings, or field experiments with rainfall generators have generally large water input rates of typically 20 mm/hour or more (*Singh et al.*, 1997; *Katsushima et al.*, 2013; *Würzer et al.*, 2016b). It turns out to be difficult to have controlled, constant and spatially well distributed water input rates typically observed in nature (rainfall and melt rates of 1-5 mm/hour). The absence of studies at low water input rates makes the general validity of condition 1 we implemented uncertain. Furthermore, preferential flow was not observed for the finest grain size in *Katsushima et al.* (2013) , which, as shown by the black coloured areas in Fig. 6e, exists only for short periods of time in new snow. Although regimes with stable flow have been identified for soil (*DiCarlo*, 2013) , using larger snow samples to investigate preferential flow in snow could exclude the possibility that finger width exceeds the snow sample size for the finest grain size class.

We consider condition 2 to be a relatively well founded approach, as the role of water entry suction in forming preferential flow was clearly identified in laboratory experiments (*Katsushima et al.*, 2013) and turned out to be crucial in forming preferential flow in multi-dimensional models in agreement with laboratory experiments (*Hirashima et al.*, 2014). However, also here, the exact parameterisation of water entry suction may be different for lower water influx rates.

Condition 3 may be one of the most uncertain ones. Understanding the LWC distribution in a preferential flow path cannot be achieved by the Richards equation (*DiCarlo*, 2013). The other issue is that infiltration in an initially dry porous medium is not accurately described by Richards equation. We consider the assumption we made here that water will move from preferential flow to matrix flow based on the exceedance of a threshold in saturation one of the least supported by experimental results.

The refreezing of preferential flow (condition 4) is mainly limited by knowledge about the number of preferential flow paths that are actively transporting water, which in itself is dependent on ~~snow cover conditions. Multi-dimensional snowpack models~~ snowpack conditions. Laboratory experiments at low input rates and with initially sub-freezing snow, using detailed temperature measurements and dye-tracer to follow the wetting, may help here to develop a better understanding of the heat exchange processes between preferential flow paths and surrounding snow matrix, as a function of preferential flow area and the number density of active preferential flow paths. Results from laboratory experiments and multi-dimensional snowpack models may thereby allow to quantify the amount of refreezing of percolating melt water in flow fingers. This knowledge is of crucial importance, as it determines the efficiency of preferential flow to heat deeper layers of the snowpack. Furthermore, refreezing of preferential flow probably slows down the downward propagation of the fingers.

The term preferential flow can be interpreted ambiguously. Two phenomena are known to cause deviations from a matrix infiltration pattern: flow fingering and macropore flow. Here, we consider flow fingering purely as the result of instabilities of the wetting front, which can occur in porous media with a uniform pore space distribution. Generally the prerequisite for this effect (coarse grains and low infiltration rates) is fulfilled for snow. However, once flow fingering is occurring in snow, microstructural changes of the snow grains in preferential flow paths will change the pore space distribution to a bimodal or multi-modal one. This has its equivalent in soils in, for example, worm holes, root channels and cracks. This effect is not considered in the dual domain approach we propose, although it may have a profound impact on the efficiency of preferential flow paths. Modifications to the parameters of the preferential flow domain can be imagined to better represent a multi-modal pore space distribution. On the other hand, snow microstructure inside and around preferential flow paths may not always consist of an ice matrix where Richards equation would be a good description of water flow. However, a dual domain approach does not require both domains to be solved with Richards equation, and another description of water flow in the preferential flow domain may be more appropriate.

Our simulations have a relatively low reproduction success of observed ice layers. The sensitivity study has revealed that one factor is the delicate balance between refreezing and further percolation. This is expected to be particularly delicate in alpine

~~snow covers~~snowpacks, where the cold content is low and the ice layers are often thin. For cold regions, for example the Greenland Ice Sheet, the abundance of ice layers observed in ice cores may be easier to reproduce in simulations~~. Microstructural~~, as microstructural transitions formed by summer melt-freeze crusts below cold new snow from the accumulation period are more easy to capture in simulations. In contrast with alpine ~~snow covers~~snowpacks, where the ground heat flux often maintains melting conditions at the snowpack base, firn temperatures are generally well below freezing, and create a large refreezing capacity.

