Please find the original comments in regular, our original responses as published in the Online Discussion in *italics*, and the final changes made to the manuscript in **bold**. Page and line numbers in italics and bold text refer to the original and revised manuscript, respectively. A track-changed version of the manuscript can be found after the response to reviewers.

1 Reviewer 1

In the manuscript "Influence of snow surface processes on soil moisture dynamics and streamflow generation in alpine catchments", the authors present a comprehensive modeling study using the model Alpine3D which was complemented with new descriptions for simulating soil moisture and streamflow. The distributed model was forced using meteorological station data at several points and validated by means of snow depth, soil moisture, and runoff measurements.

1.1 General Comments

The manuscript presents a modeling study using a detailed set of modules and methods to tackle the challenge of simulating the hydrology in a complex mountainous catchment with a fully distributed, spatially highly resolved model. The focus lies on the simulation of snow depth, soil moisture and the respective interplay of precipitation, snow melt, and runoff dynamics. The study gives valuable insights in the involved hydrological processes. The manuscript is well elaborated and written and is technically of very high quality. I recommend its publication after minor revisions. Generally, the presented analysis is a bit incomplete because of the lack of a groundwater description in the model. This is mentioned in the manuscript at the respective sections. But it should be emphasized even more that this is a major zhortcoming of the study and it should be addressed in future work with the model setup. Another criticism is the description of the presented streamflow model. It is not quite clear to me how it was coupled to the model and what the flux input at or from different depths mean (sections 3.2 and 4.3). As I understand it, the water fluxes from the soil model at three different depths (lateral flux or excess out of the respective soil layer?) were taken and "streamed" into an external streamflow model. This streamflow model is calibrated using the respective fluxes which produces the shown streamflow simulations for three different depths. This approach is quite unusual and definitely needs further explanation in the manuscript. Why is the flux taken separately from the depths and not combined? The runoff dynamics clearly reveal that a groundwater module is missing. But this missing groundwater module could be "replaced" by a calibrated low flow component of the water flux (baseflow) which seems to be totally missing (Fig. 7, underestimated low flow / baseflow in the winter months). All other presented findings regarding soil moisture, freezing, as well as event-based precipitation and melt are well elaborated and very interesting. Some more questions that need clarification are listed in the following specific comments.
We thank the reviewer for his positive remarks about the study and his constructive comments. We will take them into consideration when revising the manuscript. Regarding the ground water flow: here the issue is mainly that only the streamflow model treats groundwater flow, simulating the water storage dynamics of the deep soil compartment. However, there is no feedback to the Alpine3D model, such that a rising water table cannot be simulated in the Alpine3D model. One could envisage an approach where the level of the reservoirs in the streamflow model is coupled to the lower boundary of the SNOWPACK module in the Alpine3D model. However, it is not guaranteed that this approach will improve the soil moisture or streamflow simulations, as it also requires detailed information about soil properties and soil depths throughout the catchment. We will provide a more extensive discussion on ground water flow in the revised manuscript.

This comment is similar to the general comment of Reviewer 2 and for simplicity, we give the same response here: As both reviewers raise similar concerns, it is clear that we need to pay particular attention to describe the coupling between the Alpine3D and streamflow model in more detail and with more clarity when revising the manuscript. The streamflow model is a spatially explicit hydrologic response model at sub-catchment scale. Each sub-catchment is identified based on geomorphological analysis of the watershed. The model simulates the water storage dynamics in two soil compartments, namely an upper and lower one, of each sub-catchment using a travel time distribution approach. Outflow from the upper compartment represents interflow, while that from the lower component represents baseflow. We would like to point out that our model is reproducing baseflow, albeit too low at the end of the winter. If one would be particularly interested in correctly representing baseflow, a recalibration of the streamflow model with a focus on the statistics for the winter period would allow to have a more accurate representation of baseflow. But we do not agree with both reviewers that the baseflow is absent. Furthermore, the streamflow model needs a surface scheme, to provide the influx into the system. For this, we use the Alpine3D model. However, it is somehow arbitrary where to draw the boundary between the surface scheme and the streamflow model. For this, we tested 3 scenarios: a soil flux at 2, 30 and 60 cm depth. So we do not use the fluxes combined, but we used the three fluxes as three different scenarios. Although it would be similar as running 3 separate simulations, with either 2, 30 or 60 cm of soil, this approach would have the disadvantage that specifying the lower boundary condition for the Alpine3D model becomes tricky. For example, at 3 m depth, one can assign a constant geothermal heat flux and a water table and this would hardly influence the snowpack dynamics. On the other hand, at 2 cm below the surface, a constant geothermal heat flux would provide a too strong heating of the snowpack, as the soil buffer is not represented. Therefore, we choose the approach of doing a single simulation, and extracting soil water fluxes at three depths in order to test how to achieve an optimal coupling between the surface scheme Alpine3D and the streamflow model. This is illustrated in Fig. 3 in Comola et al. (2015). We will rewrite the Methods section discussing the model coupling thoroughly, in order to better explain our approach.

First, we exchanged the wording "streamflow model" for "hydrologic response model" throughout the manuscript, to emphasize that the model is not only treating streamflow, but the hydrologic response from the catchment, based on input water fluxes from the surface scheme provided by Alpine3D. We now state in the abstract that the groundwater description is missing in the Alpine3D model, see P.1, L.8. As we now explain in the revised section about the hydrologic response model, this model is describing inter- and groundwater flow, see P.8, L.7-L22. This section is also revised to better explain the coupling strategy between Alpine3D and the hydrologic response model.

Please find our response to other issues raised by the reviewer below.

1.2 Specific Comments

- P.1 L. 6: "in close proximity to" instead of "in close proximity of"
  Will be corrected, thank you.
  Corrected, see P.1, L.6.

- P. 1 L. 9-15: "Streamflow simulations performed with a spatially-explicit hydrological model using a travel time distribution approach coupled to Alpine3D provided a closer agreement with observed streamflow at the outlet of the Dischma catchment when including 30 cm of soil layers. Performance decreased when including 2 cm or 60 cm of soil layers. This demonstrates that the role of soil moisture is important to take into account when understanding the relationship between both snowpack runoff and rainfall and catchment discharge in high alpine terrain." The differences in NSE for three simulations

are so small that I would not give this strong statement. It is also not at all an evidence for your second statement as you show no simulations without the new soil model, see comment below (P. 10 L. 18/19). It is for sure correct that soil moisture has to be taken into account but you show no real proof in this work.
We agree with the Reviewer that the abstract was not accurately reflecting the results from our study at this point. Note that NSE coefficients are all very similar, as we recalibrated the streamflow model for each case individually. However, the conclusion about the importance of soil is not only drawn based on the NSE coefficients for discharge, but also for the relationship between initial soil moisture and runoff coefficients. We will rephrase this part of the abstract when revising the manuscript.
Corrected, see P.1, L.9-21.

- P.1 L. 17: "which shows" instead of "and this shows"
  Will be corrected, thank you.
  Corrected, see P.1, L.21.

- P. 3 L. 7: Rephrase: "The measurement site Weissfluhjoch (WFJ), which is focused on snow-related measurements, as well as several permanent meteorological stations are located in close proximity to the area." instead of "The measurement site Weissfluhjoch (WFJ), which is focussed on snow-related measurements, is located in close proximity of the area, as well as several permanent meteorological stations."
  Will be rephrased, thank you.
  Rephrased, see P.3, L.19-21.

- P. 3 L. 14: "of total precipitation" instead of "of all precipitation"
  Will be corrected, thank you.
  Corrected, see P.3, L.27.

- P. 4 L. 7: Better use "focused", not "focussed" (see also above P. 3 L. 7)
  Will be corrected, thank you.
  Corrected, see P.4, L.20.

- P. 5 L. 14: Lower computational costs compared to what other approach? Please add an example for clarification!
  It was meant here: the bucket scheme for snow has a lower computation cost than the full Richards equation and the bucket scheme is an appropriate choice when the main interest is for seasonal and daily time scales. We will improve the wording of the manuscript at this point.
  Corrected, see P.6, L.2.

- P. 5 L. 21: Remove brackets in citation!
  Will be corrected, thank you.
  Sentence has been rephrased, see P.6, L.3-4.

- P. 6 L. 13: Rephrase the first two sentences / the beginning of this section ("Two important components to initialise Alpine3D simulations are the digital elevation model (DEM) for the Davos area, provided by the Swiss Federal Office of Topography (swisstopo). Also the soil has to be initialised for each pixel, although limited information is available.") e.g.: "Two important components to initialise Alpine3D simulations are the digital elevation model (DEM) and distributed soil information. The DEM is provided..."

Thank you for the suggestion, this part will be rephrased.
Corrected, see P.6, L.30-32.

- P. 7 L. 6: Either remove "on a computer cluster from 2008." or preferably provide some more information about the HPC system (e.g. type and clock speed of nodes). I guess the 14 hours per year using 36 CPU cores are the necessary wall clock time (or CPUh?). Please add this information in the manuscript.
  We will revise the sentence as follows: "Using 36 CPU cores from a HPC system consisting of in total 32 compute nodes with two 6-core AMD Opteron 2439, 2.8 GHz processors per compute node, the computation took on average 14 *hours wall clock time for a single year, mainly depending on the snow height in the winter season."*
  Corrected, see P.7, L.25-27.

- P. 7 L. 11: Remove "also".
  Will be corrected, thank you.
  Corrected, see P.7, L.32.

- P. 7 L. 12: Why didn't you additionally inspect hourly values if you have the respective measurements? You could add at least some examples for showing the model performance on a smaller, hourly timescale, which would be very interesting to see.
  We agree with the reviewer that it is interesting to see the hourly behaviour of the soil moisture measurements and simulations. We therefore plan to amend the manuscript with an additional figure showing for one station an example of hourly soil moisture, during both the melt season as well as the summer season (see Fig. 1).
  The figure has been added as Fig. 7 and is now discussed in P.9, L.24-27 an P.9, L.29 - P.10, L.2.

- P. 8 L. 6 ff and above and Figures 3–5: Consequently use one throughout the manuscript: either "snow depth" or "snow height" (personally, I prefer "depth").
  We will use the term "snow depth" throughout the manuscript and in the figures.
  This has been corrected throughout the manuscript.

- P. 8 L. 12 ff and Fig. 3: Please try to remove the measurement errors in Fig. 3 (high frequency fluctuations, especially in the summer months)! In June / July 2012 and 2013, the model seems to miss the measured spring snow fall at stations (a) and (b). Why does this happen? Add a respective explanation in the manuscript.
  These measurement sites showing the high frequency fluctuations measure over a meadow and the snow depth measurements are not only recording the grass growth, but are also receiving a noisy signal from the grass. A few times during the summer, the grass below the snow depth sensor is mowed by farmers, which is also visible in the signal. We did not explain this in the original manuscript, but, as also suggested by Reviewer 2, we plan to explain the measured signal in the revised manuscript. We do not want to filter the signal, as it is a typical signal for grass growth and thereby recognizable as such.
  Explanation has been added in P.9, L.17-18.

- P. 8 L. 15: To be consistent with the section title of 4.1 either remove "Measurements and Simulations" or add it in 4.1
  Thank your for pointing out the inconsistency, we will shorten section title 4.2.
  Corrected, see P.9, L.19.

- P. 9 L. 20: "S1" instead of "S3"
  Will be corrected, thank you.
  Corrected, see P.11, L.3.

- P. 9 L. 27: Are the r2 values calculated using the daily or hourly values? I guess daily, but please add this in the manuscript for clarification.
  These concern hourly values. As the reviewer was expecting daily average values, we changed the graph accordingly (no significant change in results). We are sorry for causing confusion, but we will add this information in the manuscript.
  Corrected, see P.11, L.10.

- P. 10 L. 12: Remove "us".
  Will be corrected, thank you.
  Corrected, see P.12, L.2.

- P. 10 L. 15: Please either explain your concept of the "virtual lysimeter" or use another notion! I think you are referring to the water fluxes at the three depths, but this is not clear here.
  This indeed refers to the water fluxes at the three depths. We will rephrase this sentence and will replace the term "virtual lysimeter" with an explicit description.
  Rephrased, see P.12, L.4-5.

- P. 10 L. 18/19: I am not sure if I understand this right, but the statement "The results suggests that the updated soil module of SNOWPACK is contributing to a better prediction of streamflow in the summer months." is misleading or drawn without any evidence. You show no Alpine3D runoff result without the new model, because – as I understand it – there was no soil moisture or runoff description in the model before. So a valid statement would be something like "The results show that the new soil module of SNOWPACK is enabling a simulation of streamflow."
  We agree with the reviewer that the statement was misleading. There actually has been a very basic soil module in SNOWPACK for many years now, where water flow was described using a bucket-type approach. However, we did not want to aim for a comparison, as some very important physics is missing in the old module, for example water retention and water flow rates as a function of soil moisture. We think that a base-line soil model in a physics based model should at least apply Richards equation or something similar to describe water flow in soil. Nevertheless, taking soil water fluxes at 2 cm depth can be regarded as almost equivalent to directly routing snow melt and rainfall to the runoff routine (P7, L21-23), which we found to give a lower score than integrating 30 cm of soil layers. Our aim is to show that using a physics based description of soil processes improves the simulation of catchment discharge. We will rephrase parts of the manuscript to better explain our reasoning, which we think is in line with the suggestion by the reviewer.
  Rephrased, see P.12, L.8-11 and an improved description of the methodology is now present in P.8, L.8-22.

- P. 11 last paragraph of section 4.4: The conclusions here are of course valid but were somehow clear before your study and should be underlined with existing literature.
  We will refer to the appropriate literature in this section.
  The references has been added, see P.13, L.6-9.

- Fig. 2, 3, 4, 5 and S1 – S5: Please add the year to the time-axis. This makes it much easier to look at when you write about single years in the text.

This is a very good suggestion and the appropriate changes will be made.

Please find the updated figures in the revised manuscript as well as the updated Online Supplement.

- Fig. 7, caption: typo "tics"
  Will be corrected, thank you.
  Corrected, see caption of Fig. 9, which was previously Fig. 7.

- Fig. 8, caption: I cannot see any data points plotted on the x-axis as stated in the caption. When you add them, please add the real value somehow because it is of interest how negative the NSE values are in these periods.
  Sorry for raising the confusion, but this remark referred to an earlier version of the plots, where NSE coefficients for summer 2012 were negative, due to, as was found later, a data processing error. This has been resolved. Now all NSE coefficients are positive and the manuscript will be updated accordingly.

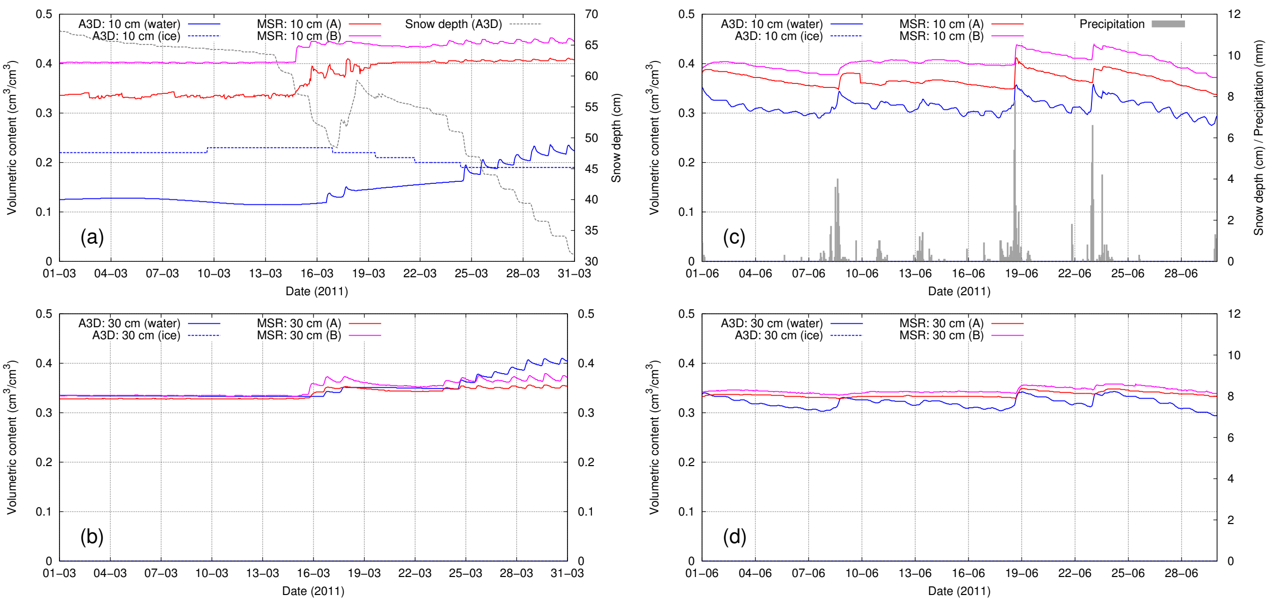

Figure 1: Measured and simulated soil moisture at the IRKIS station SLF2, for 10 cm depth (a, c) and 30 cm depth (b, d), during the snow melt season (a, b) and a snow-free summer month (c, d). In (a) simulated snow depth and in (c) precipitation is shown.

