# **SECTION 1: Comments from referees**

#### **Review 1**

Interactive comment on "Implementation of a

5 physically based water percolation routine in the

Crocus (V7) snowpack model" by

Christopher J. L. D'Amboise et al.

N. Wever (Referee)

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10 Received and published: 2 May 2017

1 General comments

The manuscript by d'Amboise et al. discusses the implementation of a solver for Richards equation into the detailed, multi-layer Crocus snow model. This equation describes water flow in porous media, such as snow, and previous studies have already

- 15 shown that snowpack models can benefit from implementing this equation. It generally seems to provide a better representation of liquid water content (LWC) distributions and snowpack runoff behaviour. In that sense, the study represents an important step for the Crocus snow model. Also the study can be considered an important indepenC1 dent verification of the results achieved with the SNOWPACK model, where the solver
- 20 for Richards equation has been found to considerably improve the description of liquid water flow in snow in several aspects. I found the manuscript well written and pleasant to read, but there are also some language and grammar issues (see technical corrections below). I value and appreciate the effort undertaken by the Crocus team. Based

on my experience, I know that introducing new routines to a snowpack model with such a big impact as a new water percolation routine is a serious and difficult piece of work. My first main concern with the study presented by the authors is that the results presented here are not convincingly showing that the model behaves numerically stable.

- 5 Distributions of liquid water content look different from distributions achieved with the SNOWPACK model. The absence of a comparison with field data of profiles of liquid water content or snowpack runoff makes it impossible to judge the validity of these results. I will do a few suggestions for additional verification of the numerical scheme, which I hope will provide convincing evidence that the model behaves numerically stable.
- 10 My second main concern is that the general message of the manuscript is not clear and very open and may potentially confuse readers (see below).

2 Specific comments

I have the following remarks related to the numerical scheme:

1. Especially the alternating wet and dry snow layers shown in Fig. 9 and 11, and

- 15 discussed in p10,127, are very suspicious. It looks like a numerically oscillating solution. If it is a true LWC distribution, it is recommended to have a higher vertical resolution in the simulations (i.e., more snow layers) in order to better represent the strong gradients between the wet and dry snow layers. But the simulated values of 10%-15% seem unrealistic. Such high values may occur ocC2
- 20 casionally above capillary barriers, as shown in the work by Avanzi et al. (2016), but I'm not convinced that it should happen so regularly in the simulations shown in Fig. 9 and 11. Particularly because the artificial large snow falls create a very homogeneous stratification, such that ponding is not expected to occur. So actually

I wonder if this is not a representation of the fact that the Crank-Nicolson scheme can be prone to spurious oscillations? As far as I know, Crank-Nicolson schemes are generally considered globally stable, but irregular initial conditions may lead to oscillatory behaviour. The current simulations are done with only the

- 5 optimal time step for Richards equation. But are the model results sensitive to the time step inside the Richards solver? If the model is forced to run with much smaller time steps, are the results different? Or if the model is run with higher grid resolution, or by switching of remeshing, are the results different? As far as I know, the oscillations from the Crank-Nicolson scheme can be reduced by
- 10 smaller time steps and/or higher grid resolution. Also stability criteria for Crank Nicolson schemes exists, which could be discussed by the authors. Note that I also have a suggestion to initialize the model more stable, see point 6 below, which may also improve numerical stability. Maybe if possible also provide additional motivation for the choice of a semi-implicit scheme instead of a fully implicit
- 15 one. Is the discretization (Crank-Nicolson + Picard iteration for Richards equation) used here newly developed in this work or has it been applied before? If so, please add the references.
  - 2. The mass balance is verified in the Picard scheme with a threshold of 10–4 . The
- 20 authors should add units here, but for now I assume it is the mass balance error in m3

/m3 or kg/m2

. I think that this value is set too large to judge mass conserving

behaviour of the model. The minimum time step in the solver is 10–10 s (p16,l28). If the solver has a mass balance error of 10–4 with a time step of 10–10 s, this implies a mass balance error of 16 m3

/m-3

5 /s or 110 kg/m2

/s, or 16 kg/m2

/s, depending

on the units. But this is a potentially large mass balance error! This

C3

- 10 means that if bugs in the numerical scheme or in the implementation of boundary conditions exist, the solver can "cheat" upon the mass balance check by choosing small time steps. Note that in the current version of SNOWPACK, this is also possible. During development of the solver we were particularly paying attention to the smallest time step in combination with the mass balance check. However,
- 15 we relaxed the condition, by setting a low minimum time step, also allowing the solver to "cheat" the mass balance check. The motivation is to have a more robust solver for end-users. For this review, I analysed the time step distribution for running 15 years of Weissfluhjoch simulations using Richards equation with SNOWPACK, and the smallest time step during this period is about 2x10–5 s.
- 20 The maximum allowed mass balance error in SNOWPACK is 1x10–10 kg/m2 for

the entire model domain. The combination of smallest time step found in this simulation setup, together with the mass balance criterion gives 5x10-6 kg/m2

As can be seen in the Fig. 1 below, these small time steps happen very seldom for 15 years of simulations.