Another factor contributing to the low probability of detection is the small vertical and sometimes small horizontal scale on which ice layer formation happens in alpine snowpacks, which is difficult to capture in simulations. A correct simulation of the snow microstructure is thereby a prerequisite for simulating ice layer formation, although it is difficult to achieve. As an example, buried surface hoar may provide a marked microstructural transition on which liquid water may pond and build ice layers. Whether or not the simulation is able to simulate correctly the burial of surface hoar, contributes to the failure or success in reproducing ice layers. Such a failure or success will remain throughout the rest of the snow season.

6 Conclusions

We proposed a dual domain approach for modelling liquid water flow in snow, which separates the pore space in a part that is representing matrix flow and a part that is representing preferential flow. This dual domain approach for physics based snowpack models is able to simulate preferential flow paths such that, by using two tuning parameters, a better agreement with the onset of snowpack runoff can be achieved. The difference between the first modelled and measured 20 mm w.e. cumulative snowpack runoff decreased from approximately 8 days too late to 3 days too early. Furthermore, preferential flow ponding on microstructural transitions inside the snowpack and subsequent spreading in the matrix flow domain can simulate the otherwise lacking formation of dense layers by the model. Around 20 % of observed ice layers in the field over 16 snow seasons were correctly simulated by the model in the form of a layer exceeding a dry snow density of 700 kg m^{-3}. We showed that a dual domain approach is able to provide a physics based description of preferential flow and ice layer formation that is corresponding to findings in laboratory and field experiments. However, the formulation has two parameters that were calibrated for this study. Although we do not resolve individual flow paths, as is done in multi-dimensional snowpack models, a dual domain approach can quantify the net effect of preferential flow on a snowpack in a 1-D snowpack model with much lower computational costs than multi-dimensional models and only marginally larger computational cost compared to 1-D non-multidomain models.

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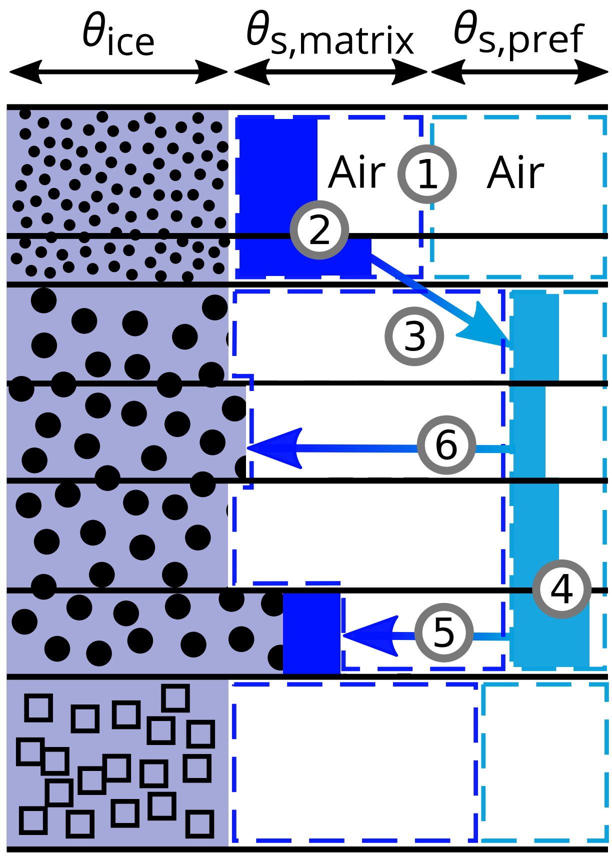

Figure 1. Schematic overview of the dual domain implementation for the SNOWPACK model, in which the pore space that can be occupied by liquid water is separated into a part for matrix flow ($\theta_{\mathrm{s,matrix}}$) and a part representing preferential flow ($\theta_{\mathrm{s,pref}}$). The numbers refer to processes described in the text.