2 Reviewer 2

The manuscript mainly presents a comprehensive, multi-objective model validation study of an extension of the complex, physics-based Alpine 3D model. The model's performance to represent streamflow, snow depth, soil moisture and soil temperature/freezing is analyzed for 3 years in a Swiss mountain catchment and its surrounding. This evaluation is a framed by the context of the importance of soil moisture as a pre-disposition for floods. This framing – for my taste – is a bit wanted, and the title is somehow misleading. However, the quality of the model validation study is of a high standard and certainly of high importance. Especially the parallel evaluation of snow, soil and streamflow representation is cool. Although the overall impression of the article is very good, I do have some moderate remarks. The manuscript is certainly within the scope of HESS, it my knowledge of original content and can be a valuable article after my concerns are addressed.
We thank the reviewer for the constructive comments and positive remarks about our study. We will take them into consideration when revising the manuscript. As we will discuss below, we agree that the title may be considered confusing and we propose a modification of the title. However, we would like to keep the framing of the study of soil moisture as a predisposition for flooding. This notion is introduced in the introduction section, with, in our opinion, appropriate citations. Furthermore, we do find evidence that our model framework is able to reproduce the relationship between soil saturation at the onset of large rainfall or snowmelt events and the discharge behaviour in the Dischma catchment.

2.1 General comments:

- As mentioned before, I find the title a bit misleading, as it reads as the influence of snow processes on soil moisture and streamflow is analyzed. Instead, the focus is clearly on the model validation to reproduce the linkage between snow, soil and streamflow. I would recommend a rephrasing of the title.
  We agree that the title is somewhat misleading, so we suggest to add the word "Simulating" in the beginning of the title, so we propose now: "Simulating the influence of snow surface processes on soil moisture dynamics and streamflow generation in alpine catchments".
  The title has been revised to: "Simulating the influence of snow surface processes on soil moisture dynamics and streamflow generation in an Alpine catchment".

- Alike reviewer 1 (I haven't read his comments until I finished my review), I do not understand the usage of the soil water fluxes for streamflow generation. As reviewer 1 wrote to the point, why should one just take one of the fluxes (-2cm indicating surface runoff, -30 cm indicating interflow, -60 cm indicating baseflow). I also had a look in the cited publication, yet I find the entire concept very unusual and irritating. Because of this (I guess), the interpretation of the influence of soil moisture (Page 10, lines 14 ff) on streamflow is a bit simple. E.g. "neglecting the soil layers almost completely, by routing the 2 cm flux to the runoff model, is reducing the model efficiency". – This is logical as you neglect interflow and baseflow in summer months and interflow widely considered to be the dominant process in alpine catchments. Hence, the concept of this streamflow generation needs to be clarified and its strong limitation in terms of dynamic runoff generation should be discussed. Furthermore, effects of this simplified approach on the interpretation should be discussed.
  This comment is similar to the general comment of Reviewer 2 and for simplicity, we give the same response here: As both reviewers raise similar concerns, it is clear that we need to pay particular attention to describe the coupling between the Alpine3D and streamflow model in more detail and with more clarity when revising the manuscript. The streamflow model is a spatially explicit hydrologic response model at sub-catchment scale. Each sub-catchment is identified based on geomorphological analysis of

the watershed. The model simulates the water storage dynamics in two soil compartments, namely an upper and lower one, of each sub-catchment using a travel time distribution approach. Outflow from the upper compartment represents interflow, while that from the lower component represents baseflow. We would like to point out that our model is reproducing baseflow, albeit too low at the end of the winter. If one would be particularly interested in correctly representing baseflow, a recalibration of the streamflow model with a focus on the statistics for the winter period would allow to have a more accurate representation of baseflow. But we do not agree with both reviewers that the baseflow is absent. Furthermore, the streamflow model needs a surface scheme, to provide the influx into the system. For this, we use the Alpine3D model. However, it is somehow arbitrary where to draw the boundary between the surface scheme and the streamflow model. For this, we tested 3 scenarios: a soil flux at 2, 30 and 60 cm depth. So we do not use the fluxes combined, but we used the three fluxes as three different scenarios. Although it would be similar as running 3 separate simulations, with either 2, 30 or 60 cm of soil, this approach would have the disadvantage that specifying the lower boundary condition for the Alpine3D model becomes tricky. For example, at 3 m depth, one can assign a constant geothermal heat flux and a water table and this would hardly influence the snowpack dynamics. On the other hand, at 2 cm below the surface, a constant geothermal heat flux would provide a too strong heating of the snowpack, as the soil buffer is not represented. Therefore, we choose the approach of doing a single simulation, and extracting soil water fluxes at three depths in order to test how to achieve an optimal coupling between the surface scheme Alpine3D and the streamflow model. This is illustrated in Fig. 3 in Comola et al. (2015). We will rewrite the Methods section discussing the model coupling thoroughly, in order to better explain our approach.

First, we exchanged the wording "streamflow model" for "hydrologic response model" throughout the manuscript, to emphasize that the model is not only treating streamflow, but the hydrologic response from the catchment, based on input water fluxes from the surface scheme provided by Alpine3D. We now state in the abstract that the groundwater description is missing in the Alpine3D model, see P.1, L.8. As we now explain in the revised section about the hydrologic response model, this model is describing inter- and groundwater flow, see P.8, L.7-L22. This section is also revised to better explain the coupling strategy between Alpine3D and the hydrologic response model.

Please find our response to other issues raised by the reviewer below.

- The description of the different soil layers is unclear: You introduced increasing soil layer magnitudes (from 2cm to 40 cm) up to a soils depth of 300 cm in the model. However, you take water fluxes from 2, 30 and 60 cm. Moreover you compare these to soil moisture measured at 10, 30, 50, 80, and 120 cm depth. And finally, you take the average of the upper 40 cm (page 10, line 25) as the soil moisture state within the catchment. As these number do not match at a first glance, a clarification is advisable. Maybe a sketch would help.
  We think this is a very good suggestion and we will add a descriptive illustration in the revised manuscript. Please find the new figure below as Fig. 3. Note that the layer spacing was erroneously reported as ranging from 2 cm to 40 cm, where it should have been from 2 cm to 25 cm. This will be corrected in the revised manuscript.
  The figure has been included as Fig. 2 in the revised manuscript. Text in P.7, L.16 has been corrected.

- In the manuscript, the SNOWPACK and Alpine3D are described as two separate models (e.g. in the model description and partly in the introduction). But as written in the Conclusion, SNOWPACK is a module of Alpine3D and as I understand an integrated part of Alpine3D. This should be clarified throughout the text, especially in the beginning (Aims section)

The reviewer is correct, the SNOWPACK model serves as the snow and soil module for the distributed Alpine3D model. When revising the manuscript, we will pay attention that this is correctly formulated throughout the manuscript.

This has been rephrased where necessary, see for example P.5, L.31-32.

- As the Dischma catchment is an alpine catchment I assume that skeleton fraction is a major issue, both for measuring the "correct" soil moisture as well as for simulating the soil moist dynamics. Please, clarify how and if the skeleton fraction was considered in the pedo-transfer-function and how it was considered in the selection of the measuring location (and how representative the selection in terms of skeleton fraction is). Moreover, please discuss if the found biases in the soil moisture and soil temperature simulations can be explained by skeleton fraction. Finally (I hope I did not miss it), how do the soil types of all measuring stations represent the soil types in the Dischma catchment.

  - We agree that the skeleton fraction in alpine catchment is an important factor to take into account. For example, the study by Rössler and Löffler (2010) demonstrates in a sensitivity study that changing the skeleton fraction has an impact on streamflow and soil moisture simulations. They particularly describe the effect of an increase in porosity, and associated changes in hydraulic parameters. However, the study by Rössler and Löffler (2010) also points out that spatial variability of the skeleton fraction is largely unknown. In the current version of the SNOWPACK model, which provides the surface scheme for the Alpine3D model, the skeleton fraction is not taken into account, as the SNOWPACK uses prescribed soil types. We actually found that for some sites we get an adequate soil moisture simulation without considering the skeleton fraction, whereas for other sites the simulations are showing less agreement with measurements. But these contrasting results indicate that with the current information, only ad-hoc modifications of the skeleton fraction are possible, as we cannot separate well enough between the soil moisture sites based on available information (land use and soil permeability). For further development of the SNOWPACK and Alpine3D model, this certainly is an area of attention. As discussed by Brakensiek and Rawls (1994), neglecting rock fragments in soil may overestimate hydraulic conductivity. Thus, the bias in soil moisture we found can be explained by an overestimation of hydraulic conductivity in the model, which would bring down liquid water faster. As wetter soils need more energy to freeze, the underestimation of soil moisture in the top layer may also result from this bias. The above mentioned points will be discussed in the revised manuscript.

  We discuss this now in P.7, L.11-14 and the possible effect on our simulations in P.10, L.17-23.

  - The representativeness of the soil moisture measurement sites is given by that the Grossalp and Pischa stations were located in the "alpine meadow" class, which is 21.1% of the land use coverage (see Table 4 in the original manuscript). The Uf den Chaiseren, Dorfji and Stillberg stations are located in the "mixed forest", "bush" and "bare soil" class, respectively, which is found in 12.9%, 7.3% and 6.0% of the Dischma catchment, respectively. The SLF2 and Golf Course stations would officially fall into the category of "settlement", but one would describe the area as "alpine meadow". We will add this information to the manuscript.

  Please find this information in P.5, L.13-18.

- The description of the meteorological data is quite long and very detailed. I would suggest to just briefly describe the table 2.

  When revising the manuscript, we will put effort in shortening this section.

  We shortened the section, see P.4, L.16 - P.5, L.28. However, we whish to keep a certain level of

detail, as some of the datasets collected in this research will be made publicly available via doi: 10.16904/17.

2.2 Specific comments:

- Page 1, line 11, and 12: Please clarify the word "including", as you do not combine the three layers.
  As our description of the coupling to the streamflow model was clearly confusing in the original manuscript, we plan to revise this part of the abstract as: "Streamflow simulations performed with a spatially-explicit hydrological model using a travel time distribution approach coupled to Alpine3D provided a closer agreement with observed streamflow at the outlet of the Dischma catchment when driving the streamflow model with soil water fluxes at 30 cm depth. Performance decreased when using the 2 cm soil water flux, thereby mostly ignoring soil processes. This demonstrates that the role of soil moisture is important to take into account when understanding the relationship between both snowpack runoff and rainfall and catchment discharge in high alpine terrain. However, using the soil water flux at 60 cm depth to drive the streamflow model also decreased its performance, indicating that an optimal soil depth to include in the simulations exists."
  Please find the revised abstract regarding this point in P.1, L9-17.

- Page 2, line 29: "small scale surface processes". Please, specify the scale.
  This refers to 10-100m scale, on which wind drifts form, and for which local topography strongly influences the energy balance via the slope aspect, angle and local shading. We will amend the manuscript at this point.
  Specified, see P.3, L.2-4.

- Page 3 ,line 5: Please, specify the catchment size.
  We will report that the catchment size that is represented by the gauging station is 43.3 km^2, as reported by the Swiss Federal Office of the Environment (Federal Office for the Environment (FOEN), 2017).
  Specified, see P.3, L.18.

- Page 3, line 13 ff & Figure 2: How did you separated snow from rain here.
  In the manuscript, we did all separations of precipitation in rain and snowfall based on an air temperature threshold of 1.2 °C for half-hourly measurements. We will specify this in the manuscript where necessary.
  Specified, see P.3, L.28-29.

- Page 3, and Table 1: A comparison to the long term norm period would be interesting
  We agree with this suggestion. We now add the 10-year averages to the table, which corresponds to the period for which the streamflow simulations were performed. Note that we came across an inconsistency. The data shown was not based on the same meteorological dataset as used for the Alpine3D simulations. Particularly an undercatch correction was not taken into account when constructing Table 1 and Fig. 2 in . This will be corrected.
  10 year averages were added to Table 1.

- Page 4 and Figure 1: "Golfplatz" in the Figure versus "Golf course" in the text. "SLF2" site is named "SLF" in the map. How were the boarders of the Dischma catchment defined (topography based from the model?). I would recommend some light, partly transparent background color for the names, to improve readability. I have to admit, I am not a fan of topographic maps as background, especially if the legend is missing. Any chance to replace it with a more generalized map?

Thank you for pointing out these inconsistencies in labelling; they have been resolved. Furthermore, we added a white, slightly transparent box behind the labels. Unfortunately, an illustrative map that is not a topographic map is not available. However, in order to increase readability, we switched to a less detailed map. See the new map below in Fig. 2 in this document. The Dischma catchment border is provided by the Swiss Federal Office of the Environment (FOEN). We plan to amend the manuscript at this point, and explain that model grid points with the center point inside the (sub-)catchment border polygon are considered being part of the (sub-)catchment.

Please find the updated map as Fig. 1 and the mapping of the catchment polygons on P.8, L.20-22 in the revised manuscript.

- Page 6, line 5 ff: Are the interpolations done for each time step?
  Yes, as with the other parameters, the interpolation for precipitation is also done at every Alpine3D time step of 1 hour with the help of the MeteoIO library. This will be made clear in the revised manuscript.
  Please see P.6, L.21-22.

- Page 6, line 14: I do not think that "initialization" is the correct term. Is it not parameterization?
  This sentence will be revised based on a suggestion by Reviewer 1. We now term it "soil properties".
  Corrected, see P.6, L.31-33.

- Page 7, line 21. "sub-catchments" – so is this approach some kind of HRU approach?
  Although it sounds similar to a HRU approach, a major difference is that the surface processes at every grid point inside a sub-catchment are explicitly resolved by the Alpine3D model, for example by taking into account variations in altitude, incoming solar radiation as a function of aspect and slope angle. It is only determined here which grid cell is draining to which sub-catchment and the residence time within the sub-catchment, based on terrain analysis only (and not soil properties, land use, etc.). We will revise the description of the coupling of Alpine3D to the streamflow model, hopefully adequately avoiding confusion with the HRU approach.
  Please find the revised description of the coupling of Alpine3D to the streamflow model on P.8, L7-21.

- Page 7, line 33: Again, the soil moisture is calculated for the first 40 cm. Can you clarify its relation to the 30 cm stated before and after.
  We will add Fig. 3 to the revised manuscript (see below), indicating the soil layering in the simulations, as well as the soil moisture measurement depths. The choice for 40 cm is motivated by the fact that the upper soil moisture measurements taken at 10 cm and 30 cm will more or less represent the upper 40 cm of the soil. The dielectric sensor 10HS for soil moisture used in this study measures approximately a volume of 1.32 l, as specified by the manufacturer. We will amend the manuscript at this point.
  Please find the Figure as Figure 2 in the revised mansucript. The measurement volume of the sensors is listed on P.5, L20 and the explanation is added to P.8, L.33-34.

- The definition of a rainfall event is a bit broad. Do you used mowing 12 h sum? What if a rainfall event is ended by falling below the 3mm thresholds criteria, but followed by a >10mm event again. Why do you choose a time window of 12 mm. Did you do any concentration time analysis?
  Yes, a 12 h moving sum was used, we will specify this in the manuscript. In the case mentioned by the reviewer (rainfall falling below 3mm, but followed by a >10mm event), two events will be taken into the analysis. The time window of 12 hours was arbitrarily chosen, motivated by the fact that we aimed to select rather intense events. In total 168 rainfall events and 301 snowpack runoff events were selected

(i.e, on average 16.8 and 30.1 events per year, respectively). The average duration of an event was 21.8 hrs (rainfall) and 20.9 hrs (snowpack runoff). On average, there are 6.8 days in between rainfall events, excluding the winter season. There are 1.3 days in between snowpack runoff events, excluding the summer season. We will add this information to the revised manuscript.
Please find the added information on P.9, L.3-7.