3. A check of the second norm of the deficit vector could help to verify the correct

- 5 implementation of the matrix inversion to solve the equation. Given:  $A \cdot b = x$ , where x is the new solution of the pressure head, then the deficit vector is defined as  $d = A \cdot b - x$ , where d is the deficit vector. It should hold that the second norm of the vector, in case of correct implementation, is (close to) 0. Note that in an attempt to optimize the execution time of the SNOWPACK model, we removed
- 10 the deficit norm check from the code, after using it first to successfully verify a correct implementation of the solver using this check.

4. An overall report for the Crocus model as a whole of the mass balance may
also be necessary to verify a correct implementation: Delta SWE = evaporation/condensation
+ sublimation/deposition + snow/rain fall + runoff?

15 5. With the numerical scheme for Richards equation in the SNOWPACK model, weC4

found that an improved stability was achieved by initializing dry snow layers (the authors call it "prewetting") based on pressure head instead of LWC. The chosen form of Richards equation uses gradients in pressure head, thus it may be

20 better to reduce gradients in pressure head when initializing the dry snow layers. Therefore, we used the procedure to determine for the whole domain the lowest pressure head in a layer corresponding to a prescribed minimum LWC. This value of the pressure head was then used to initialize dry snow layers, such that only gradients due to gravity are present. It ensures that no snow layer is initialized with a LWC above the prescribed minimum value, while at the same time starting the simulation with a numerically stable pressure head distribution.

6. I noticed in the source code that C (dtheta/dh) is limited to -1-15. For what reason?

- 5 C is supposed to be the exact derivative of the water retention curve. An artificial cut-off seems unnecessary and may introduce mass balance errors?
  7. Section 6.2 and p16,15-6: why not implement a free-drainage boundary condition at the bottom of the snowpack, instead of all the trouble it seems to give to use the SURFEX upper soil layer? We recently modified the SNOWPACK model such
- 10 that it can run Richards equation without soil layers, and using a free drainage boundary condition seemed to work well. In SNOWPACK, we implemented freedrainage by setting the flux at the bottom of the lowest snow element similar to the flux at the top of the element, while only allowing downward flux (otherwise setting flux to 0). In case of only one snow element, we set the flux equal to the
- 15 hydraulic conductivity in this element.

I have the following remarks regarding the manuscript itself:

1. The message of the manuscript is ultimately very unclear and open. The authors apparently don't trust the new water percolation scheme enough to use it for validation (p16,19). That basically indicates to readers that this publication is not

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intended to encourage users of the Crocus model to use the new percolation scheme. But what is then the main message of the manuscript? What are the next steps to improve the trust in the validity of the new routine? Are there any further developments needed or planned? The authors should also provide clear instructions of how to repeat the experiments. I was able to download the source code, but did not find any manual or readme to compile nor did it seem to contain the necessary files to run the test cases.

- 5 2. I don't agree with the last sentence of the abstract. First, the absence of validation limits the value of any comment about applicability, but basically the same uncertainties in water retention curves for different snow types and for high density crusts, and also many of the feedback mechanisms are present in the SNOWPACK model too. Nevertheless, we have now demonstrated several times
- 10 that solving Richards Equation is having usefull applications for the SNOWPACK model, in spite of all the uncertainties. For example for assessing wet snow stability (Wever et al., 2016a; Vera Valero et al., 2016) as well as in a detailed analysis of rain-on-snow events (Würzer et al., 2017) and for reproducing ice layers (Wever et al., 2016b). As shown in Table 1 in Wever et al. (2015), different
- 15 water retention curves or different methods to determine the hydraulic conductivity at the interface nodes (arithmetic vs geometric) have limited influence on the statistics for runoff, whereas the statistics clearly improve over the bucket scheme. Therefore, I don't agree with the statement of "limited applicability" with the reasons provided in the rest of the sentence.
- 20 3. The discussion section is nicely written and provides an interesting introspective discussion about the uncertainties and potential feedback mechanisms in water percolation modelling. Note that, however, many of the feedbacks are hypothesized or based on results of other studies. The manuscript itself does not present

material supporting or quantifying the strength of those feedbacks (no validation or sensitivity study). It would be good if the discussion could be made stronger.