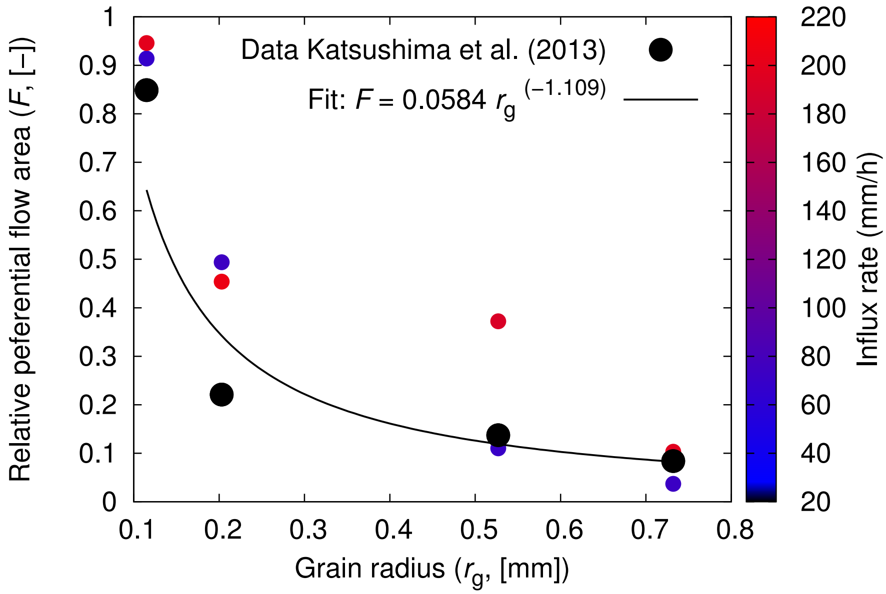

Figure 2. Relationship of the area involved in preferential flow as a function of grain radius. Data points represent laboratory experiments by *Katsushima et al.* (2013), presented quantitatively by *Hirashima et al.* (2014). Data points are coloured based on the water influx rate used in the experiments. The large black dots denote the data points used for determining the fit (solid line), corresponding to the lowest influx rate per grain size class.

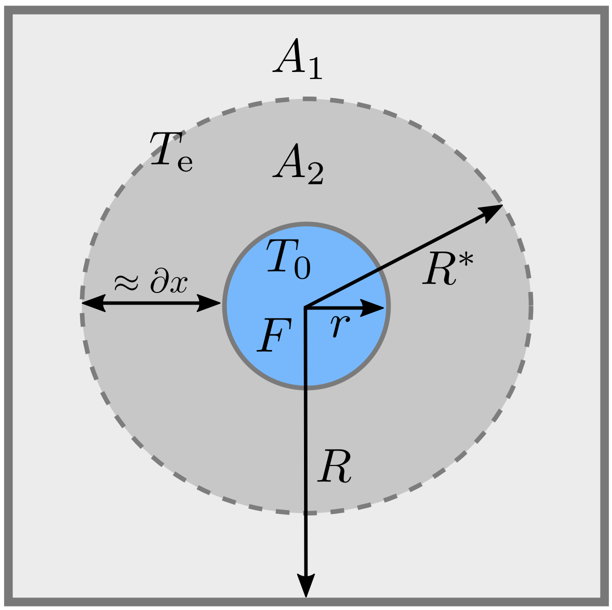

Figure 3. Schematic representation of a preferential flow path with radius r and surface F inside a 1 m^2 snowpack (i.e., $R = 0.5$ m), seen from above (not to scale), to approximate ∂x. The preferential flow path is assumed to be at melting temperature T_0, the rest of the snowpack at temperature T_e. R^* is the radius such that surface areas A_1 and A_2 are equal. When assuming a linear temperature gradient, T_e is found at distance R^*.