- Page 8, line 14, and Figure 3. A comment on the vegetation growth (?) during summer would be nice.
Thank you for this suggestion, we will discuss this in the revised manuscript.
Please find the discussion of this point in the revised manuscript P.9, L.17-18.

- Page 9, line 27 ff. In my opinion, the r2 is not the appropriate statistical measure here, as it does not consider any systematic offsets/biases. The application of the RMSE or similar would be more fair. Furthermore, can you set your results in light of other models of soil moistures in alpine terrains? Also to show that your results are pretty good.
We are actually interested in to what extend the simulations are able to reproduce the variability in soil moisture. As the comparison of the two measured soil moisture sensors at a single station and single depth shows, often a bias is already present between both measurements. This suggests a bias in the sensors which could be resolved by recalibration of the sensors. We therefore do not necessarily want to express the existing bias in the statistical measure and we prefer to keep the results for r^2. Note that the existence of a bias can be clearly identified by readers by the soil moisture figures we show. We will clearly discuss the existence of a bias in the revised manuscript. Regarding the comment about citation of existing literature, the most important studies we are aware of that both simulate and measure soil moisture in alpine terrain are the studies by Gurtz et al. (2003); Rössler and Löffler (2010); Kumar et al. (2013); Pasolli et al. (2013); Brocca et al. (2013); Pellet et al. (2016). We will discuss our results in light with the results published in these studies.
Please find the discussion of this point in the revised manuscript P.11, L.20-25. Note that we explicitly mention the bias in the conclusions (P.13, L.21), including the bias between two measurements at the same depth at the same site (P.13, L.22).

- Page, line 10: "however, ..." Isn't this finding clear and logical as you only consider "deeper" water fluxes
This is true, and we will rephrase this sentence.
We amended this sentence, see P.11, L.32 - P.1, L.3.

- I am looking forward to the revised manuscript.
Thank you.

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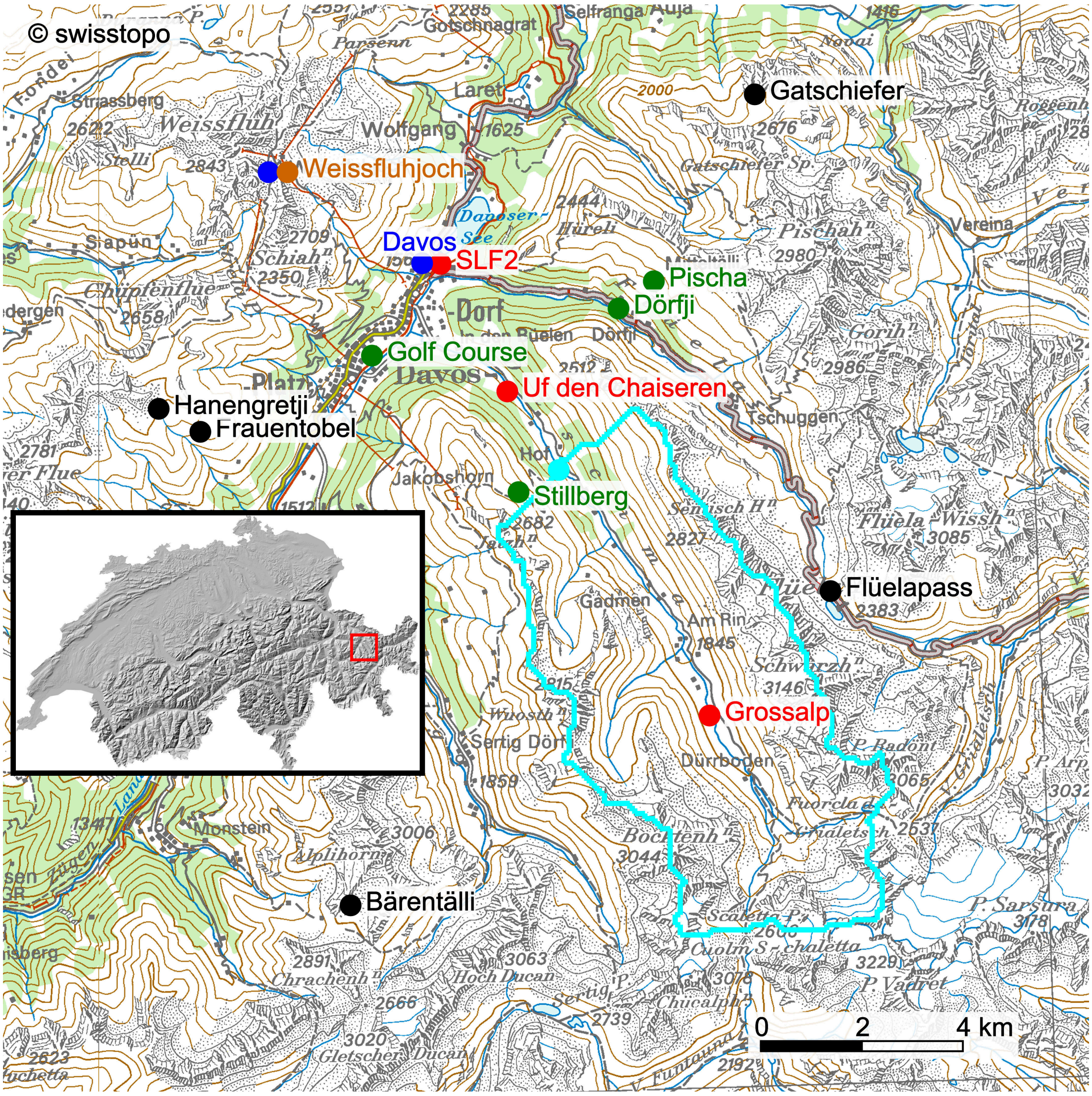

Figure 2: Topographical map of the simulated domain, showing the locations of the stations. IMIS stations are shown in black, IRKIS stations in red, SensorScope stations in green, SwissMetNet stations in blue and Weissfluhjoch in brown. The Dischma catchment and the gauging station measuring streamflow in the Dischmabach at the outlet of the Dischma catchment are shown in cyan. The inset shows the location of the simulation domain (red square) in Switzerland. Maps reproduced by permission of swisstopo (JA100118).

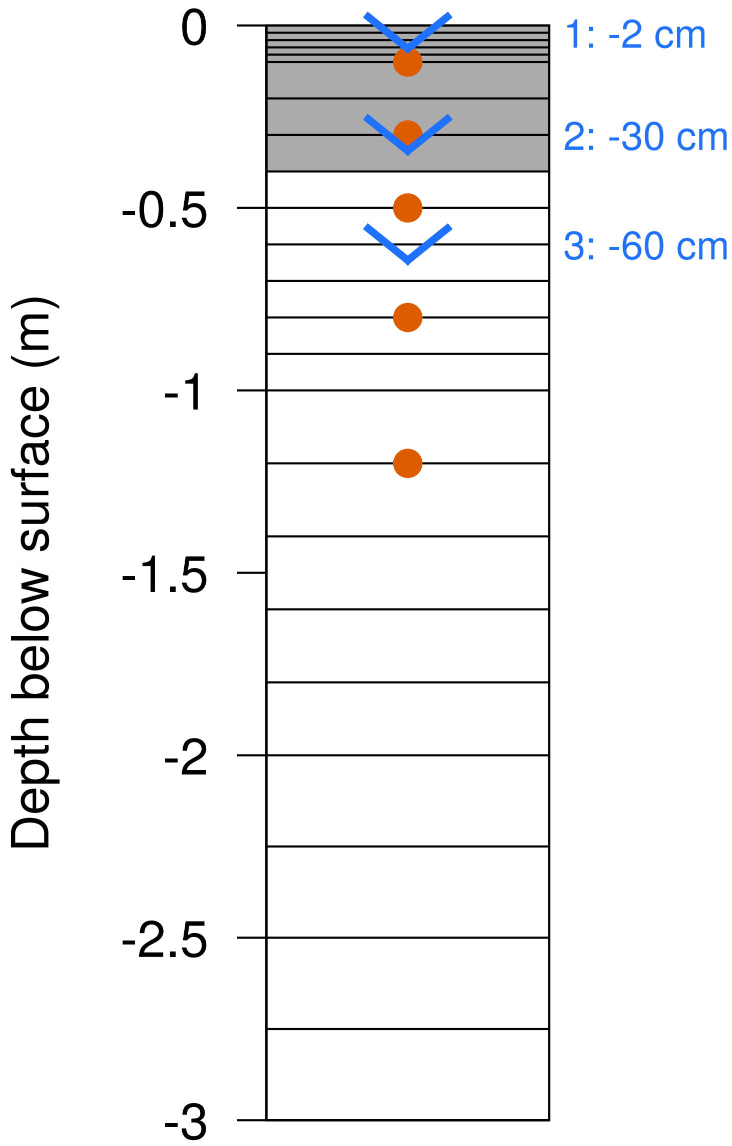

Figure 3: Soil layering as used in the Alpine3D model. The three water fluxes used to drive the streamflow model are shown in blue arrows. The soil moisture measurements are indicated by brown circles.

Influence Simulating the influence of snow surface processes on soil moisture dynamics and streamflow generation in alpine catchmentsan Alpine catchment

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Abstract. The assessment of flood risks in alpine, snow covered catchments requires an understanding of the linkage between the snow cover, soil and discharge in the stream network. Here, we apply the comprehensive, distributed model Alpine3D to investigate the role of soil moisture in the predisposition of a catchment the Dischma catchment in Switzerland to high flows from rainfall and snow melt for the Dischma catchment in East Switzerlandsnowmelt. The recently updated soil module of the physics based, multi-layer snow cover model SNOWPACK, which solves the surface energy and mass balance in Alpine3D, is verified against soil moisture measurements at seven sites and various depths inside and in close proximity of to the Dischma catchment. Measurements and simulations in such terrain are difficult and consequently, soil moisture was simulated with varying degrees of success. Differences between simulated and measured soil moisture mainly arises from an overestimation of soil freezing and an absence of a ground water groundwater description in the Alpine3D model. Both were found to have an influence in the soil moisture measurements. Streamflow simulations performed with Using the Alpine3D simulation as the surface scheme for a spatially-explicit hydrological hydrologic response model using a travel time distribution approach coupled to Alpine3D for interflow and baseflow, streamflow simulations were performed for the discharge from the catchment. The streamflow simulations provided a closer agreement with observed streamflow at the outlet of the Dischma catchment when including when driving the hydrologic response model with soil water fluxes at 30 cm of soil layersdepth in the Alpine3D model. Performance decreased when including using the 2 cm or 60 cm of soil layers. This demonstrates soil water flux, thereby mostly ignoring soil processes. This illustrates that the role of soil moisture is important to take into account when understanding the relationship between both snowpack runoff and rainfall and catchment discharge in high alpine terrain. However, using the soil water flux at 60 cm depth to drive the hydrologic response model also decreased its performance, indicating that an optimal soil depth to include in surface simulations exists and that the runoff dynamics are controlled by only a shallow soil layer. Runoff coefficients (i.e., ratio of rainfall over discharge) based on measurements for high rainfall and snowmelt events were found to be dependent on the simulated initial soil moisture state at the onset of an event, further illustrating the important role of soil moisture for the hydrological processes in the catchment. The runoff coefficients using simulated discharge were found to reproduce this dependency and this which shows that the Alpine3D model framework can be successfully applied to assess the predisposition of the catchment to flood risks from both snowmelt and rainfall events.

1 Introduction

Alpine catchments are sensitive to flooding events (*Frei et al.*, 2000), with positive contributing factors being, for example, the topography, high rainfall rates and shallow soil depths (*Weingartner et al.*, 2003). The presence of a snow cover, acting as a water storage over winter, may dampen flood risks during some parts of the year (*Weingartner et al.*, 2003), but also provides an important contribution to catchment scale runoff via meltwater in spring. Correct estimations of snow cover and snowmelt distributions are therefore essential for accurate streamflow simulations (*Maurer and Lettenmaier*, 2003; *Berg and Mulroy*, 2006; *Seyfried et al.*, 2009; *Koster et al.*, 2010). Additionally, rain-on-snow events may significantly increase the liquid water outflow from the snowpack (*Mazurkiewicz et al.*, 2008; *Wever et al.*, 2014a; *Würzer et al.*, 2016) (*Mazurkiewicz et al.*, 2008; *Wever et al.*, 2014a; W
many flooding events have been caused by such events (*Marks et al.*, 2001; *Rössler et al.*, 2014).

However, accurate simulations of liquid water draining from the snowpack due to snowmelt or rainfall (henceforth termed snowpack runoff) are not sufficient to understand catchment runoff. The degree of saturation of the soil was found to determine the eventual effect of snowpack runoff on streamflow (*McNamara et al.*, 2005; *Seyfried et al.*, 2009; *Bales et al.*, 2011). This effect is not limited to snowpack runoff, but is also found for rainfall (*Bales et al.*, 2011; *Penna et al.*, 2011). During the winter months, the snow cover basically decouples the soil from the atmosphere and the upper boundary for the soil is determined by the state of the snow cover on top (*McNamara et al.*, 2005; *Kumar et al.*, 2013). Often, the hydrological processes are strongly reduced during winter time, such as groundwater flow and streamflow, until the spring snowmelt provides liquid water again to the hydrological system. A model system to assess the hydrological hydrologic response of a catchment is therefore required to simulate both the soil and the snowpack accurately.

To assess this coupling between snowmelt, soil moisture and streamflow, the use of physics based models of snow surface process descriptions in hydrological models seems attractive as they should not require calibration for the specific application. For example, *Rigon et al.* (2006) show that the physics based hydrological model GEOtop, which includes a relatively simple physics based snow scheme, is able to provide accurate streamflow simulations for small catchments, where a snow cover is present for extended periods during the winter season. *Kumar et al.* (2013) also found that using a physics based model approach for snow related processes in the PIHM model achieved a slightly better performance for streamflow simulations than a temperature index approach. The results in their study suggest that this improvement is linked to the spatial variability of snow distribution and snowmelt, which provides a strong control on other components of the hydrological cycle, like soil moisture or streamflow. In *Warscher et al.* (2013), a similar comparison was made by comparing a temperature-index approach with an energy balance approach to determine snowmelt in the physics based hydrological model WaSiM-ETH. Their results show that the energy balance approach provides improvements particularly at the small spatial scales typical of high alpine headwater catchments. However, the improvements rapidly decrease with increasing scale. It has been argued that simple temperature index based snowmelt models may perform well after careful calibration (*Kumar et al.*, 2013; *Comola et al.*, 2015a) and those models are still commonly used in operational flood forecasting. Nevertheless, physics based snow models may be considered more reliable when extrapolating to other conditions such as for climate change scenarios (e.g., *Bavay et al.* (2013)) or to catchment catchments where limited calibration data is available.

The fully-distributed Alpine3D model is typically applied for detailed studies of small scale surface processes in alpine catchments where snow plays an important role (*Lehning et al.*, 2006; *Mott et al.*, 2008; *Groot Zwaaftink et al.*, 2013). In alpine terrain, considering the length scales less than a few 100 m is important as on these scales, wind drifts determine the snow accumulation and local topography heavily influences the energy balance via the slope aspect, angle and local shading. In this study, the recent addition to the SNOWPACK model of a solver for Richards Equation for soil (see *Wever et al.* (2014a, 2015)) is verified against soil moisture measurements in the vicinity of Davos, Switzerland. The SNOWPACK model additionally provides a physics based description of soil-snow-vegetation processes provides the surface scheme in the Alpine3D model framework, using physics based descriptions of soil-snow-vegetation processes (*Gouttevin et al.*, 2015). Here, the capabilities of Alpine3D to capture the soil moisture state and its influence is assessed. Furthermore, the Alpine3D model provides the surface scheme for a travel time distribution hydrologic response model to simulate catchment discharge (*Comola et al.*, 2015b; *Gallice et al.*, 2016a) and here the role of soil moisture in the coupling of Alpine3D to the hydrologic response model, as well as the influence of the soil moisture state on streamflow generation in the catchment is assessedinvestigated.