C6

For example, the authors may want to discuss how water retention curves for

- 5 crusts potentially look like, and how strong this influences LWC distributions or snowpack runoff?
  - 4. p4, section 2.1: Maybe explicitly state that the working of the bucket scheme in Crocus is very similar to the SNOWPACK model. p4,19: Is the bucket size always fixed to 5% of pore space? The sentence following this sentence is a
- 10 bit confusing, as if there are additional constraints. Should the sentence "For Crocus, ..." not better read "This makes the holding capacity proportional to the density of the snow layer, \*but\* independent of snow grain type or surrounding environment." It it also not clear what is meant by "surrounding environment" and how it could potentially influence the holding capacity?
- 15 5. p8,114: please provide a bit more detail on how the amount of evaporation is determined. Atmospheric forcing only provides the latent heat flux, which needs to be partitioned in evaporation and sublimation. How is Crocus doing it? Note that a reason for numerical problems with Richards equation can be when the prescribe evaporation flux exceeds the available water. For this reason SNOWPACK
- 20 employs a system where the evaporation cannot exceed the amount of water available in the upper element plus the amount of water that can be advected from below given the hydraulic conductivity there. Similar for influx, although typically unrealistic large rainfall rates (>> 200 mm/hr) are necessary to exceed the

absorption limit in snow of liquid water. In reality melt ponds form in snow only when liquid water cannot leave the snowpack below, not because the water input rate exceeds the snow absorption capacity.

6. p13,l20: "such that the criteria to enter the percolation routine has been met."

5 This is very confusing at it is for the first time mentioned that there are criteria whether or not to enter the percolation routine. Which criteria are meant here?
7. p14,113: Many examples can be found to show that preferential flow has a much C7

smaller typical spatial scale. See for example Fig. 2 in Techel and Pielmeier

10 (2011), or Fig. 1a in Würzer et al. (2017). Many other examples can be found in literature.

8. p15,12-3: "this claim needs validation": I think it depends on the application. During the first wetting, grain shape will probably play a very important role. New snow getting wet probably retains much more liquid water initially than the water

- 15 retention curve developed for melt forms will provide. For wet snow avalanche prediction, the first-wetting is often considered of crucial importance and I think improvements in the description of water flow in new snow and faceted snow (generally less shear strength) are required. On the other hand, for many hydrological applications, often the runoff behaviour during a melt season is important,
- 20 for which the assumption of melt forms is justified.

9. p15,119: This is a bit confusing wording, as principally, I would say that snow layers are initialized with the "pre-wetting" amount. But here, it is probably meant initialization when the routine is being called during a Crocus time-step.

10. p15,126-28: Although I agree with the statement, it cannot be considered a conclusion of \*this\* work. It has not been demonstrated that the water flux over the crust is over- or underestimated (no validation done), neither has it been shown that the simulations are sensitive to the hydraulic parameters for crusts (no sensitivity

5 study done).

11. Fig. 5: This figure is only mentioned once in the manuscript, and is not discussed at all. Please discuss the agreement between model and observation, or remove the snow profile.

12. I think the manuscript should not only show results for LWC distributions inside

10 the snowpack, but also snowpack runoff.

#### C8

3 Technical corrections / minor comments:

• General: note that Calonne et al. (2012) determined permeability, which can be related to conductivity. But in principle they did not publish conductivity experiments.

 General: please mention somewhere the CPU time needed to run the simulations, compared to the bucket scheme.

• General: there is a change of tense sometimes, compare for example section 4.3 with 3.4.

• General: sometimes "Figure" and sometimes "Fig." is used to refer to figures.

 Abstract: "this routine is based on". Why the wording "based on"? I would write here: "this routine solves Richards equation".

• p2,l2-3: note that simulations using Richards Equation have already been used for the assessment of wet snow avalanche activity (Wever et al., 2016a) and for

determining the initial conditions for wet snow avalanche dynamics simulations (Vera Valero et al., 2016). Given that the authors discuss this topic in particular, they may consider citing these studies here.

• p2,116: This would not be the way I would explain the precondition for flow fingering,

5 but I also have not the evidence to object against it. Maybe verify with

DiCarlo (2013)? I think this is a more up-to-date citation that may be cited here aswell.

• p3,l3: "Greenland Ice Sheet" (capitalized)

- p3,18: "ice crusts": in line with the International Classification (Fierz et al., 2009),
- 10 this should be "layers". The mentioned study concerned more with ice layers than

C9

with ice crusts. Similar p3,14: lenses are discontinuous ice layers. In this case, I think it should be layers rather than lenses.

• p6,119: "kr" should be kr.

- 15 p7,117: Here and elsewhere: I prefer "conductivity of snow"
  - p7,eq 13: I assume the second equation should read  $\Delta z$ bot
  - p7,114: I assume the reference should point to Eq. 13 instead of 11.
  - p7,124: citation style of Celia et al. is wrong (without parenthesis)
  - p8,l3: "computation step" is a vague term. I think this refers to the iteration level
- 20 k+1? Maybe write: "the pressure head h at iteration level k+1.".
  - p8,129: maybe specify: "Air temperature become as cold ..."
  - p9,114-15: please rewrite sentence
  - p10,l2: wrong figure reference

• p11,110: "there is a complicated one-to-many relationship ..." Actually it seems to be very simple: below 2x10–5 there seems to be almost no effect, so the

prewetting should just be below this value ...

p11,l14-15: I understand what is meant here, but it may be unclear for readers without a strong snow modelling background. I would explain the remeshing procedure in the model description.