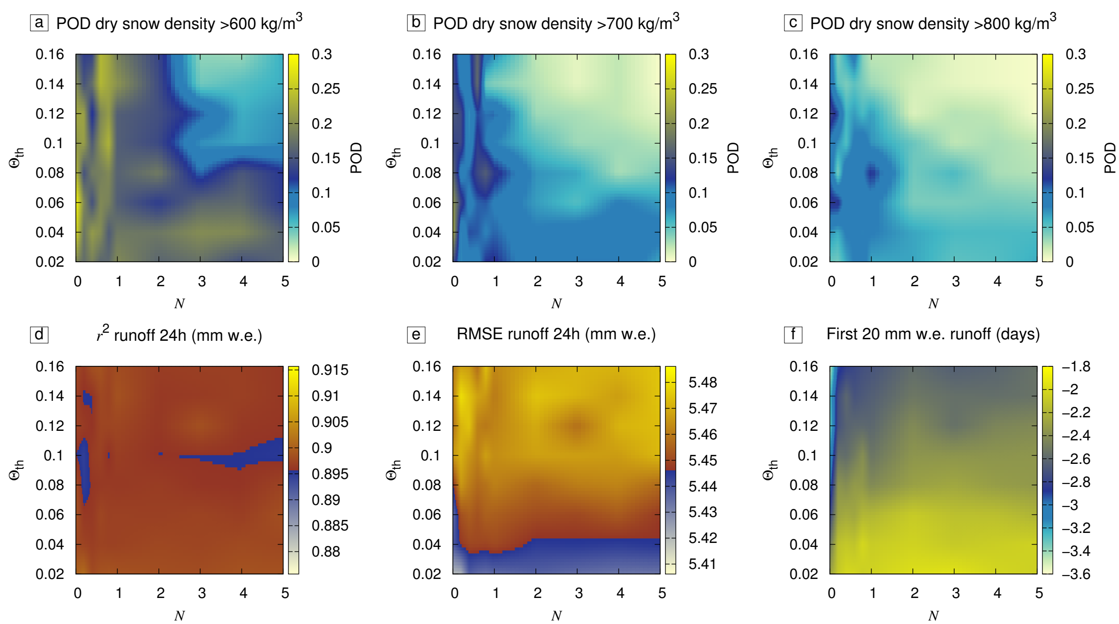

Figure 4. Interpolated results of the sensitivity study for the parameters N and Θ_{th} for the probability of detection (POD) when modelled dry snow density exceeds 600 kg m^{-3} (a), 700 kg m^{-3} (b), or 800 kg m^{-3} (c) within 20 cm of the observed ice layer. For runoff, the r^2 for daily sums of runoff (d), the RMSE error for daily sums of runoff (e) and the number of days difference between modelled and measured passage of 20 mm w.e. since March, 1 of each snow season (f). The jump in colour scale from blue to red in (d) and (e) mark the score achieved with matrix flow only.