2 Study Area and Data

2.1 Study Area

The Davos area is located in the Canton Graubünden Grisons in east Switzerland. The studied area is defined as an area of 21.5×21.5 km^2 and stretches over an elevation range from about 1250 m above sea level (a.s.l.) to 3218 m a.s.l. Some small glaciers exist in the highest parts, covering about 0.86 km^2 (*Zappa et al.*, 2003). The Dischma catchment is an unregulated catchment of 43.3 km^2 in the Davos area and has been subject to previous studies concerning streamflow from the Dischma river (e.g., *Zappa et al.* (2003); *Lehning et al.* (2006); *Bavay et al.* (2009); *Schaefli et al.* (2014); *Comola et al.* (2015b)). The measurement site Weissfluhjoch (WFJ), which is focussed on snow-related measurements, is located in close proximity of the area, as well as several permanent meteorological stations are located in close proximity of the catchment. Figure 1 shows the studied area, including the measurement stations and the gauging station for streamflow measurements of the Dischmabach in the Dischma catchment. Streamflow datahas Quality controlled streamflow data, catchment properties and the border polygon have been provided by the Swiss Federal Office for the Environment (FOEN) (*Federal Office for the Environment (FOEN)*, 2015, 2017) . Simulations presented in this study consist of three winter seasons, from October 1, 2010 to September 30, 2013.

Snowfall plays an important role in the Davos area. Table 1 shows the precipitation sums for two heated rain gauges at two elevations in the region. About 40% to 80% of all total precipitation falls as snow at the lower and upper parts of the Dischma catchment, respectively (*Zappa et al.*, 2003). Precipitation in the Davos area is commonly separated into rain and snowfall based on an air temperature threshold of 1.2 °C. The winter months are dominated by snowfall at all elevations in the area. In the meteorological summer months (June-August), about 257% of the precipitation amounts still consist of snowfall at 2536 m a.s.l. At the lower rain gauge, almost all precipitation falls as rain in the meteorological summer months. There exists The two precipitation gauges show a strong elevation gradient in precipitation: at 2536 m a.s.l., precipitation amounts are about

1.9 times higher than at 1590 m a.s.l. This elevation gradient may, however, overestimate the true areal-mean gradient because the upper site may be limited representative for the Dischma catchment (*Wirz et al.*, 2011; *Grünewald and Lehning*, 2015). Furthermore, the area exhibits a climatological northwest - southeast gradient in precipitation ~~(not shown)~~(*Vögeli et al.*, 2016) .

Figures 2a and 2b show the daily temperature and precipitation amounts separated in snowfall and rainfall, for both locations with a heated rain gauge. The yearly cycle in temperature has a similar amplitude at both elevations. Maximum daily temperatures occasionally surpassed 20°C at 1590 m a.s.l. and 15°C at 2536 m a.s.l. The minimum daily temperatures reached −20°C and −25°C, respectively. Note that those low temperatures were reached after significant snowfall in the months before. Therefore, the isolating snow cover is expected to have prevented an impact of these cold days on soil freezing.

An important event in the meteorological forcing can be found in winter season 2011-2012, which was dominated by large snowfalls in December, January and February. Maximum measured snow ~~height~~ depth was higher than in the other simulated years. Cold temperatures in those months were followed by a relatively warm spring season, resulting in relatively high snowmelt rates. Also the spring of snow season 2010-2011 was relatively warm, compared to the spring of 2012-2013. None of the summer periods were outspokenly dry or wet, and precipitation occurred homogeneously distributed over time, with the exception of the dry November 2011, in which no precipitation occurred. Finally, total precipitation at WFJ in summer 2011 was similar to summer 2012, whereas the summer 2013 was rather dry in Davos.

2.2 Data

Several measurement sites are located or were temporarily installed in the vicinity of Davos. Their locations are shown in Figure 1. The sensitivity of Alpine3D simulations to input data coverage as well as specific interpolation and modelling choices is discussed in detail in *Schlögl et al.* (2016). Here we operate with a standard set-up as described below and distinguish between ~~the~~ 5 types of meteorological stations (see Table 2)~~:~~.

~~(i) IMIS stations : those stations~~ IMIS stations are permanently installed operational meteorological stations in the Swiss Alps, especially ~~focussed~~ focused on usage for avalanche warning (*Lehning et al.*, 1999). The stations measure at 7.5 m above the ground and ~~are designed for long-term operational use. For this purpose, they~~ receive regular maintenance and quality control. One exception is SLF2 in Davos-Dorf, which is used as a test station for new sensors or hardware. During the winter season 2011 and for a large part of winter season 2012, the relative humidity sensor was providing erroneous data due to a faulty test sensor. The IMIS stations provide a good spatial coverage of the common meteorological parameters, but due to limited energy availability, lack heated rain gauges to assess solid precipitation.

~~(ii) IRKIS stations: these stations were temporarily set up for this study. They are based on the IMIS design, although they are smaller than IMIS stations with aheight of 4.5 m. The IRKIS stations were additionally equipped with soil moisture sensors at 10, 30, 50, 80 and 120 cm depth. At each depth, two sensors were installed at approximately 50 cm distance. The IRKIS station SLF2 was using the IMIS station SLF2, but soil moisture sensors were installed in close vicinity. IRKIS stations report weather and soil moisture conditions at a time resolution of 10 minutes~~In the Davos area, two heated rain gauges are present, located at the SwissMetNet stations WFJ (2536 m a.s.l./2691 m a.s.l.) and Davos-Dorf (1590 m a.s.l.), operated by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). These stations thereby provide, after applying an undercatch correction, relatively accurate measurements of solid precipitation in winter, in addition to high quality measurements of common meteorological parameters. For example, these stations also provide incoming shortwave and longwave radiation using ventilated and heated sensors to prevent riming and snow covering up the sensors. At WFJ, shortwave and longwave radiation sensors located at a local mountain peak of 2691 m a.s.l. were used in this study. These sensors experience almost no shadowing from surrounding mountain peaks. The WFJ measurement site at 2536 m a.s.l. is equipped with ventilated temperature and relative humidity sensors. Moreover, several backup sensors are present, allowing for filling data gaps.

~~(iii) SensorScope stations : to improve the data quantity and the area covered by measurements,~~

The IRKIS and SensorScope stations were temporarily set up for this study. IRKIS stations are based on the IMIS design, but with a sensor height of 4.5 m. SensorScope stations (*Ingelrest et al.*, 2010) were installed in less accessible terrain ~~for a period of approximately 2-3 years~~to increase quantity and area covered by measurements. Operation of these type of stations in the harsh winter conditions appeared to be more difficult than expected and the sometimes hazardous locations of the measurement sites was hindering maintenance during the winter season. Due to several outages of the stations and broken sensors, the meteorological measurement series contain many gaps and are not used as input in this study. The IRKIS and SensorScope stations were ~~also~~ additionally equipped with soil moisture sensors at 10, 30~~and~~, 50 cm depth. At IRKIS stations and the Golf Course ~~station, sensors were additionally~~ SensorScope station, soil moisture sensors were also installed at 80 and 120 cm depth. ~~Also here~~This is schematically illustrated in Fig. 3. At each depth, two sensors, labelled "(A)" and "(B)" here, were installed at ~~each depth. In this study, we consider the soil moisture data to be useful for validation~~approximately 50 cm distance. The IRKIS station SLF2 was using the IMIS station SLF2, but soil moisture sensors were installed in close vicinity. IRKIS stations report weather and soil moisture conditions at a time resolution of 10 minutes. SensorScope stations measure at a time resolution of 1 minute, sending their data using GPRS cell phone networks.

~~(iv) SwissMetNet stations: the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) operates meteorological stations in the SwissMetNet network. In the vicinity of Davos, two SwissMetNet stations are present: at the WFJ (2536 m a.s.l.) and in Davos-Dorf (1590 m a.s.l.). They are equipped with a heated rain gauge, providing relatively accurate measurements of solid precipitation in winter, and incoming shortwave and longwave radiation sensors. At WFJ, shortwave and longwave radiation sensors located at a mountain peak of 2691 m a.s.l. were used in this study. These sensors experience almost no shadowing from surrounding mountain peaks, compared to the ones at the WFJ measurement site (see below) and could be considered more representative for the Davos area.~~

~~(v) WFJ: this measurement site serves as the main research site for the WSL Institute for Snow and Avalanche Research SLF and is focussed on snow related processes (*Marty and Meister*, 2012; *WSL Institute for Snow and Avalanche Research SLF*, 2015-09-29) . The site is equipped with an IMIS type station, as well as a heated rain gauge that is part of the SwissMetNet network. Furthermore, ventilated temperature and relative humidity sensors are present as well as incoming and reflected shortwave and incoming and outgoing longwave radiation sensors. Several backup sensors are present, allowing for filling data gaps.~~ The choice for the soil moisture measurement sites is motivated by the availability of an accessible flat area and by possibly well representing the catchment soil types. The Grossalp and Pischa stations were located in the "alpine meadow" land use class, which is 21.1% of the land use coverage (see Table 3). The Uf den Chaiseren, Dorfji and Stillberg stations are located in the "mixed forest", "bush" and "bare soil" classes, respectively, which are found in 12.9%, 7.3% and 6.0% of the Dischma catchment, respectively. The SLF2 and Golf Course stations would officially fall into the category of "settlement", but one would describe the area as "alpine meadow".

At the soil moisture measurement sites, Decagon 10HS soil moisture sensors were installed, which have a volume of influence of 1320 mL, or a volume of approximately 11x11x11 cm (*Decagon Devices*, 2014). *Mittelbach et al.* (2012) present an in-depth comparison with other types of soil moisture sensors. A few important issues related to the Decagon 10HS sensors that are relevant for this study were reported. In their study, the liquid water content values from the sensors exhibited a soil temperature dependency. The sensors were also found to hardly register values above 0.40 m^3 m^{-3} and it was concluded that the 10HS is showing a decreased sensitivity with increasing liquid water content. Consequently, the sensors are unable to follow fluctuations in wet soil conditions. For some of the sites and depths where we installed these type of sensors, the measured LWC is around or above 0.40 m^3 m^{-3}. We therefore expect a strongly reduced dynamic response in these locations. However, many of the installed sensors were recording values well below 0.40 m^3 m^{-3} and provide useful measurements. The dielectric constant of ice is much lower than for water, making the sensors mostly sensible to the liquid water content part only.

3 Methods

3.1 Simulation Setup

SNOWPACK is a one-dimensional physics based multi-layer snow cover model (*Lehning et al.*, 2002a, b), which provides the surface scheme for Alpine3D. Richards equation (*Richards*, 1931) is used to describe soil moisture dynamics and numerically solved using finite differences scheme over the model layers (elements). Water flow in snow is solved by the bucket scheme, which provides accurate snowpack runoff estimations on daily and seasonal time scales (*Wever et al.*, 2014b), and has noticeable lower computational costs for distributed simulations(in the order of a factor 2-3) than using the full Richards equation for snow. The liquid water outflow from the snowpack is prescribed as the upper boundary condition for the Richards equation for the soil , which is solved in SNOWPACK as described in (*Wever et al.*, 2014b). In snow-free conditions, the upper boundary condition is defined by rainfall, evaporation and deposition resulting from the latent heat flux. Phase changes in soil are calculated following *Wever et al.* (2015). Water retention curves in the SNOWPACK model are based on the van Genuchten model (*van Genuchten*, 1980) via predefined soil types as in the ROSETTA class average parameters (*Schaap et al.*, 2001).

To run simulations for the Dischma catchment, the Alpine3D model system is used, which describes surface processes in complex terrain by performing distributed SNOWPACK simulations (*Lehning et al.*, 2006). For describing the high spatial variability in incoming and outgoing long long- and shortwave radiation, including shadowing effects and the surface reflections of shortwave radiation, a detailed energy balance module is available (*Michlmayr et al.*, 2008). An additional module considers drifting snow (*Lehning et al.*, 2008; *Mott et al.*, 2010), including sublimation processes (*Groot Zwaaftink et al.*, 2013). These drifting snow modules are not used in this study, as the location of the measurement sites are not prone to significant drifting snow effects, except for the Grossalp station. Moreover, the calculation of the wind fields and snow drift is posing a high computational demand compared to the other modules. The different modules and the coupling strategy is described in *Lehning et al.* (2006).

The Alpine3D simulations were run for a domain of 21.5 km$\times$21.5 km with a grid cell size of 100 m$\times$100 m, giving a total size of 215×215 grid cells. The model was run in hourly time steps, providing meteorological forcing data per time step for each pixel by interpolating from the meteorological stations in and just outside the Davos area using the MeteoIO library (*Bavay and Egger*, 2014). Per hourly time step, 4 SNOWPACK time steps are executed at 15 min. resolution.

~~The~~ At each Alpine3D model time step, the precipitation measurements from the heated rain gauges in Davos and WFJ were interpolated over the grid by using the elevation gradient from the measurements. The commonly used temperature threshold in the SNOWPACK model of 1.2 °C was used to separate precipitation into rain and snowfall. Air temperature, relative humidity and wind speed were also interpolated over the grid, using the station data as indicated in Table 2 and applying ~~IDW~~ inverse distance weighting interpolation with lapse rates calculated from the available data. Only IMIS stations were used for spatial interpolations, except for the radiation components. Incoming longwave radiation was interpolated using a lapse rate between both SwissMetNet stations providing radiation. Shortwave radiation is provided by the radiation module, using the measurements from WFJ. The radiation balance is closed by the SNOWPACK simulations at each grid points, when SNOWPACK calculates the surface temperature and surface albedo.

Two important components to initialise Alpine3D simulations are the digital elevation model (DEM) ~~for~~ and distributed soil information. For the Davos area, the DEM is provided by the Swiss Federal Office of Topography (swisstopo). ~~Also the soil has to be initialised for each pixel, although limited information is available. We based soil properties~~ Soil properties were based on the land use classification, as provided by swisstopo (*Zappa et al.*, 2003). Table 3 lists the land use classes, the percentage of areal coverage in the simulated area and the soil ~~initializations~~properties. Pixels that were defined as glacier, ice, firn, road, settlements, rivers and lakes (6%) were initialised in a state that represents the land use class. Other vegetation free areas are classified as rocky surface. This class is assigned to 29% of the pixels and consist for a large part of ground moraine and scree slopes, whereas solid rock and rock walls are sparse in the Davos area. The rocky surface pixels were initialised uniformly with loamy sand. This is based on observations when installing soil temperature sensors at the WFJ, which is located in the rock class and for which plausible simulations were obtained using this soil class (*Wever et al.*, 2015). All other pixels (65%), including forests, meadows, pasture, bare soil, and occasional pixels that are defined as agricultural use were initialised using an upper layer of 60 cm consisting of silt loam and a lower layer of 240 cm consisting of sandy loam. This choice is based on observations when installing the soil moisture sensors at the IRKIS and SensorScope stations. The soil permeability classification provided by the Swiss Federal Office for Agriculture (FOAG) shows generally high permeability in the area surrounding Davos, which confirms the choice for soil types with no clay content. To determine thermal properties of the soil, literature values were taken (Table 4). For thermal conductivity, a wide range of values is reported and a strong dependence with water content is present. We used values corresponding to typical soil saturation values, based on work by *Ochsner et al.* (2001) and *Bachmann et al.* (2001). The skeleton fraction of the soil is largely unknown, and altough it may impact the soil hydraulic properties significantly (*Brakensiek and Rawls*, 1994) and thereby soil moisture and streamflow simulations

(*Rössler and Löffler*, 2010) , the SNOWPACK model currently does not support pedotransfer functions that take the skeleton fraction into account, and hence, it was neglected in our simulations.

A soil depth of 3 m was simulated, subdivided into 23 layers, as illustrated in Fig. 3. The layer spacing was 2 cm near the surface, increasing to ~~40~~25 cm at 3 m depth. The densely spaced surface layers are necessary to describe the large gradients of temperature and moisture occurring in this region. The lower boundary condition at 3 m depth was set as a water table condition for the liquid water flow and as a constant upward geothermal heat flux of 0.06 W m^{-2} for the heat equation.

For the simulations, atmospheric stability was taking into account when calculating the turbulent heat fluxes, using the modified Stearns correction ~~(*Schlögl et al.*, 2017)~~ (*Schlögl et al.*, 2017) . The roughness length during the presence of a snow cover was defined to be 0.015 m below 1900 m a.s.l. and 0.002 m otherwise. This division is based on the generally rougher terrain below 1900 m, due to the presence of trees or large bushes, whereas above 1900 m, mainly meadows and scree fields are present. When pixels are snow free, they were assigned a roughness length of 0.02 m.