• p12,110: typo: "witch"

• p12,l21: "simulated data sets simulation" I suggest "synthetic data sets simulations"



• p13,117: "and but does not have" please reformulate

• Appendix A: This time stepping is method is very similar to the one I used, and

I based it on the work by Paniconi and Putti (1994). Maybe give them credits by

citing their work?

- 15 p14,119: "on visual grain size measurements"
  - p15,l7: "where, " —> ", where"
  - p15,l11: "grain" —> "grains"
  - p16,19: "is used to deal"
  - p16,l24: "criteria are met"
- 20 p16,l28: "within"
  - p17: eq. A1 is not numbered as such
  - p17,113: "lower density snow that found": please reformulate.
  - p17,l17: "density not included"

- p17,119-20: please reformulate. This sentence cannot start with "while".
- Appendix B.3: Note that it should read "Daanen" and not "Dannen".
- References: a few still point to discussion papers, where final papers have already been accepted and published, for example: Avanzi et al. (2015) and Wever
- 5 et al. (2016). Please provide DOIs consistently when available.
  - Fig. 5: Specify here also from which date the snow profile is.
  - Fig. 7: subfigure B is wrongly labelled C
  - C11

4 References

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10 C12
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Interactive comment on Geosci. Model Dev. Discuss., doi:10.5194/gmd-2017-56, 2017.

C13

Fig. 1. Time step histogram in Richards equation solver in the SNOWPACK model for 15 years of WFJ simulations.

C14

## 5 Review 1.1

Interactive comment on "Implementation of a

physically based water percolation routine in the

Crocus (V7) snowpack model" by

Christopher J. L. D'Amboise et al.

#### 10 N. Wever (Referee)

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Received and published: 7 June 2017

In the review, I used the wrong definition of the free-drainage boundary condition, using

the term constant flux instead of constant hydraulic gradient. So correctly: in SNOWPACK,

we implemented free-drainage by setting the hydraulic gradient at the bottom of the lowest snow or soil element equal to the hydraulic gradient at the top of the element, while only allowing downward flux (otherwise setting flux to 0). Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2017-56, 2017.

20 C1

#### **Review 2**

Geosci. Model Dev. Discuss.,
doi:10.5194/gmd-2017-56-RC2, 2017
© Author(s) 2017. CC-BY 3.0 License.
5 Interactive comment on "Implementation of a physically based water percolation routine in the Crocus (V7) snowpack model" by
Christopher J. L. D'Amboise et al.
Anonymous Referee #2
10 Received and published: 30 May 2017
Overall, this is an interesting modeling paper that describes the improvements in the

Crocus(V7) snowpack model. The current modification improves the modeling of the water storage in the snowpack, and once further validated, could be an invaluable contribution to the state of art in snowpack modeling. Below I have a couple questions

15 and minor suggestions, most of which are editorial.

Abstract L15. Pendular and funicular regime (scientific jargon). Need to explain that first.

Section 2. First paragraph. I am confused. Is it a three models coupled system (SURC1

20 FEX, ISBA, and Crocus)? If yes, then title should be changed.

The current formulation of the Richards equation 1 does not account for presence of ice and air in snowpack. How do authors think the results would change by introducing them in the equation 1?

P4. L30. h should it be H?

P5. L2,5. The notation is confusing pressure head (h), and retention curve h(theta)? P5. L10. Equation 3. If it is water retention curve function then should be h(theta) When water percolates through the snow layer and freezes at the bottom. The pressure

5 and volume at the bottom grid cell increases due to ice formation. How does the model handle the increase in pressure due to ice formation?

It would be interesting to plot pressure head changes with time on Figures 8 and 9. Section 6.6. Authors are referring to the different routines, like 'C13' and so on. It is confusing to read those notations and have no idea where they come from. For clarity,

10 I suggest to make a chart including all the important routines.

There are figures, like Figure 11, which have the same legend. I suggest to make one

legend, and put A) and B) as a subtitle or place the text inside the figure.

Interactive comment on Geosci. Model Dev. Discuss., doi:10.5194/gmd-2017-56, 2017.

C2

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# **SECTION 2:** Author's response

#### **Reply to review 1**

#### **Response to review:**

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We would like to thank the reviewer for the constructive comments. We hope that the plots included in this document convince the reviewer that the Richards routine is acting in a numerically stable manner and the non-physical results are caused by the feedbacks discussed in the text. Therefore, we still feel that validation on lysimeter and snow pits data will not add to this work. The feedback issues are similar to the issues that the reviewer faced when developing a similar routine in the SNOWPACK model. However SNOWPACK and Crocus have different structures and slightly different equations (physical or empirical), so the issues presented are similar but unique to Crocus.

The abstract and conclusion have had major changes to highlight that the routine is complete but does not couple well in the Crocus or SURFEX model in the current state. The model code has been revised to ensure a free-flowing bottom boundary and a head based pre-wetting, as recommended by the reviewer. Relevant sections have been revised describing the new pre-

5 wetting mechanism and the free-flowing bottom boundary. Figures 2, 3 and 6-10 have also been reproduced based on the revised model. Similarly, the results section has been revised to reflect the new bottom boundary and pre-wetting.