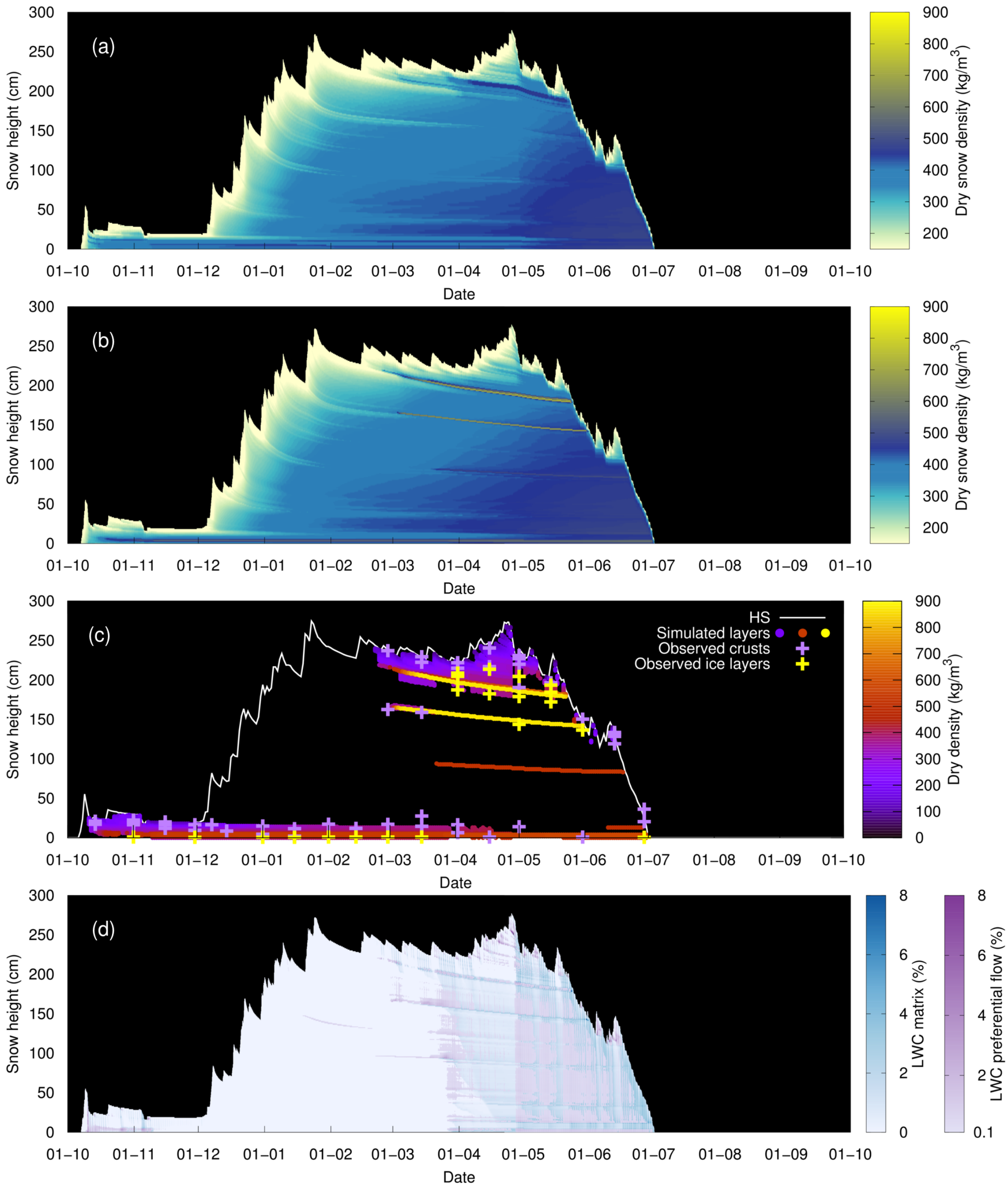

Figure 5. Dry snow density without considering preferential flow (a) and with preferential flow using high resolution simulations (b), validation with field observations (c) and liquid water content in the matrix and preferential flow domain for the simulation with preferential flow (d), for snow season 2012. In (c), modelled layers are shown when they are either a melt-freeze crust, or have a dry snow density exceeding 500 kg m^{-3}. For visibility, values of LWC in preferential flow below 0.1 % are ignored in (d).