Alpine3D has recently been extended with MPI support, allowing for the parallelisation of the distributed SNOWPACK and energy balance simulations. Using 36 CPU cores from a HPC system consisting of in total 32 compute nodes with two 6-core AMD Opteron 2439, 2.8 GHz processors per compute node, the computation took on average 14 hours wall clock time for a single year, mainly depending on ~~snow height~~ the snow depth in the winter season~~, on a computer cluster from 2008.~~ .

3.2 Analysis

The soil moisture measurements series were first cleaned from erroneous data, like negative values, or data from broken sensors after visual inspection of the time series. Then, data was aggregated to hourly and daily time scales by calculating average soil moisture contents over the respective time spans. From the simulations, the modelled soil moisture values were extracted for each depth at which ~~also~~ measurements were taken. The output resolution was 1 hour and ~~also here,~~ daily values were calculated by averaging the hourly values.

As the area of Davos is dominated by snowfall in winter, a separation is made for yearly, summer and winter periods. The summer months are defined as the period from June through October. At the elevation of the soil moisture stations, snowfall episodes are almost absent in these months and the winter snow cover has melted completely by the beginning of June. The winter months are defined as the period from November through May, when a snow cover is present. Note that typically, the snow cover melts away in April or May at the stations and in those months, the soil moisture is expected to be strongly influenced by the snowmelt from the snowpack.

The streamflow from the Dischmabach is calculated using a ~~streamflow model that uses~~ spatially explicit and semi-distributed hydrologic response model that casts the soil moisture dynamics in a travel time distribution ~~approach, as outlined in *Comola et al.* (2015b) a described in detail in *Gallice et al.* (2016b) . In this study, three inputs for the streamflow model are defined by soil water fluxes in 55 sub-catchments, taking the flux in~~ framework (*Comola et al.*, 2015b; *Gallice et al.*, 2016a) . Specifically, the model simulates hydrologic transport within sub-catchment soil compartments and stream network, identified through geomorphological analysis of the digital elevation model (*Tarboton*, 1997) . An upper soil compartment is recharged by a water flux provided by the surface scheme of the Alpine3D model. Part of the outflow from the upper soil compartment generates interflow, which represents the fast hydrologic response. The remaining part recharges a lower soil compartment, where the slow groundwater flow in generated. However, it is a-priori not clear where to draw the boundary between the surface scheme and the hydrologic response model. To investigate this, we tested 3 scenarios by using the soil water flux at 2, 30 ~~or~~ and 60 cm depth ~~, respectively~~(see Fig. 3). This approach allows the Alpine3D model to run with a thick soil layer (3 m), easing the choice of lower boundary condition for the soil (geothermal heat flux and a water table). The 2 cm flux represents a case where almost all water input into the soil from both ~~snow melt~~ snowmelt as well as rainfall is directly routed using the ~~streamflow~~ hydrologic response model, while at the same time ensuring that evaporation is taken into account. It basically represents the case where soil is neglected for the discharge simulations. The simulations using the flux at 30 or 60 cm depth are performed to verify the sensitivity of the ~~streamflow~~ hydrologic response model to the thickness of the soil layers used in Alpine3D.

~~The travel time distribution approach separates the soil in an upper and lower compartment, where the upper one represents the fast response and the lower one the slow response . The method has~~ The water flux at all grid points whose centerpoint is inside the polygons of the 55 sub-catchments is summed and provided to the hydrologic response model. The sub-catchments are determined by analyzing the digital elevation model (*Comola et al.*, 2015b) .

It is noteworthy that the hydrological model is parsimonious in terms of calibration parameters, owing to the explicit analysis of the catchment's geomorphological complexity and the physically-based simulation of surface processes provided by alpine3D. In particular, the two compartments and the recharge rate in the travel time distribution approach of the hydrologic response model gives three parameters that require calibration: the average travel time of the upper and lower soil compartment (day) and the maximum recharge rate of the lower compartment from the upper compartment (mm day^{-1}). Here, all three approaches which define the input for the ~~streamflow~~ hydrologic response model are independently calibrated with measured discharge from October 2004 to September 2009, using Monte-Carlo simulations with 5000 repetitions. The best combination of coefficients was determined based on the highest Nash-Sutcliffe Model Efficiency (NSE) coefficient (*Nash and Sutcliffe*, 1970). The period from October 2009 - September 2014 was used for validation.

To analyse the effect of soil moisture on streamflow generation, we calculated the average soil saturation in the top 40 cm of all pixels inside the Dischma catchment. This is the approximate depth which is captured by the volume of influence of the soil moisture sensors at 10 and 30 cm depths. Furthermore, we defined rainfall events as events for which the moving 12 hour sum exceeds 10 mm. The time series for the event selection was determined by taking the average value of both heated rain gauges. The start of ~~the~~ an event is defined as the first time step for which precipitation is present, and the end was determined when the cumulative 12 hour sum fell below 3 mm, after first reaching 10 mm. A similar approach was done for snowpack runoff from the model, where snowpack runoff is considered analogue to rainfall. With this procedure, in total 168 rainfall events and 301 snowpack runoff events were selected (i.e, on average 16.8 and 30.1 events per year, respectively). The average duration of an event is 21.8 hrs (rainfall) and 20.9 hrs (snowpack runoff). On average, there are 6.8 days in between rainfall events, excluding the winter season. There are 1.3 days in between snowpack runoff events, excluding the summer season, showing that these events are concentrated in the spring season.

4 Results and Discussion

4.1 Snow Height

Figure 4 shows measured and simulated snow depth by Alpine3D for stations SLF2, Uf den Chaiseren and Grossalp. In snow ~~season~~ seasons 2011 and 2013, the snow ~~height~~ depth in the Alpine3D simulations is satisfyingly reproduced at both SLF2 and Uf den Chaiseren. The snow ~~height~~ depth at Grossalp is overestimated in all snow seasons. This is explained by the fact that this particular site is relatively sensitive to wind eroding snow from the surface. The snow depth in snow season 2012 is overestimated at all stations, which is related to unusual meteorological circumstances of large snowfalls accompanied by strong winds, which lead to an overestimation of precipitation as measured by the heated rain gauge (also discussed in *Wever et al.* (2015)). Nevertheless, the snow cover development at those three sites is overall satisfactorily simulated in Alpine3D for providing an upper boundary for the soil. In the summer months, grass growth below the sensor is visible as an increase in snow depth with a highly noisy signal. Mowing activity is indicated by sudden decreases in snow depth.

4.2 Soil Moisture~~Measurements and Simulations~~

Figures 5 and 6 show measured and simulated soil moisture time series at all depths for 2 of the 7 stations in the area of Davos. Similar figures for the other 5 stations can be found in the Online Supplement. Temporal variations in soil moisture in the area of Davos are clearly dominated by winter periods, in which the presence of a snow cover reduces or inhibits water influx at the top of the soil for several months. This phase is followed by the snowmelt phase in spring, when liquid water draining from the snowpack is providing liquid water again to the soil. This is illustrated by way of example in Figures 7a,b for the SLF2 measurement site for the snowmelt season 2011. The onset of wetting of the soil due to snowmelt is well predicted. It illustrates that using the bucket scheme for water flow in snow is justified on daily and seasonal time scales (*Wever et al.*, 2014b) . The diurnal cycle of snowmelt is also visible as a diurnal cycle on soil moisture levels, well reproduced by the simulations. The summer months are generally snow-free (Figures 5 and 6), and soil moisture measurements show fluctuations on short time scales of a few days, related to rainfall and evaporation. A detailed example hereof is shown in Figures 7c,d for the snow-free month June 2011 for the SLF2 measurement site. Particularly large rainfall events are strongly influencing soil moisture, compared to small ones. Generally, the simulated soil moisture reacts more strongly to incoming rainwater and is also showing stronger fluctuations on sub-daily time scales than in the measurements.

At several stations, soil freezing is indicated by the soil moisture sensors. Significant soil freezing was occurring in snow season 2011, as clearly ~~indicated~~ visible at SLF2 (Figure 5) and Uf den Chaiseren (Figure 6), as well as Stillberg (see Figure S2 in the Online Supplement). The soil freezing was promoted by a long period with no snow or only a shallow snow cover, allowing the soil to cool. For the stations SLF2 and Uf den Chaiseren, the onset of the freezing is rather well predicted in the Alpine3D simulations. At most stations, the soil freezing front does not seem to reach the sensor at 30 cm depth. Only at Uf den Chaiseren and Stillberg, the minimum soil moisture at this depth in this particular snow season is slightly lower than in the other snow seasons, which may be indicative of slight soil freezing here.

The simulations show soil freezing at 10 cm depth in all snow seasons at most stations, for at least a short period of time, which is more soil freezing than captured in the soil moisture measurements. The overestimation of soil freezing in the simulations may be partly related to neglecting the presence of vegetation at the measurement sites. All sites are covered by grass, or rough pasture and bushes. To account for the insulating effects of the canopy, some soil freezing schemes consider the presence of a canopy when calculating soil phase changes (e.g., *Giard and Bazile* (2000)). Due to the lack of possible validation data, we did not implement this. Furthermore, the amount of soil freezing is also dependent on the amount of liquid water available. At stations Grossalp and Golf Course, the soil is wetter than simulated, which would require a higher heat flow out of the soil before freezing may start ~~. Finally,~~ and uncertainties in soil thermal properties may also play a role here. Finally, the neglectance of the skeleton fraction in our simulations could lead to an overestimation of hydraulic conductivity and introduce a negative bias in soil moisture (*Brakensiek and Rawls*, 1994) . However, as discussed by *Rössler and Löffler* (2010) , the spatial variability of the skeleton fraction is generally unknown. For example, for some sites we get an adequate soil moisture simulation without considering the skeleton fraction, whereas for other sites the simulations are showing less agreement with measurements. This would then only allow for an ad-hoc modification of the skeleton fraction, as we cannot separate well enough between the soil moisture sites based on available information (land use and soil permeability).

The relatively dry summer of 2013, most pronounced at low elevations as indicated by the difference in summer precipitation from both heated rain gauges (Table 1), is clearly visible in the simulations by a drop in soil moisture at all depths, reaching the lowest values of the entire measurement period. Unfortunately, soil moisture sensors had stopped working at many stations by this time, but at the site SLF2 and Stillberg, a good correspondence is found in the 10 cm measured and simulated soil moisture series. At the Uf den Chaiseren site, the recession curve in this summer is particularly present at the sensors at 50 and 80 cm depth, and absent in the highest sensor.

Some features are found that likely relate to hydrological processes that are not simulated in the Alpine3D model. For example, at the Uf den Chaiseren site, the soil moisture at 80 and 120 cm is clearly influenced by a rising water table in the late snowmelt season. This is indicated by the sudden rise to high values of saturation, remaining constant afterwards (Figure 6). The soil at the Golf Course station appeared to be close to saturation for extended periods of time (see Figure S5 in the Online Supplement), which is congruent with observations when installing the sensors. The location of these two stations close to the Dischmabach (Uf den Chaiseren) and Landwasser river (Golf Course), which are partly fed by meltwater from the glacierised area, supports this interpretation. The apparent interaction with ~~ground water~~ groundwater levels at these stations is not considered in the simulations, as the ~~ground water~~ groundwater table is fixed at the lower boundary of the soil column in the model domain. Similarly, the measurements at 10 and 30 cm depth at the Grossalp station (see Figure ~~S3~~ S1 in the Online Supplement) also indicate high saturation of the soil, for which no source of water could be found. Due to the insensitivity of the soil moisture sensors in wet soil conditions, discrepancies between simulations and measurements as found at the sites Grossalp and Golf Course can only be assessed qualitatively and provide insights on the limitations of the measurements and simulations. In contrast with the other measurement sites, the soil moisture sensors at the Pischa station show a very dynamic response (see Figure S3 in the Online Supplement). We cannot exclude that during the installation of the sensors, the soil was disturbed in such a way that afterwards, efficient preferential flow paths occurred along the boundaries of the displaced soil layers.

Figure 8 shows the r^2 values between daily averaged measured and simulated soil moisture values for the various depths for the full period and for the summer months only. Here, soil moisture was taken as the sum of ice and water to compensate for the overestimation of soil freezing. Only the values for the sensor with the highest r^2 value of the two sensors per depth are shown. Generally, the highest r^2 is achieved for 30 cm and 50 cm depth. Closer to the surface, the overestimation in soil freezing, as well as the generally large gradients in soil moisture reduces the agreement. For deeper layers, ~~ground water~~ groundwater dynamics as discussed above, which is not considered by the model, could be identified as contributing to lower model agreement. Results for the summer months show higher r^2 values for the 10 cm and 30 cm soil moisture sensors. These layers are particularly influenced by rainfall in these months, for which timing is more accurate in the model than the onset of snowpack runoff which determines soil moisture fluctuations in large periods of the year. For deeper layers, the model performance is comparable to the performance for the full year.

The r^2 values indicate that for many sites, some of the variability in soil moisture is adequately captured. This spatially varying reproducibility of soil moisture is a typical result for physics-based soil models applied in alpine terrain, as for example found also by *Rössler and Löffler* (2010); *Kumar et al.* (2013); *Pasolli et al.* (2013) . Better agreement (r^2 between 0.8 and 0.95) may be achieved by calibrating the water retention curves, or related soil parameters, to the soil moisture measurements (*Gurtz et al.*, 2003; *Brocca et al.*, 2013; *Pellet et al.*, 2016) , although the lack of distributed soil information would make a distribution of this calibration over the model domain difficult and not very meaningful.

4.3 Streamflow

Figure 9 shows the measured and simulated streamflow at the outlet of the Dischmabach in the Dischma catchment. The winter periods are clearly identifiable by the hydrograph falling back to baseflow. Furthermore, high discharge is particularly found in spring, during the snowmelt season which typically lasts from April to June in the Dischma catchment (*Griessinger et al.*, 2016). During the summer period, streamflow slowly decreases, interrupted regularly with peaks in streamflow due to rainfall. These general discharge patterns are well captured in the simulations, regardless of the depth below the surface where the liquid water flux is routed to the runoff model. However, the fast dynamics on daily time scales in the Dischmabach streamflow is underestimated in the simulations, particularly when using the flux at 60 cm depth, for which the deep soil layer apparently has a too strong dampening of the incoming water in order to reproduce daily streamflow behaviour. Improvements in reproducing the dynamic response on short time scales in the simulations could probably be obtained by including lateral water transport in Alpine3D, which would allow ~~us~~ to account for the fast surface runoff, which for example takes place over highly saturated or impervious soils.

The three simulations of streamflow differ in the ~~water input~~ depth at which the soil water flux was used for the travel time distribution approach. Figure 10 displays the NSE coefficients per year as well as the average for ~~the three virtual lysimeters defined in the model~~these three depths based on daily discharge. For the full validation period, the NSE ~~coefficient~~ coefficients for either the 2 cm, 30 cm or 60 cm flux ~~provide~~ show very similar scores of around 0.8. When the calculation of NSE coefficients is limited to the snow melt season (April-June) or the summer season (June-October) only, differences become more pronounced. Highest NSE coefficient is achieved with the flux at 30 cm depth. The results suggests suggest that the updated soil module of SNOWPACK is contributing to a better enabling a good prediction of streamflow in the summer months. Interpreting the flux at 2 cm depth as the effect of routing snowpack runoff and rainfall minus evaporation to the hydrologic response model, it shows that including 30 cm of soil layers improves the discharge simulation.

We hypothesize that in the Dischma catchment, the snow melt season is providing large water fluxes from the snow to the soil, compared to the soil water dynamics, making it the dominant factor in predicting stream flow. In the summer months, however, the predisposition of the soil is also an important factor, thus neglecting the soil layers almost completely, by routing the 2 cm flux to the runoff model, is reducing the model efficiency. The improved results of the 30 cm soil simulations as opposed to using much deeper soils suggests that the temporal dynamics of near-surface water fluxes exert a relevant control on the hydrologic response of these Alpine catchments.