#### **Response to comments:**

For this section the authors' responses are shown in black, where the reviewer's comments are in blue. Quotes ("") and *italic font* show changes to the manuscript.

#### 10

#### 1 general comments:

The manuscript by d'Amboise et al. discusses the implementation of a solver for Richards equation into the detailed, multilayer Crocus snow model. This equation describes water flow in porous media, such as snow, and previous studies have already shown that snowpack models can benefit from implementing this equation. It generally seems to provide a better representation

- 15 of liquid water content (LWC) distributions and snowpack runoff behaviour. In that sense, the study represents an important step for the Crocus snow model. Also the study can be considered an important independent verification of the results achieved with the SNOWPACK model, where the solver for Richards equation has been found to considerably improve the description of liquid water flow in snow in several aspects. I found the manuscript well written and pleasant to read, but there are also some language and grammar issues (see technical corrections below). I value and appreciate the effort undertaken by the
- 20 Crocus team. Based on my experience, I know that introducing new routines to a snowpack model with such a big impact as a new water percolation routine is a serious and difficult piece of work. My first main concern with the study presented by the authors is that the results presented here are not convincingly showing that the model behaves numerically stable. Distributions of liquid water content look different from distributions achieved with the SNOWPACK model. The absence of a comparison with field data of profiles of liquid water content or snowpack runoff makes it impossible to judge the validity of these results.
- 25 I will do a few suggestions for additional verification of the numerical scheme, which I hope will provide convincing evidence that the model behaves numerically stable. My second main concern is that the general message of the manuscript is not clear and very open and may potentially confuse readers (see below).

We based our work off the reviewer's description of the routine that was implemented in the SNOWPACK model and described in Wever et al 2014. The review states "the study can be used as an independent verification of the results achieved with the SNOWPACK model". However there are many small differences between the Crocus and SNOWPACK models, specifically in the model structure and some of the physics or empirical relation.

- 5 It is important to understand that issues that deal with coupling and feedback are unique to the Crocus model, but probably quite similar to issues faced when implemented in the SNOWPACK model. However, issues with parameter sets that are not a result of feedback will be common for both SNOWPACK and Crocus (grain size of crusts, strong dependence of density and grain size). Therefore, conclusions we draw from the Richards routine inside the Crocus model, may not directly apply to the Richards routine inside the SNOWPACK model.
- 10 To address the numerical stability of the routine, we turned off the two largest feedback contributions, the snow metamorphism and compaction routines (SNOWCROMETAMO & SNOWCROCOMPACTN), see Fig. A.



Figure A shows results from the synthetic data set run without the compaction and metamorphism routines. Note that the snow layers are comprised of new snow grains at low density.

Figure A shows the Richards routine behavior is stable, without any "oscillations" or the wet, dry pattern which is seen in Fig

15 9 & 11 of the original manuscript.

Figure B shows the same data set with the metamorphism routine still turned off, but with the compaction routine turned on.



Figure B shows results from the synthetic data set run with the compaction and without the metamorphism routine.

The oscillating pattern appears again. We show here that the pattern of wet, dry layers is not a result of a numerically unstable solution or oscillating solution in the Richards routine, but most likely an effect of an incomplete description of wet snow compaction.

- 5 Results (not shown) which used the metamorphism routine and not the compaction routine are more difficult to associate with the striped pattern. Water percolated down only after the LWC became very high > 20%. Water percolated very slow and did not reached the bottom of the snow pack by the end of the synthetic simulation, when run without compaction routine. It is very likely that the high LWCs made by the metamorphism routine will amplify the striped pattern made by the compaction routine.
- 10 The second main concern is that the message of the manuscript is not very clear. We agree that the manuscript should be more forward with the message.

We have addressed this issue by adding a few sentences to the abstract and conclusion about steps needed for further development of Crocus and the Richards routine. Together with addressing many of the points made below we feel it is clearer now.

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#### **2** Specific comments

I have the following remarks related to the numerical scheme:

Especially the alternating wet and dry snow layers shown in Fig. 9 and 11, and discussed in p10,127, are very suspicious. It looks like a numerically oscillating solution. If it is a true LWC distribution, it is recommended to have a higher vertical resolution in the simulations (i.e., more snow layers) in order to better represent the strong gradients between the wet and dry