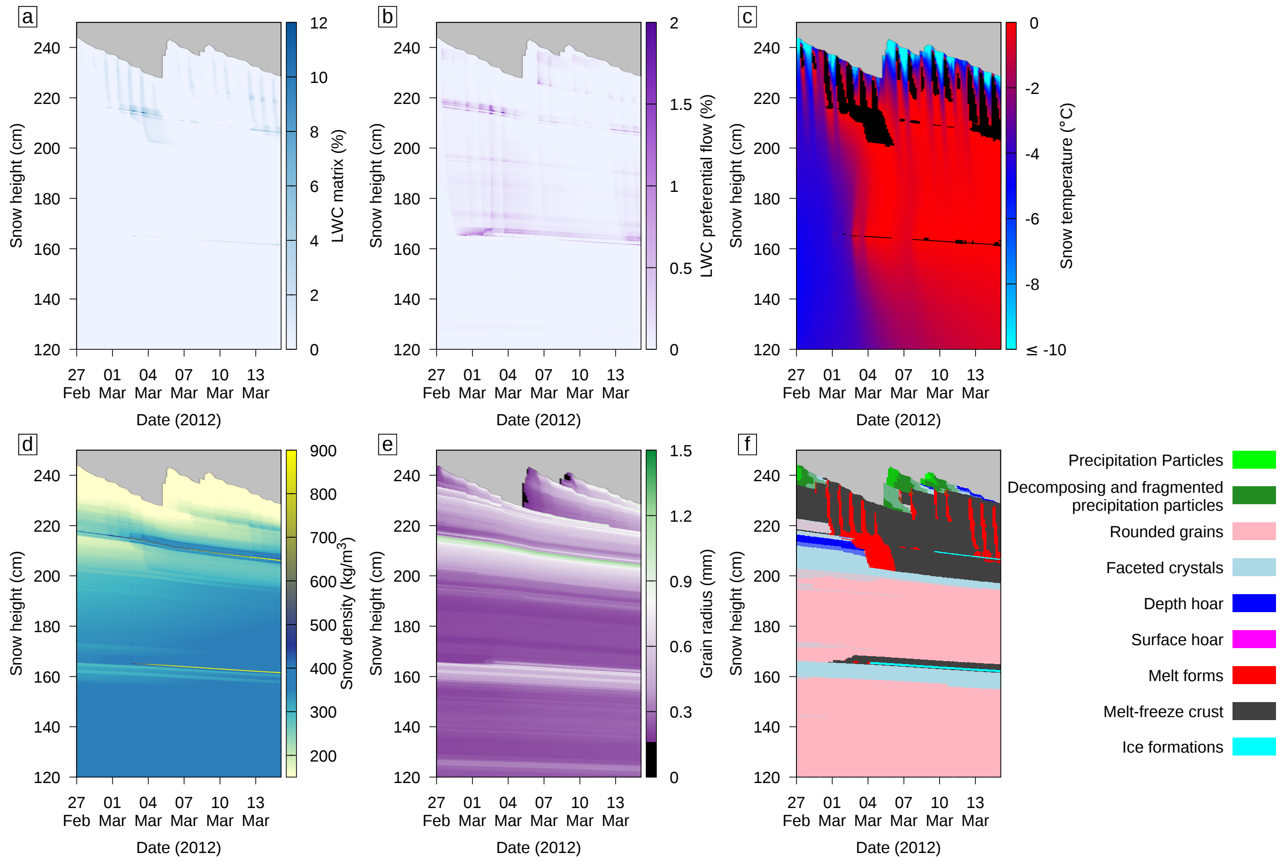

Figure 6. LWC in matrix domain (a), LWC in preferential flow domain (b), snow temperature (c), snow density (d), grain radius (e) and grain shape (f), depicting a detail of Fig. 5. Only the upper part of the snowpack is shown for the period February 27 to March 15. In (c), snow at melting temperature is coloured black to highlight wet parts, in (e), grain radii smaller than 0.16 mm are coloured black, denoting the smallest grain size class used in *Katsushima et al.* (2013) , and in (f), ice formations are defined as modelled dry snow density exceeding 700 kg/m^3.