4.4 Predisposition from Soil Moisture

The soil moisture state of the Dischma catchment is summarized as the basin wide average saturation in the upper 40 cm of the soil at the onset of a rainfall or snowpack runoff event. The water flux at this depth provided the highest skill in reproducing observed discharge after applying the streamflow hydrologic response model. Figure 11a shows the runoff coefficient (i.e., the ratio of rainfall to discharge) for the cumulative rainfall and measured discharge from the Dischma catchment as a function of catchment average soil saturation. The figure illustrates that the reduced storage capacity in wetter soils leads indeed to more of the precipitation water being routed to discharge and vice versa. In Figure 11b, it is illustrated that similar behaviour is also captured in the simulated discharge. For the Dischma catchment, we found that not only the total event runoff coefficient is determined by the soil moisture state, but also the peak runoff coefficient, defined as the ratio of the maximum peak in precipitation over the maximum, not necessarily simultaneous, discharge peak (see Fig. 11c for measured discharge). This relationship is again also found for the simulated discharge (Fig. 11d). Although the initial soil moisture is impacting the runoff coefficient for both the cumulative amounts as well as the peak values, the time lag between a peak in rainfall and measured discharge is not dependent on the soil moisture conditions (Fig. 11e). Also this result is reproduced by the simulated discharge (see Fig. 11f). All r^2 values reported in Fig. 11 test significant at the 95 % confidence level.

When the catchment is snow-covered, the melt water outflow from the snowpack can be considered analoguous to rainfall in summer. A similar analysis as presented in Fig. 11 is performed using snowpack runoff (see Fig. 12). Also here we find that the soil moisture state at the onset of snowpack runoff events influences the streamflow discharge. Similar to rainfall events, the soil moisture state influences the ratio of the cumulative measured event discharge over cumulative snowpack runoff (Fig. 12a) as well as the peak ratio (Fig. 12c). The correlation coefficients are higher for the snowpack runoff events than for the rainfall events. This higher correlation coefficient for snowpack runoff than rainfall is also found for the runoff coefficients using simulated discharge (Fig. 12b and d). Similar to rainfall events, the time delay between peaks in snowpack runoff and discharge is independent of the initial soil moisture state.

The results show In line with previous studies (*Maurer and Lettenmaier*, 2003; *Berg and Mulroy*, 2006; *Seyfried et al.*, 2009; *Koster et a* the results confirm that the simulations of the soil moisture state contribute to the understanding of how rainfall and snowpack runoff input in the hydrological system is influencing discharge from the catchment. Based on measurementmeasurements, this relationship was found for alpine catchments for summer rainfall (*Penna et al.*, 2011). However, we show that this effect is reproduced in both measured runoff coefficients as well as simulated ones and also exists for snowpack runoff. The relationship between the initial soil moisture state and runoff coefficients is similar for observed and simulated discharge as well as for rainfall or snowpack runoff events. These results suggest that simulations of soil moisture in snow dominated catchments using the Alpine3D model combined with the hydrologic response model are able to provide understanding of the discharge behaviour from the catchmentand is a crucial factor . Assessing the soil moisture state through such simulations may then help in assessing flood risksrisk.

5 Conclusions

Simulations with the spatially explicit Alpine3D model were performed for the area of Davos. The recent update of the soil module of SNOWPACK, which is used in provides the surface scheme for the Alpine3D model, shows satisfactory results for simulating soil moisture at 7 stations with soil moisture measurements in the area around Davos. The comparison included measurements at 10, 30 and 50 cm depths, and at 4 stations also at 80 and 120 cm depths. Correlation coefficients show that generally, the temporal variability is adequately captured. However, often a bias between simulated and measured soil moisture was found, as well as between two sensors at the same site and the same depth.

In winter, the amount of soil freezing was higher in the Alpine3D simulations than indicated by the measurements. The soil moisture measurements also provide some clear indications of fluctuations in ground water groundwater level above 120 cm depth. Ground water dynamics is not taken into account in the model, as the water table was fixed to the lower boundary of the soil column in the model domain. Also uncertainties in soil properties and measurements likely play an important role in discrepancies between simulations and measurements.

Relating the water flux at 30 cm depth in the soil to streamflow in the Dischma catchment using a travel time distribution approach provided a higher agreement with observed streamflow than directly using the water flux at the top of the soil or at 60 cm depth. Event This may be a result of the (on average) relatively shallow layer of soil, which influence the near-surface water dynamics in Alpine terrain and is important to consider in the simulations. The analysis of events with high rainfall or snowpack runoff with return periods of approximately 15 and 30 times per year, respectively, showed that event and peak runoff coefficients using measured discharge were found to correlate with the simulated soil moisture state at the onset of rainfall or snowpack runoff the events. Runoff coefficients for both the event as well as the peak were higher when the soil saturation was higher and vice versa. For snowpack runoff, this This effect was found to be stronger for snowpack runoff than for rainfall. Also runoff coefficients using simulated discharge exhibited a stronger relationship with initial soil saturation. The fact that a the simulated soil moisture state could be related to the effect on measured streamflow, indicates that soil module of the SNOWPACK model in the Alpine3D model framework can successfully assess the predisposition of the catchment for flood risk assessments.

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Table 1. Yearly, winter months (DJF) and summer months (JJA) precipitation sums from heated rain gauges in the area around Davos. In brackets the percentage that falls as snow, based on measured air temperature below 1.2°C calculated on half-hourly measurements. The last line lists the average over the 10 year period 2005-2014.

Year	Precipitation year mm (% snow)	Precipitation DJF mm (% snow)	Precipitation JJA mm (% snow)	Precipitation year mm (% snow)	Precipitation DJF mm (% snow)	Precipitation JJA mm (% snow)
	Davos (1590 m)			Weissfluhjoch (2540 m)		
2011	~~999~~ 1062 (~~18~~21%)	~~129~~ 145 (~~76~~77%)	~~410~~ 409 (0%)	~~1767~~ 1368 (~~65~~47%)	~~276~~ 184 (~~100~~95%)	~~536~~ 491 (~~24~~7%)
2012	~~1419~~ 1633 (~~36~~42%)	~~547~~ 717 (~~81~~83%)	516 (0%)	~~2801~~ 2337 (~~73~~63%)	~~1372~~ 1096 (100%)	~~755~~ 722 (~~22~~6%)
2013	~~1028~~ 1085 (~~24~~28%)	~~223~~ 261 (~~81~~82%)	~~297~~ 277 (0%)	~~2002~~ 1590 (~~66~~48%)	~~565~~ 400 (~~100~~98%)	~~538~~ 476 (~~39~~11%)
2005-2014	1168 (28%)	302 (76%)	453 (0%)	1659 (52%)	440 (97%)	648 (7%)

Table 2. List of stations and measured quantities at the stations that are used in this study. (X): measured and used in this study, (-): not measured, (u): unventilated (temperature) or unheated (rain gauge), (v): ventilated, (h): heated rain gauge. VWC shallow denotes soil moisture sensors at 10, 30 and 50 cm depth, VWC deep denotes soil moisture sensors at 80 and 120 cm depth.

Station name	Type	Elevation (m)	TA	RH	TSS	Wind speed	Snow ~~height~~ depth	Rain gauge	ISWR	RSWR	ILWR	VWC shallow	VWC deep
Bärentalli	IMIS	2560	u	u	X	X	X	u	-	X	X	-	-
Flüelapass	IMIS	2390	u	u	X	X	X	u	-	X	X	-	-
Frauentobel	IMIS	2330	u	u	X	X	X	u	-	X	X	-	-
Gatschiefer	IMIS	2310	u	u	X	X	X	u	-	X	X	-	-
Grüniberg	IMIS	2300	u	u	X	X	X	u	-	X	X	-	-
Madrisa	IMIS	2140	u	u	X	X	X	-	-	X	X	-	-
SLF	IMIS	1560	u	u	X	X	X	-	-	X	X	X	X
Grossalp	IRKIS	1960	v	v	X	X	X	u	-	X	X	X	X
Uf den Chaiseren	IRKIS	1590	v	v	X	X	X	u	-	X	X	X	X
Dorfji	SENS[1]	1813	-	-	-	-	-	-	-	-	-	X	-
Golf Course	SENS[1]	1537	-	-	-	-	-	-	-	-	-	X	X
Pischa	SENS[1]	2156	-	-	-	-	-	-	-	-	-	X	-
Stillberg	SENS[1]	2218	-	-	-	-	-	-	-	-	-	X	-
Davos	SMN[2]	1596	-	-	-	-	-	h	X	-	X	-	-
Weissfluhjoch	COMBI[3]	2536	v	v	X	X	X	h	X	X	X	-	-

[1] SENS: Sensorscope station.

[2] SMN: SwissMetNet station (MeteoSwiss).

[3] COMBI: Combination of IMIS, SwissMetNet and other instrumentation.

Table 3. Land use classes and corresponding soil initialisations.

Land use class	Area (%)	Soil 0-60 cm	Soil 60-300 cm
Rock	29.2	loamy sand	loamy sand
Alpine meadow	21.1	silt loam	sandy loam
Rough pasture	15.5	silt loam	sandy loam
Mixed forest	12.9	silt loam	sandy loam
Bush	7.3	silt loam	sandy loam
Bare soil	6.0	silt loam	sandy loam
Glacier, ice, firn	3.2	ice	ice
Pasture	2.6	silt loam	sandy loam
Water	1.0	water	water
Settlements	0.8	rock	rock
Road	0.5	rock	rock
Wetland	0.1	silt loam	sandy loam
Vegetables	<0.1	silt loam	sandy loam

Table 4. List of parameters for the soil types for saturated water content (θ_s), residual water content (θ_r), the van Genuchten parameters α and n, the saturated hydraulic conductivity (K_{sat} $^{(1)}$), the density of soil particles (ρ_p), the thermal conductivity of soil particles (λ) and the specific heat of soil particles (c_p).

Name	θ_s $^{(1)}$ (m^3 m^{-3})	θ_r $^{(1)}$ (m^3 m^{-3})	α $^{(1)}$ (m^{-1})	n $^{(1)}$ (-)	K_{sat} $^{(1)}$ (m s^{-1})	ρ_p (kg m^{-3})	λ W m^{-1} s^{-1}	c_p J kg^{-1} K^{-1}
Loamy sand	0.390	0.049	3.475	1.746	$1.22 \cdot 10^{-5}$	2600 $^{(2)}$	0.9 $^{(2)}$	1000 $^{(2)}$
Sandy loam	0.387	0.039	2.667	1.449	$4.43 \cdot 10^{-6}$	2600 $^{(3)}$	2.5 $^{(3)}$	801 $^{(3)}$
Silt loam	0.439	0.065	0.506	1.663	$2.11 \cdot 10^{-6}$	2700 $^{(3)}$	2.5 $^{(3)}$	871 $^{(3)}$

[1] ROSETTA class average parameters (*Schaap et al.*, 2001).
[2] *Bachmann et al.* (2001).
[3] *Ochsner et al.* (2001).

Land use classes and corresponding soil initialisations.Land use class Area () Soil 0-60 cm Soil 60-300 cm Rock 29.2 loamy sand loamy sand Alpine meadow 21.1 silt loam sandy loam Rough pasture 15.5 silt loam sandy loam Mixed forest 12.9 silt loam sandy loam Bush 7.3 silt loam sandy loam Bare soil 6.0 silt loam sandy loam Glacier, ice, firn 3.2 ice ice Pasture 2.6 silt loam sandy loam Water 1.0 water water Settlements 0.8 rock rock Road 0.5 rock rock Wetland 0.1 silt loam sandy loam Vegetables <0.1 silt loam sandy loam

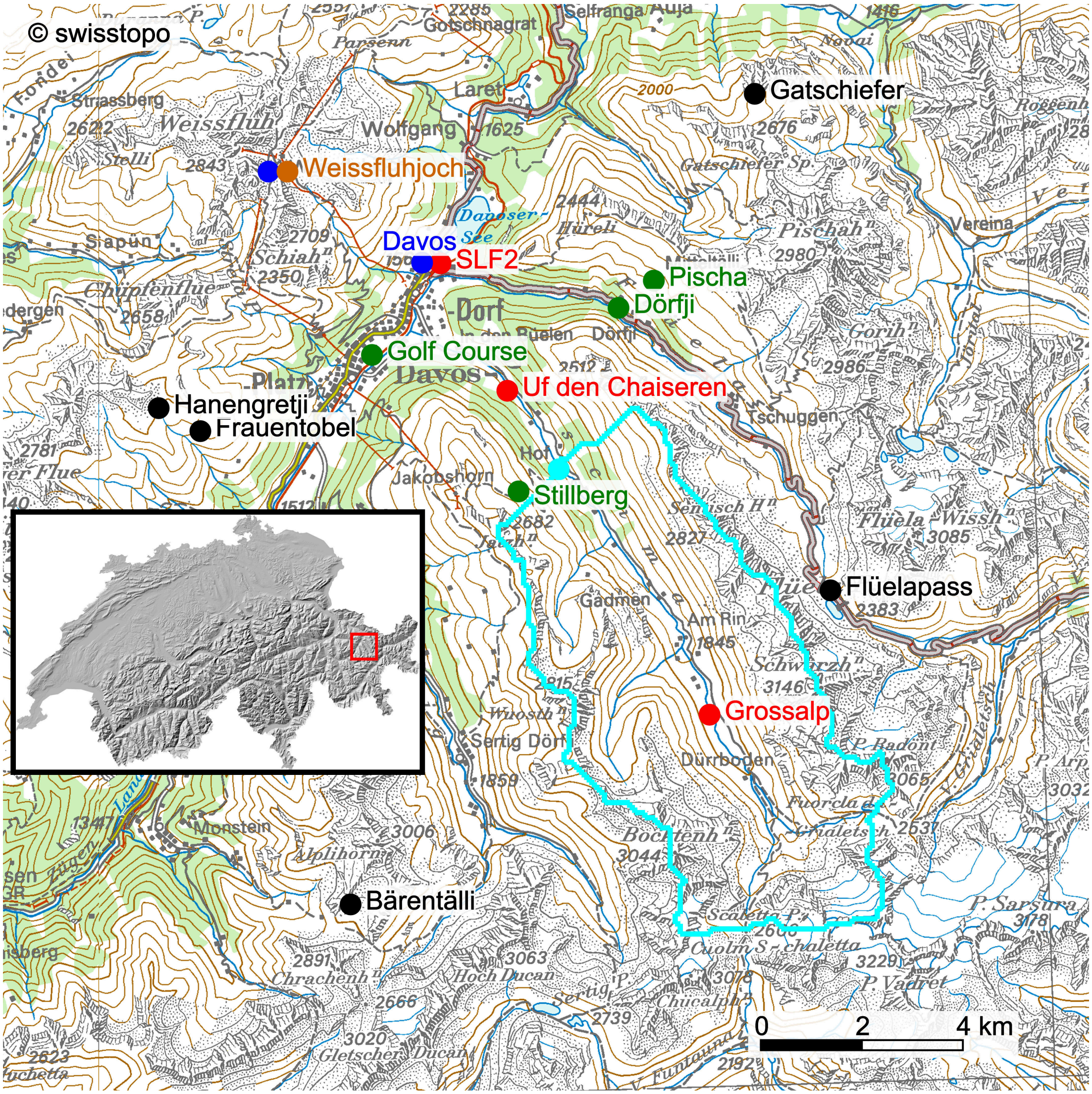
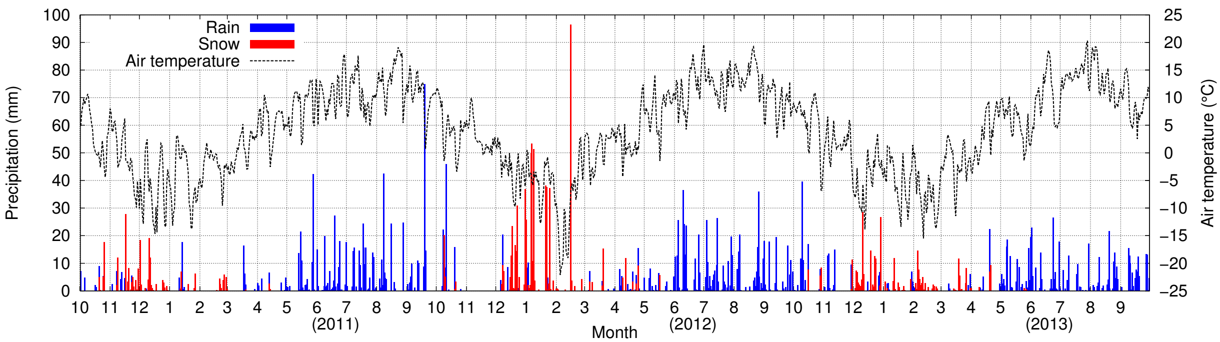
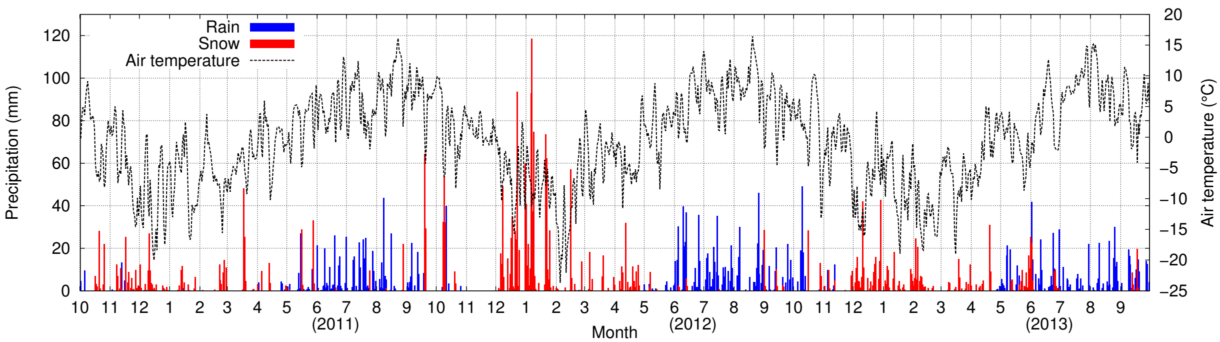


Figure 1. Topographical map of the simulated domain, showing the locations of the stations. IMIS stations are shown in black, IRKIS stations in red, SensorScope stations in green, SwissMetNet stations in blue and Weissfluhjoch in brown. The Dischma catchment and the gauging station measuring streamflow in the Dischmabach at the outlet of the Dischma catchment are shown in cyan. The inset shows the location of the simulation domain (red square) in Switzerland. Maps reproduced by permission of swisstopo (JA100118).