- 5 snow layers. But the simulated values of 10%-15% seem unrealistic. Such high values may occur occasionally above capillary barriers, as shown in the work by Avanzi et al. (2016), but I'm not convinced that it should happen so regularly in the simulations shown in Fig. 9 and 11. Particularly because the artificial large snow falls create a very homogeneous stratification, such that ponding is not expected to occur. So actually I wonder if this is not a representation of the fact that the Crank-Nicolson scheme can be prone to spurious oscillations? As far as I know, Crank-Nicolson schemes are generally considered
- 10 globally stable, but irregular initial conditions may lead to oscillatory behaviour. The current simulations are done with only the optimal time step for Richards equation. But are the model results sensitive to the time step inside the Richards solver? If the model is forced to run with much smaller time steps, are the results different? Or if the model is run with higher grid resolution, or by switching of remeshing, are the results different? As far as I know, the oscillations from the Crank-Nicolson scheme can be reduced by smaller time steps and/or higher grid resolution. Also stability criteria for Crank Nicolson schemes
- 15 exists, which could be discussed by the authors. Note that I also have a suggestion to initialize the model more stable, see point 6 below, which may also improve numerical stability. Maybe if possible also provide additional motivation for the choice of a semi-implicit scheme instead of a fully implicit one. Is the discretization (Crank-Nicolson + Picard iteration for Richards equation) used here newly developed in this work or has it been applied before? If so, please add the references. See section 1 (General comments), for remarks on the numerical stability and the root of the "oscillations".
- 20 A LWC of 10%- 15% is high but not unrealistic for snow (at least for short periods). However, these are the results obtained with the current state of the Crocus model using the Richards routine. We do not claim that the results of this routine accurately model snow properties, at this point. Yet, the routine has been added to the Crocus model and further developments of the Richards routine is dependent on development of other Crocus routines and/or the parameter sets. The parameter sets have been shown to work with the SNOWPACK model. However we are cautious with them because they make up half of the
- 25 feedback loop.

Normally the time step is restricted by the Crocus time step and the time step rules given in appendix A1 of the (original and revised) manuscript. To investigate the possible numerical nature of the oscillations, we have restricted the Richards time step permitting maximum values of 60 s, 10 s and 1s. This is based on the notion that numerical stability increases with decreasing time steps, but since the model operates with adjustable time steps, defining the maximum time step mainly affects those

30 situations when the solution procedure behaves well.

Our choice for using Crank-Nicolson with the Picard iteration to solve the Richards equation comes from a previous model developed by L. Oxarango (co-author), based on the h (head) form of the Richards equation (Tinet et al. 2011). There exists

an unpublished adaption which solves the mixed form of the Richards equation. The Richards equation has been solved using the Crank-Nicolson and a Picard iteration for a finite element scheme in Paniconi & Putti 1994.

2.2

- The mass balance is verified in the Picard scheme with a threshold of 10-4. The authors should add units here, but for now I assume it is the mass balance error in m3 /m3 or kg/m2. I think that this value is set too large to judge mass conserving behaviour of the model. The minimum time step in the solver is 10-10 s (p16,l28). If the solver has a mass balance error of 10-4 with a time step of 10-10 s, this implies a mass balance error of 16 m3 /m-3 /s or 110 kg/m2 /s, or 16 kg/m2 /s, depending on the units. But this is a potentially large mass balance error! This means that if bugs in the numerical scheme or in the implementation of boundary conditions exist, the solver can "cheat" upon the mass balance check by choosing small time steps. Note that in the current version of SNOWPACK, this is also possible. During development of the solver we were particularly provide attention to the smallest time step in approximation with the mass balance check. However, we releved the particularly provide attention to the solver time step in approximation with the mass balance check.
- particularly paying attention to the smallest time step in combination with the mass balance check. However, we relaxed the condition, by setting a low minimum time step, also allowing the solver to "cheat" the mass balance check. The motivation is to have a more robust solver for end-users. For this review, I analysed the time step distribution for running 15 years of Weissfluhjoch simulations using Richards equation with SNOWPACK, and the smallest time step during this period is about
- 15 2x10-5 s. The maximum allowed mass balance error in SNOWPACK is 1x10-10 kg/m2 for the entire model domain. The combination of smallest time step found in this simulation setup, together with the mass balance criterion gives 5x10-6 kg/m2 /s. As can be seen in the Fig. 1 below, these small time steps happen very seldom for 15 years of simulations.

We are calculating mass balance in m because the Crocus variable holding information about wetness (PSNOWLIQ) is in m

20 of water. Units have been added to the manuscript. The conversion to kg/m<sup>2</sup> is achieved by multiplication with the density of water (SI units).

Three mass balances are checked.

- 25 1. Full mass balance (mb\_15), full snow pack over crocus (15 min) time step.
  - 2. Full mass balance (mb\_rch), full snow pack over RCH variable time step.
  - 3. Mesh balance (mesh\_bal), layer mass balance over RCH variable time step. The convergence criteria have been evaluated for mb\_rch and mesh\_bal.
- 30 Figure C (mb\_15) and D (time step size). We tested the performance of the models mass balance mb\_15 using two limits on the mesh balance, 1E-4 m and 1E-6 m. mb\_15 is important to check because it checks the results that are exported to SURFEX/ISBA and other Crocus routines.

Note: The plots have been made with the new implementation of a free flowing bottom boundary and pre-wetting based on head (h) described in sections 2.5 and 2.7 of this response.



5 Figure C Difference in the mass balance over 15 minute Crocus time step with mesh balance limits on the Picard iteration. Red =1e-4, blue = 1e-6, pink is both red and blue.