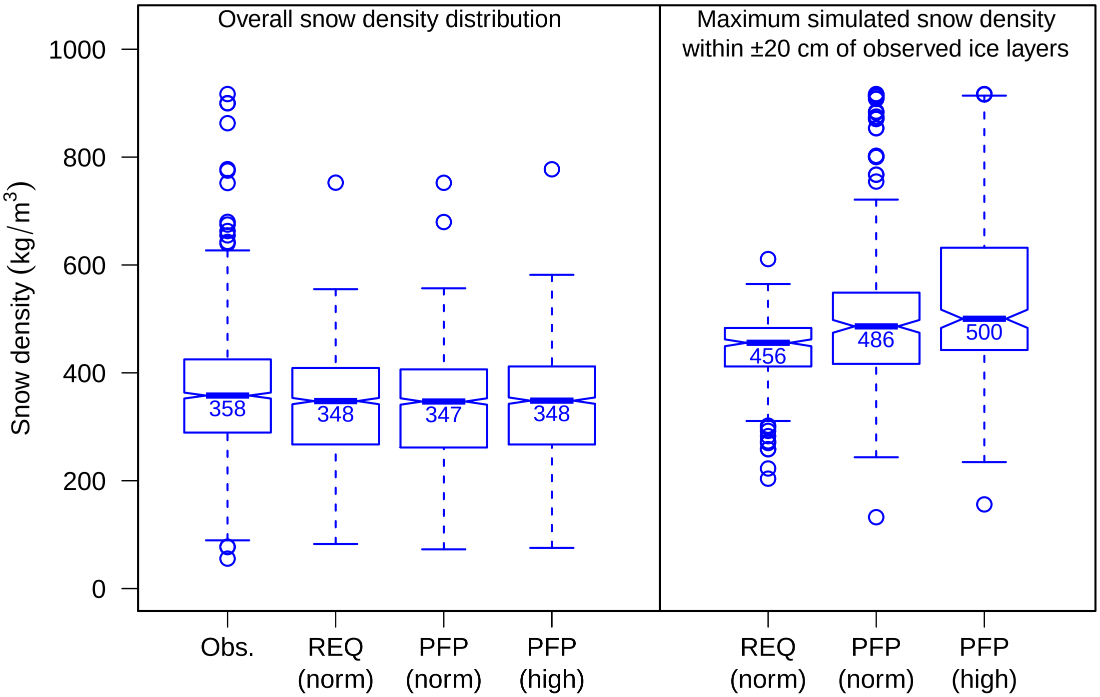

Figure 7. Box and whisker plot showing the distribution of snow density from observations (obs), simulations with Richards equation (REQ) and simulations with the dual domain approach to describe preferential flow (PFP). On the left, simulated snow density represents an aggregated snow density over multiple model layers to match the measured layer thickness. On the right, snow density of an individual model layer is shown. Boxes represent inter-quartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile), its value shown directly below the bar. Whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the inter-quartile range above the upper or below the lower quartile, respectively. Notches are drawn at ± 1.58 times the inter-quartile range divided by the square root of the number of data points. Outliers are shown as individual dots.

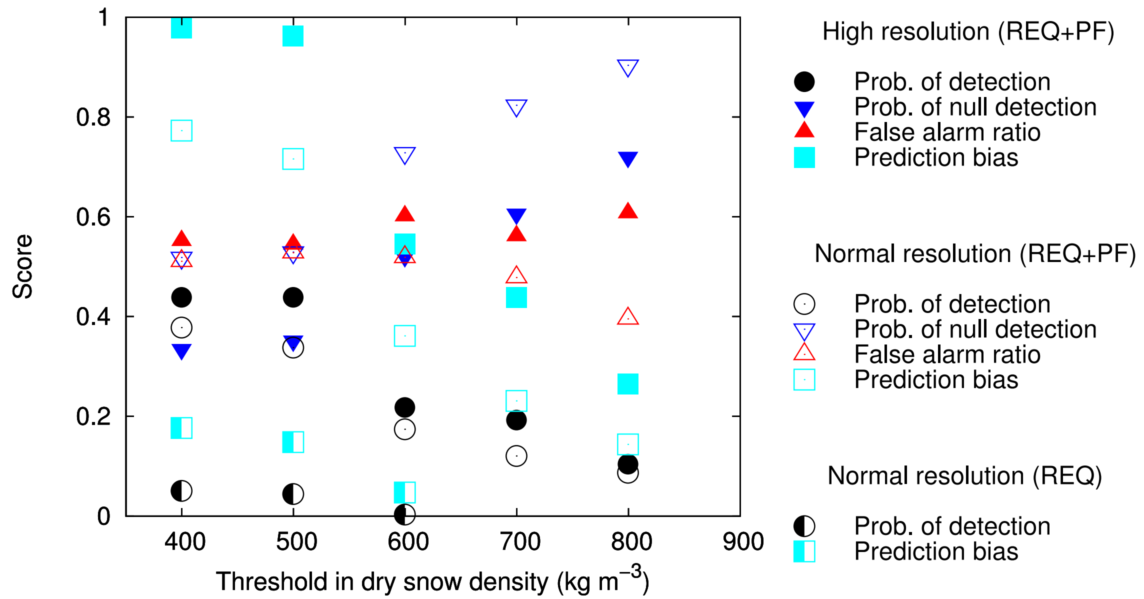

Figure 8. Contingency statistics as a function of threshold in dry snow density that defines an ice layer in the simulations, for both normal and high resolution simulations including preferential flow (REQ+PF) and normal resolution simulations using Richards equation only (REQ).