(a)



(b)

Figure 2. Daily rain and snowfall amounts and daily average air temperature for Davos, 1590 m (a) and Weissfluhjoch, 2536 m a.s.l. (b). The separation of precipitation in rain and snowfall is done for half-hourly measurements, using an air temperature threshold of 1.2 °C.

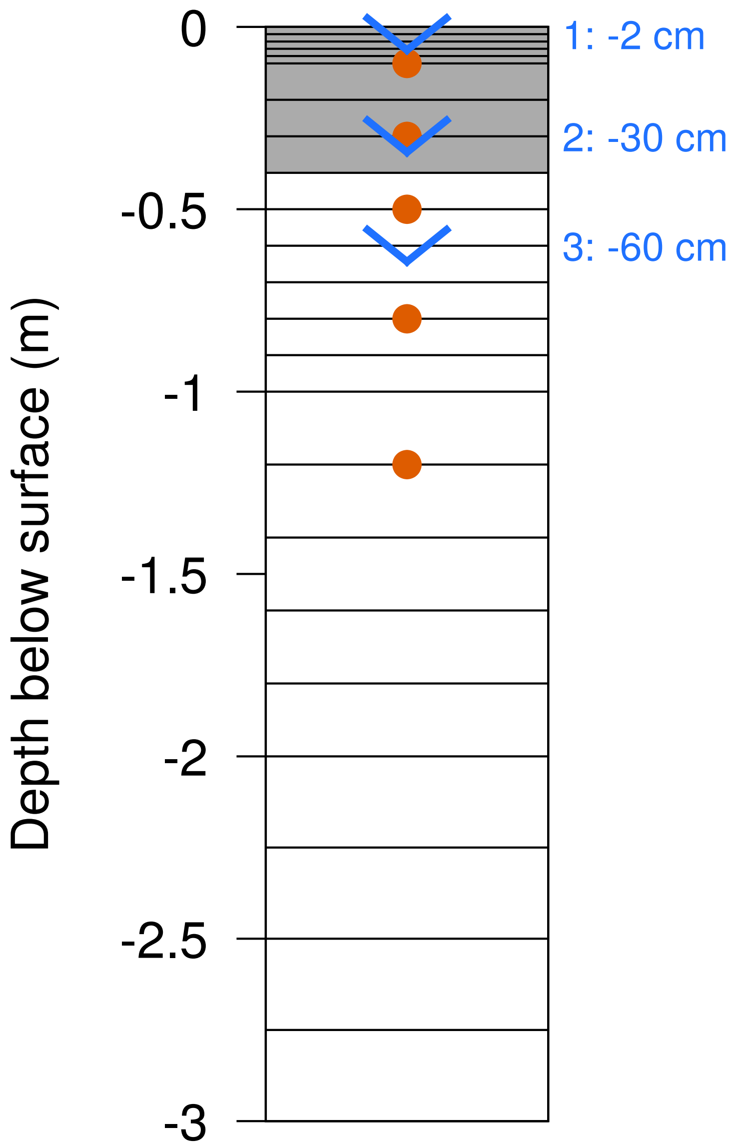


Figure 3. Soil layering as used in the Alpine3D model. The three water fluxes used to drive the hydrologic response model are shown in blue arrows. The soil moisture measurements are indicated by brown circles. The grey area is denoting the part of the soil where the initial soil saturation at the onset of rainfall or snowmelt events was determined.

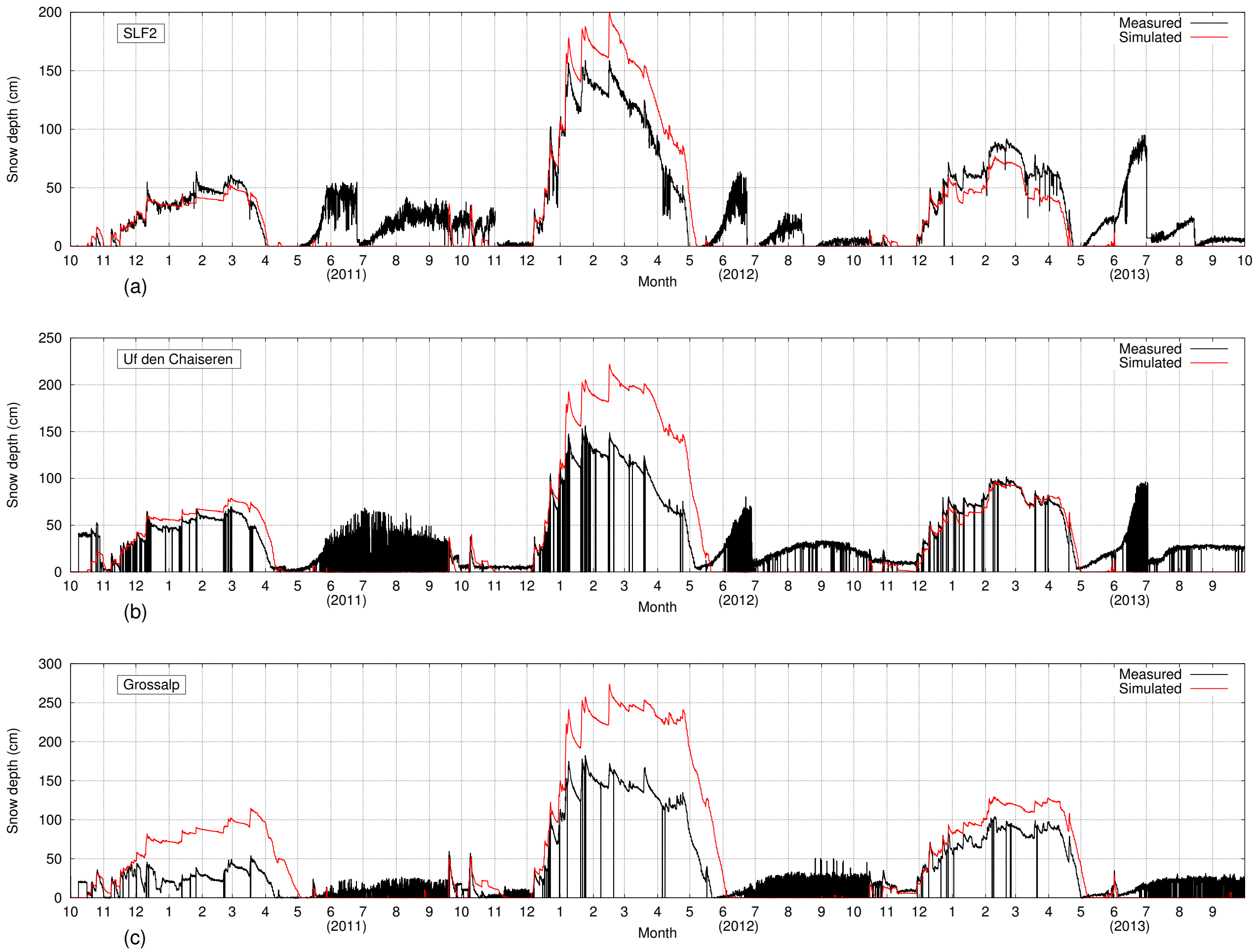


Figure 4. Measured and simulated snow depth for stations SLF2 (a), Uf den Chaiseren (b) and Grossalp (c) for the period October 2010 to October 2013. Noisy signals in the summer months arise from grass growth below the sensor.

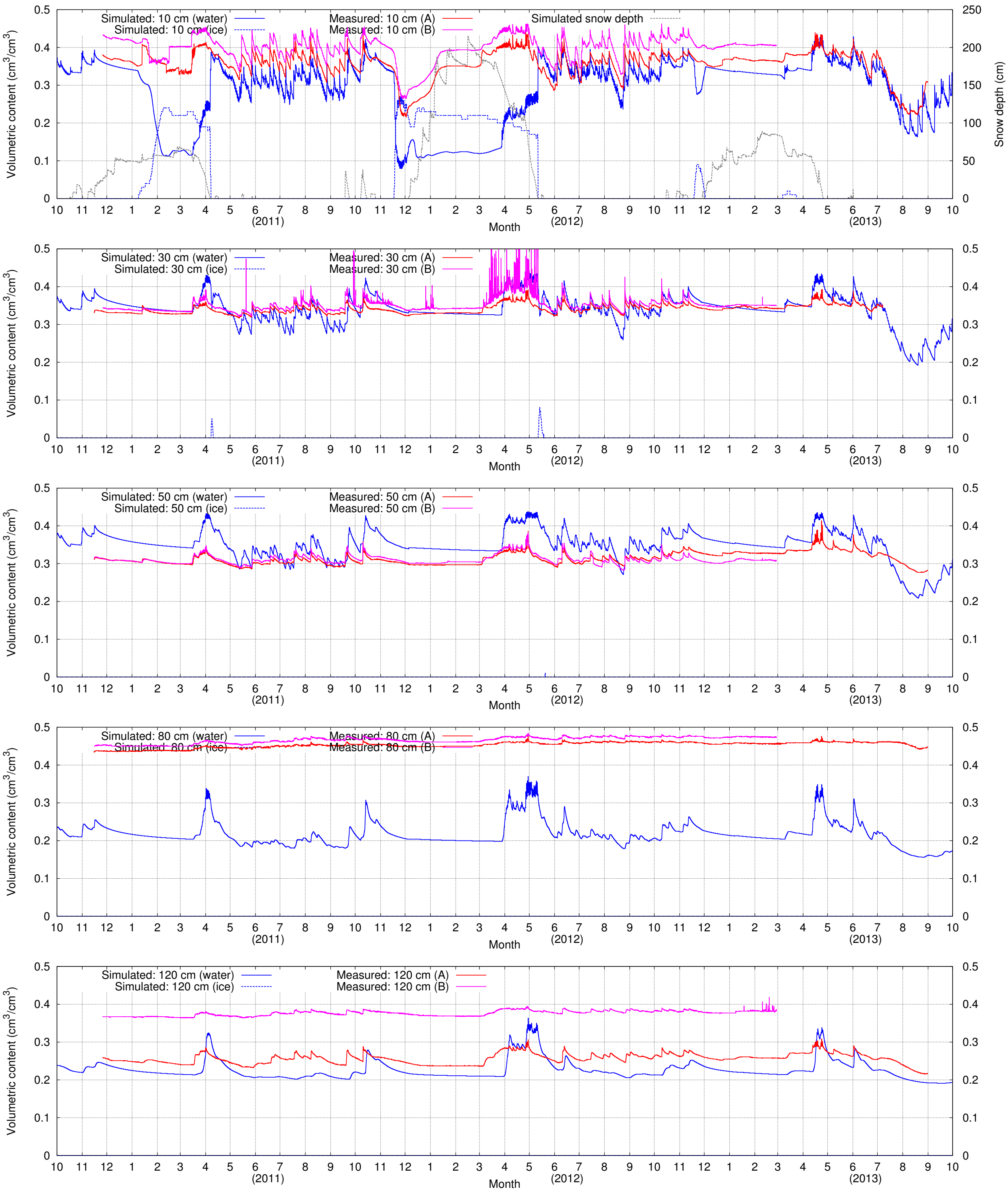


Figure 5. Measured and simulated soil moisture at the IRKIS station SLF2, for (from top to bottom) 10, 30, 50, 80 and 120 cm depth for the period October 2010 to October 2013. In the upper panel, also simulated snow ~~height~~ depth is shown.

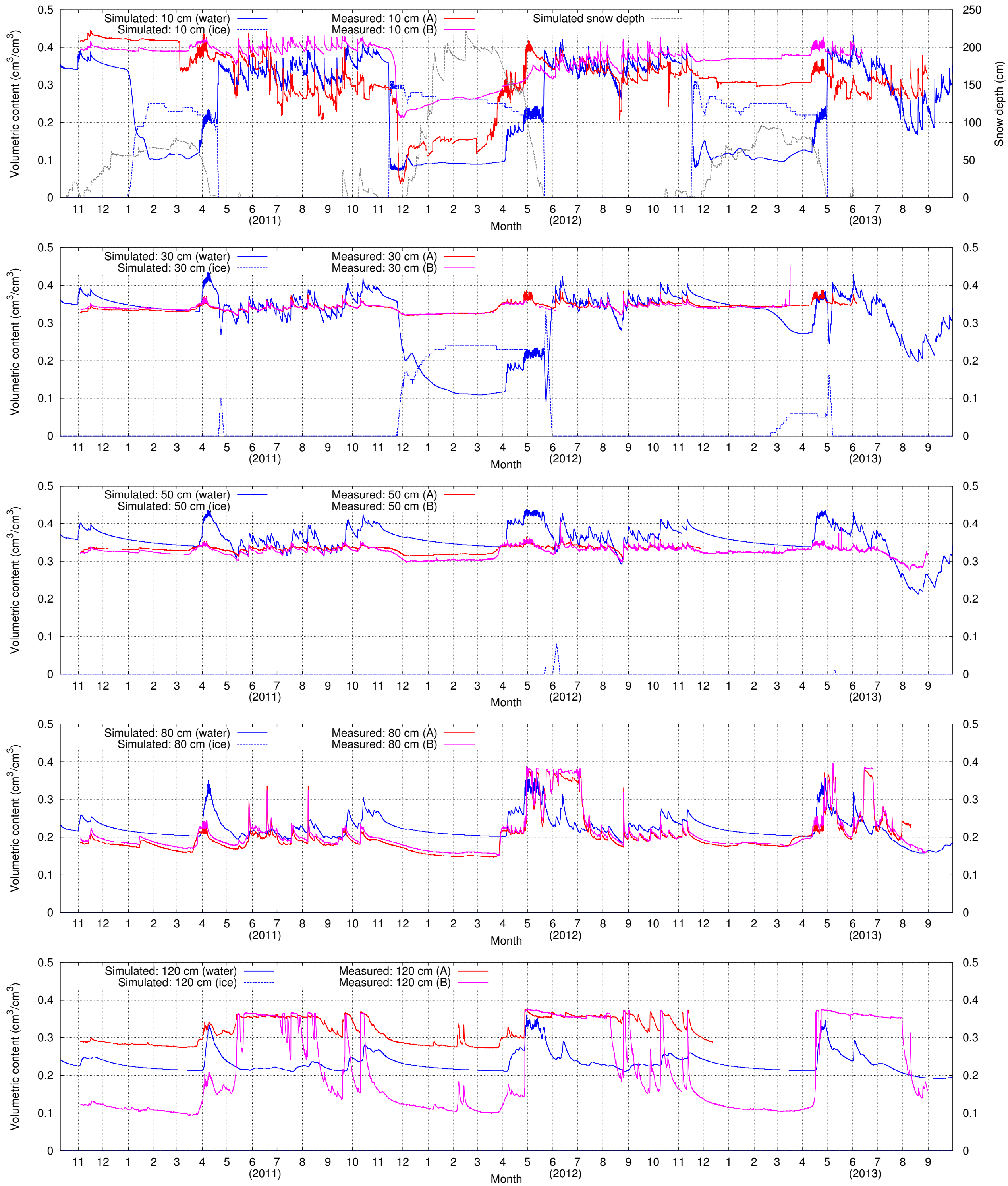


Figure 6. Measured and simulated soil moisture at the IRKIS station Uf den Chaiseren, for (from top to bottom) 10, 30, 50, 80 and 120 cm depth for the period October 2010 to October 2013. In the upper panel, also simulated snow ~~height~~ depth is shown.