Figure D Difference in the time step duration with mesh balance limits on the Picard iteration. Red =1e-4, blue = 1e-6, pink is both red and blue.

The plots (C and D) show how making a stricter mass balance limit on the Picard iteration loop, has very little effect on the on the mass balance over the 15 minute crocus time step, but has a large effect on the time step size (and therefore model run time). This is because the model "cheats" the mass balance convergence criteria by reducing the time step as the reviewer points out.

5

The mass balance is one of the many improvements needed for this routine to be used operationally. However, we feel the mass balance is in the appropriate range when compared to the performance of the SNOWPACK model for 3 reasons (see below).

10 SNOWPACK has a maximum mass balance error rate of  $5x10^{-6}$  kg/m<sup>2</sup>s. The rate in Crocus can be estimated from Figure C, and is ~ 1E-3 kg/m<sup>2</sup> s, calculation shown below. There is a difference of 3-order of magnitude between the Crocus and SNOWPACK mass balances for their respective Richards routine.

$$m b_{15\min} \sim \frac{0.001[m] * 1000 \left[\frac{kg}{m^3}\right]}{900[s]} = 0.00111 \left[\frac{kg}{m^2 s}\right]$$

In the following, we argue why this 3-order-of-magnitude difference is less problematic than it appears at a first look.

- The Reviewer implies in (section 2.1) that in their simulations SNOWPACK does not often reach LWC in the range of 10-15%. This low water content will cause a low mass balance error which depends on the amount of water involved. In contrast, in our simulations, snow layers are often in this very wet state, hence, the associated mass balance error will be larger. This effect puts the relative difference between SNOWPACK and Crocus into perspective.
- 20

25

- 2. Our synthetic forcing has been especially designed to challenge the newly implemented Richards routine. There are very strong melt events (during day hours) after the second snow event, yet during night the upper few layers completely freeze. The routine needs to pre-wet these layers and the pressure gradient will be opposing gravity at the transition between wet and dry layers. A natural snow pack will have these conditions a few times over a season, but they are not as common or strong of a melt freeze cycle as seen in the synthetic forcing. We expect that such a demanding situation will be accompanied by a larger mass balance error compared to simulations of more naturally occurring situations
- Crocus' melt routine sets up strong (and presumably spurious) pressure differences when the Richards routine is entered. The Crocus routine is stepped using constant time steps, during each of which, the Richards routine is entered which applies its own internal time steps. The high pressure gradients are presumably a result of prescribing a water supply mass during the first Richards time step, instead of a constant water supply rate over the entire Crocus time step. This glimpse will be fixed in future work, but is out of the scope for the current study. This would require changes to the melt routines (SNOWCROGONE, SNOWCROLAYERGONE and SNOWCROMELT),
   most of which would be adapting re-meshing when top layers are melted. Nevertheless, we acknowledge that this shortcoming additionally contributes to the higher mass balance error of our model.

24

Using a convergence criteria on mesh balance < 1E-6 m or 0.1 kg/m<sup>2</sup>. Which sounds like a very relaxed criteria. However, this results in a mb\_15 of ~ 0.001 m (during the worst of times) often mb\_15 is < 1E-6 m. Despite the three reasons given above there is only a difference of two orders of magnitude on the rate of mass balance error (kg/m<sup>2</sup> s) when compared with the SNOWPACK model.

#### 2.3

5

A check of the second norm of the deficit vector could help to verify the correct implementation of the matrix inversion to solve the equation. Given:  $A \cdot b = x$ , where x is the new solution of the pressure head, then the deficit vector is defined as  $d = A \cdot b - x$ , where d is the deficit vector. It should hold that the second norm of the vector, in case of correct implementation, is

(close to) 0. Note that in an attempt to optimize the execution time of the SNOWPACK model, we removed the deficit norm check from the code, after using it first to successfully verify a correct implementation of the solver using this check.
 We solve A.x = b using a Thomas algorithm function. The vector d = A.x-b has been calculated with values within the range of 1E-21m to 1E-25 m. The ratio d/b (which normalizes the deficit vector) can be used as an error estimate. We have a range from ~ 1E-15 to 1E-18 (dimensionless) for d/b.

## 15 **2.4**

An overall report for the Crocus model as a whole of the mass balance may also be necessary to verify a correct implementation: Delta SWE = evaporation/condensation + sublimation/deposition + snow/rain fall + runoff?

We show above in section 2.2 of this response, that the mass balance for the Richards routine is sub-par. Therefore we do not feel the mass balance of the full Crocus model is useful at this moment.

#### 20 2.5

With the numerical scheme for Richards equation in the SNOWPACK model, we found that an improved stability was achieved by initializing dry snow layers (the authors call it "prewetting") based on pressure head instead of LWC. The chosen form of Richards equation uses gradients in pressure head, thus it may be better to reduce gradients in pressure head when initializing the dry snow layers. Therefore, we used the procedure to determine for the whole domain the lowest pressure head

- 25 in a layer corresponding to a prescribed minimum LWC. This value of the pressure head was then used to initialize dry snow layers, such that only gradients due to gravity are present. It ensures that no snow layer is initialized with a LWC above the prescribed minimum value, while at the same time starting the simulation with a numerically stable pressure head distribution. This was a very clever hint that is now added to our routine. However the results are not noticeably different in the current state of the routine.
- 30 Text added to section 3.1 describing the new pre-wetting method (in the manuscript).