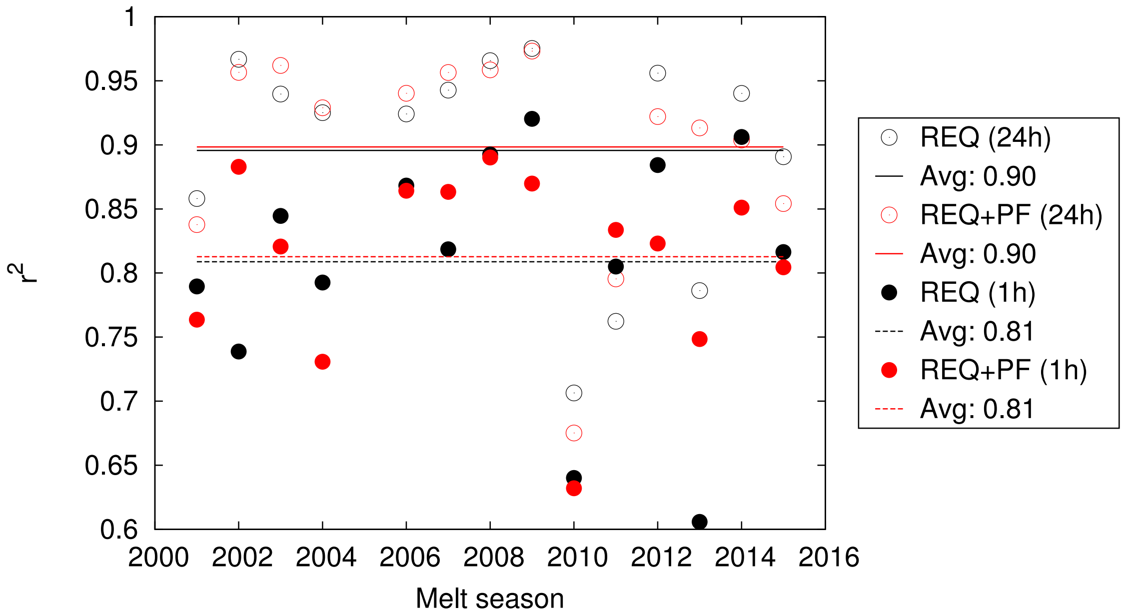

Figure 9. r^2 for both hourly and daily snowpack runoff over the period March 1 to May 31 for each snow season.

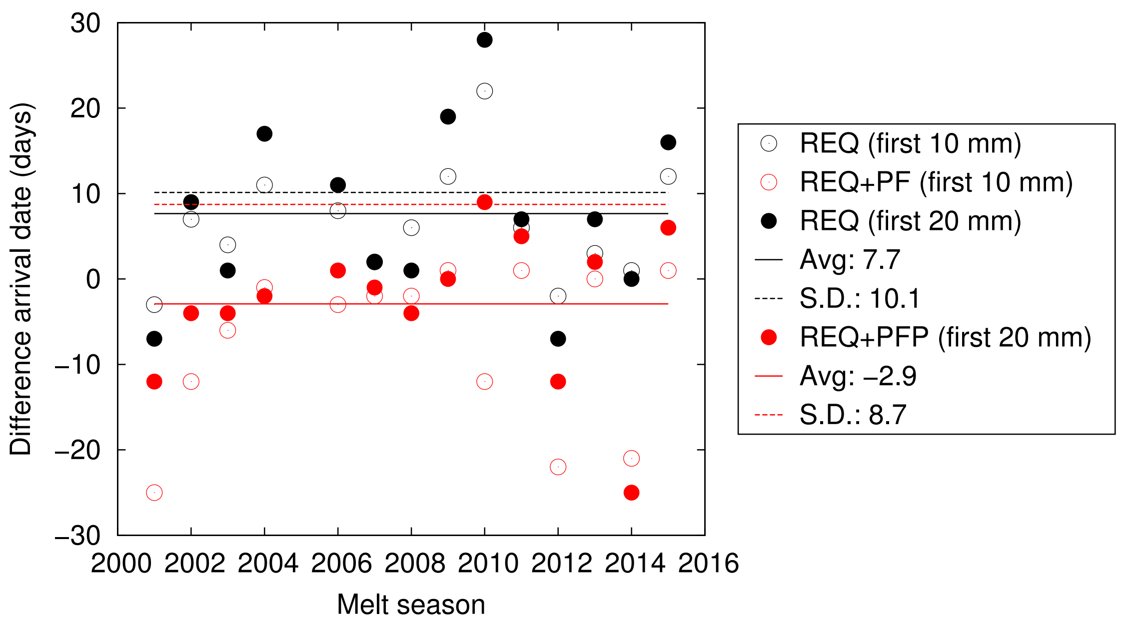

Figure 10. Difference (in days) between modelled and measured first 20 mm w.e. cumulative seasonal snowpack runoff (negative values denote modelled runoff is earlier than measured runoff).