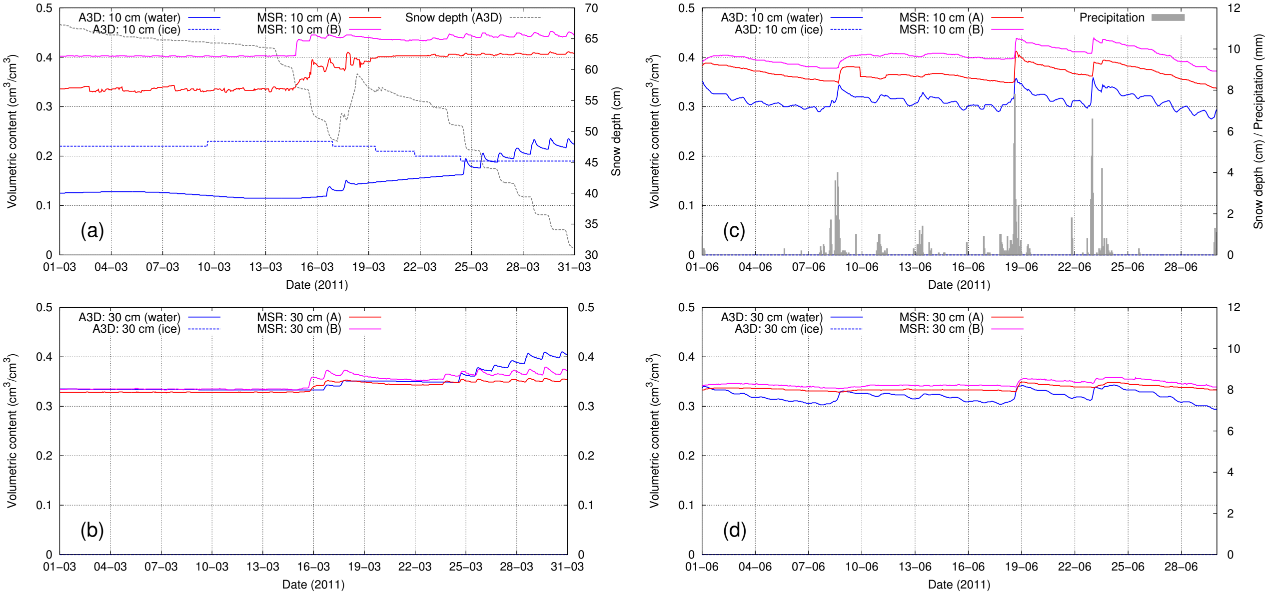


Figure 7. Measured and simulated soil moisture at the IRKIS station SLF2, for 10 cm depth (a, c) and 30 cm depth (b, d), during the snow melt season (a, b) and a snow-free summer month (c, d). In (a) simulated snow depth and in (c) precipitation is shown.

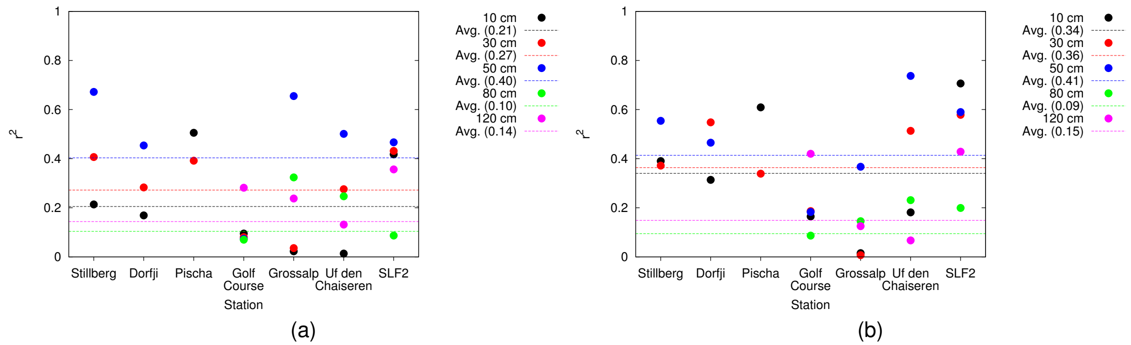


Figure 8. r^2 between measured and simulated soil moisture for the full period (a) and the summer months (b) for the 7 soil moisture stations. Dashed lines indicate the average value determined over all stations.

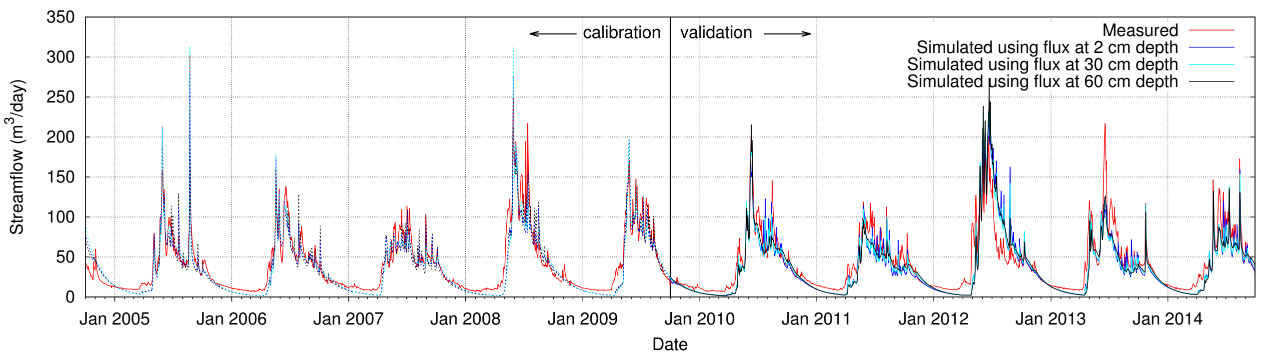
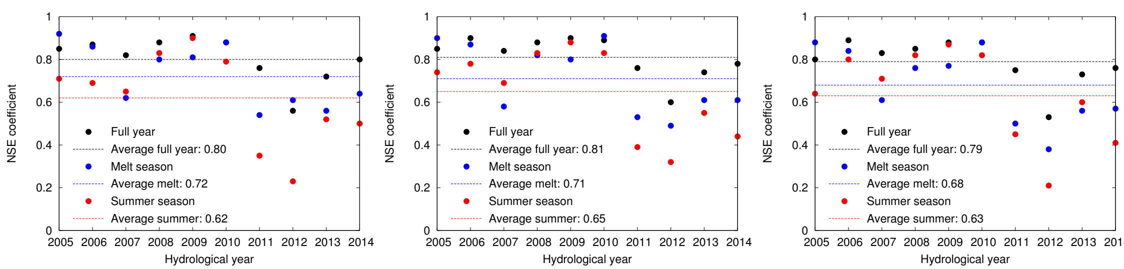


Figure 9. Measured and simulated daily streamflow for the outlet of the Dischmabach. Dashed lines denote the calibration period, solid lines denote the validation period. Major ~~ties~~ ticks on the x-axis are drawn at January 1 of each year, minor ~~ties~~ ticks are drawn at every other first of the month.



(a) (b) (c)

Figure 10. NSE coefficients for simulated daily streamflow for the outlet of the Dischmabach, using the 2 cm (a), 30 cm (b) or 60 cm (c) water flux in the soil layers~~. The NSE for the summer period for year 2012 is negative and plotted on the x-axis~~.

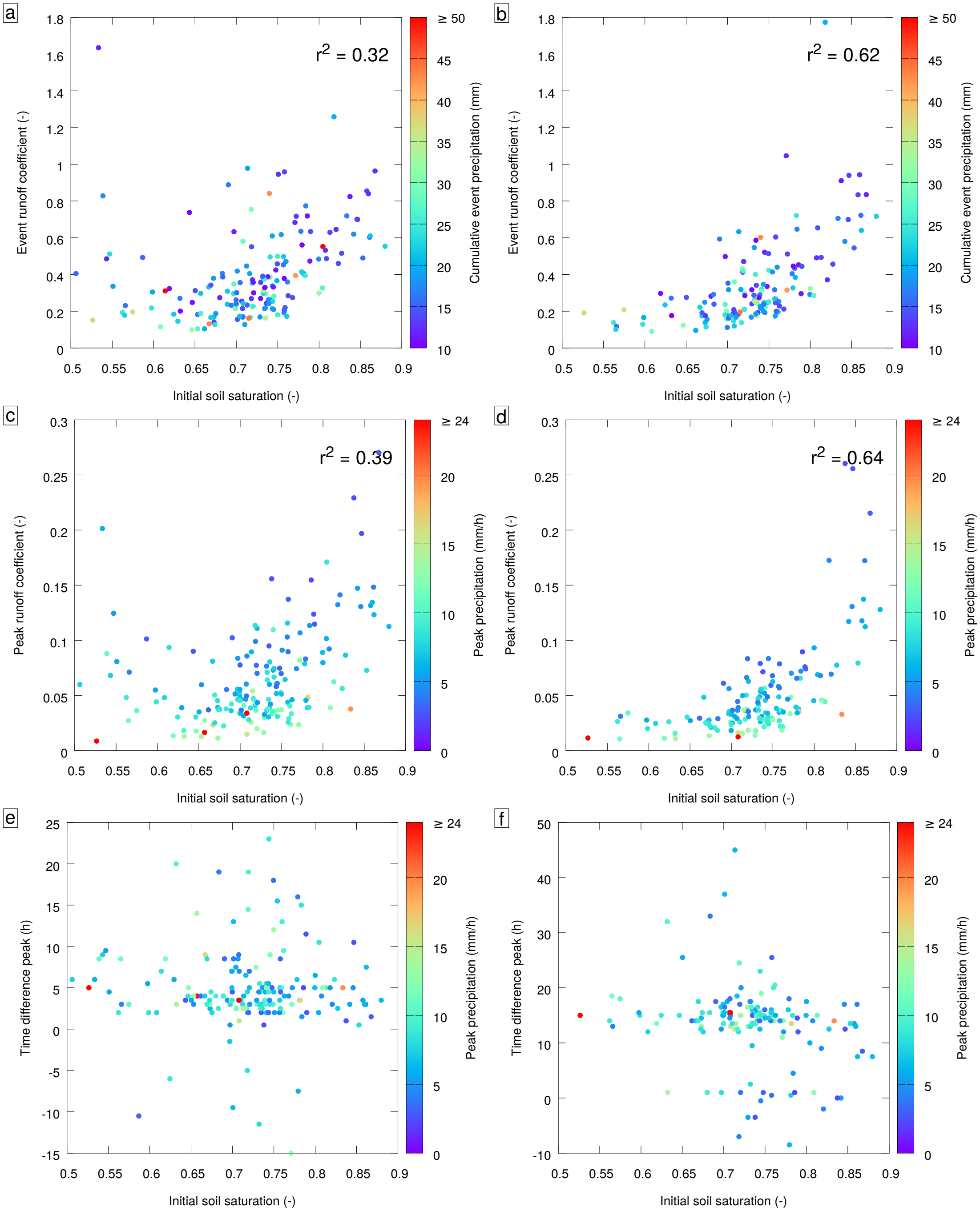


Figure 11. Rainfall event runoff coefficients for measured discharge as a function of initial soil saturation in the upper 40 cm of the soil (a) and similar for simulated discharge (b). Peak rainfall runoff coefficients for measured discharge as a function of soil saturation (c) and similar for simulated discharge (d). Time difference between peak rainfall and measured peak discharge (e) and similar for simulated peak discharge. Points are coloured according to the event rainfall sum (a and b) or the peak rainfall (c, d, e and f).

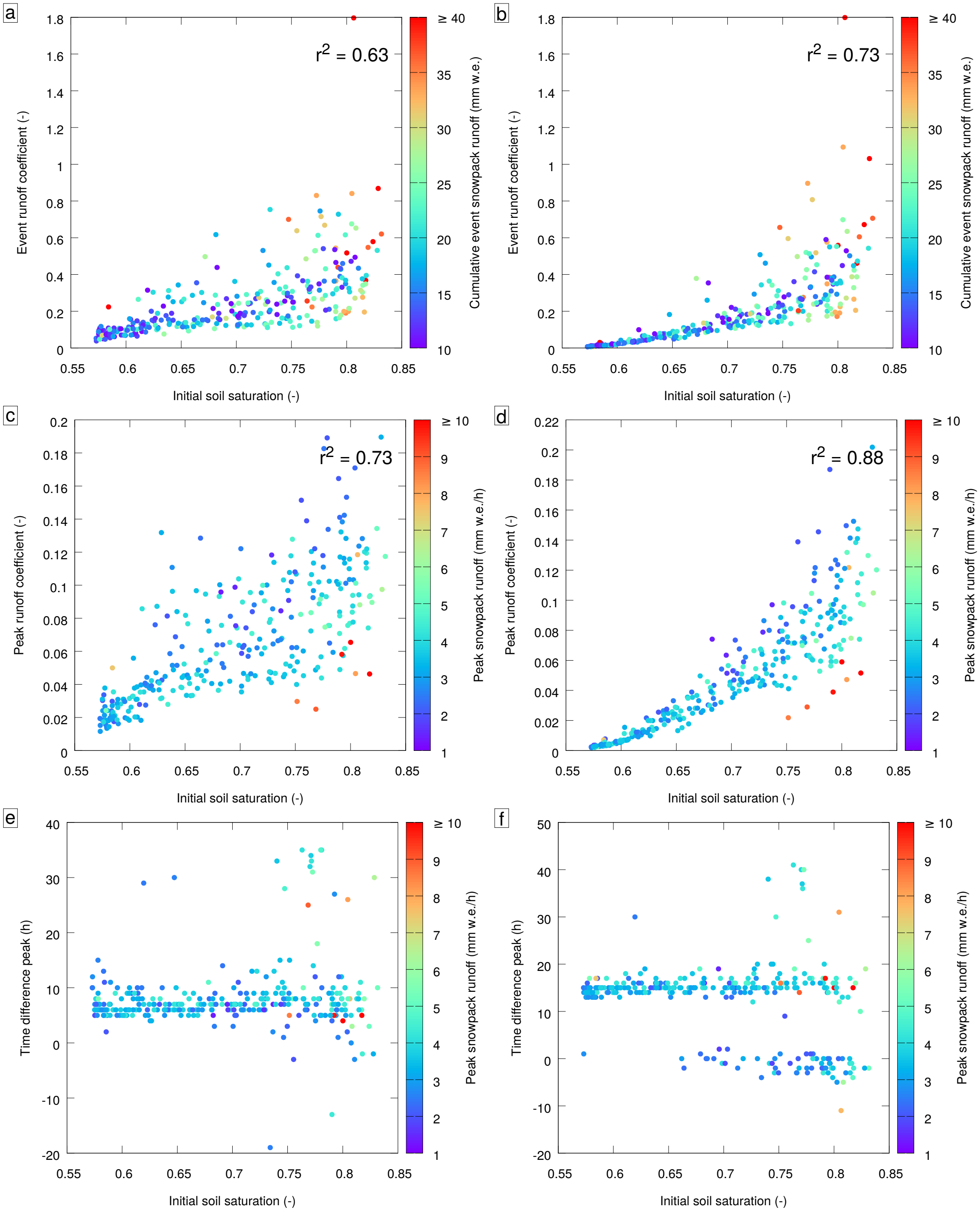


Figure 12. Snowpack runoff event runoff coefficients for measured discharge as a function of initial soil saturation in the upper 40 cm of the soil (a) and similar for simulated discharge (b). Peak snowpack runoff runoff coefficients for measured discharge as a function of soil saturation (c) and similar for simulated discharge (d). Time difference between peak snowpack runoff and measured peak discharge (e) and similar for simulated peak discharge. Points are coloured according to the event snowpack runoff sum (a and b) or the peak snowpack runoff (c, d, e and f).