2.6

I noticed in the source code that C (dtheta/dh) is limited to -1-15. For what reason? C is supposed to be the exact derivative of the water retention curve. An artificial cut-off seems unnecessary and may introduce mass balance errors?

This limit has been removed. This limit was never reached during model runs that were used for the manuscript. The limit was put in place to help understanding the evolution of variables and for debugging when we had convergence troubles.

#### 2.7

5

Section 6.2 and p16,15-6: why not implement a free-drainage boundary condition at the bottom of the snowpack, instead of all the trouble it seems to give to use the SURFEX upper soil layer? We recently modified the SNOWPACK model such that it can run Richards equation without soil layers, and using a free drainage boundary condition seemed to work well. In

10 SNOWPACK, we implemented freedrainage by setting the flux at the bottom of the lowest snow element similar to the flux at the top of the element, while only allowing downward flux (otherwise setting flux to 0). In case of only one snow element, we set the flux equal to the hydraulic conductivity in this element.

This is a good idea, and we have since added this to the routine with much success. We have previously unsuccessfully tried different bottom boundary conditions excluding interaction with the soil routine.

15 We added section 3.4.2 to the manuscript dedicated to the free flowing bottom boundary.

#### **3 Manuscript comments**

#### 3.1

The message of the manuscript is ultimately very unclear and open. The authors apparently don't trust the new water percolation scheme enough to use it for validation (p16,19). That basically indicates to readers that this publication is not intended to encourage users of the Crocus model to use the new percolation scheme. But what is then the main message of the manuscript? What are the next steps to improve the trust in the validity of the new routine? Are there any further developments needed or planned? The authors should also provide clear instructions of how to repeat the experiments. I was able to download the source code, but did not find any manual or readme to compile nor did it seem to contain the necessary files to run the test cases.

25 We have added this link to section 8 "Code and data availability" that is a walk through for running Surfex.Crocus.

https://opensource.umr-

 $cnrm.fr/projects/snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools/wiki/Basic\_functioning\_of\_s2m\_tool\_from\_snowtools/wiki/Basic\_function]$ 

We do not push for the routine to be used, but rather point out where further development is needed for this routine to work well inside the SURFEX/Crocus framework. The major developments needed for this routine to be viable are outside the

Richards routine, inside other Crocus routines and/or in better microstructure understanding/parameter sets. Therefore we feel that this is a complete work and should be reported on. This manuscript has two main messages:

- 1. The description of the new routine.
- 2. Highlighting parts of routines in Crocus that need adaptions/further development in order for the Richards routine to perform well in Crocus.

We note that the second point needs to be stated more clearly in the manuscript, and acted accordingly. Both the abstract and conclusion have significant changes.

#### 10 3.2

5

I don't agree with the last sentence of the abstract. First, the absence of validation limits the value of any comment about applicability, but basically the same uncertainties in water retention curves for different snow types and for high density crusts, and also many of the feedback mechanisms are present in the SNOWPACK model too. Nevertheless, we have now demonstrated several times that solving Richards Equation is having useful applications for the SNOWPACK model, in spite

- 15 of all the uncertainties. For example for assessing wet snow stability (Wever et al., 2016a; Vera Valero et al., 2016) as well as in a detailed analysis of rain-on-snow events (Würzer et al., 2017) and for reproducing ice layers (Wever et al., 2016b). As shown in Table 1 in Wever et al. (2015), different water retention curves or different methods to determine the hydraulic conductivity at the interface nodes (arithmetic vs geometric) have limited influence on the statistics for runoff, whereas the statistics clearly improve over the bucket scheme. Therefore, I don't agree with the statement of "limited applicability" with
- 20 the reasons provided in the rest of the sentence.

We can agree that Crocus and SNOWPACK are similar models that have some minor differences, however I think the minor differences can have major influence on the feedback systems in place. Both models "wet snow processes" were developed to be used with the bucket model. The calculations of "bucket size" differs between the Crocus (Vionnet et al 2012) and SNOWPACK (Wever et al. 2014) models. The bucket model for Crocus has a limit defined as a % of pore spaces (set to 5%

25 as default, but may be changed if desired), holding capacity has a linear relationship to density. The SNOWPACK bucket size is a piecewise linear function of pore space. Essentially, Crocus has an almost binary snow wetness model with the bucket model, the SNOWPACKs bucket model seems more dynamic (in relation to pore space). This provokes the idea that wet snow processes are handled differently in SNOWPACK and Crocus.

The feedback is suspected primarily to be between the compaction & metamorphism routines and the parameterizations of the 30 water retention curve and conductivity function. The parameterizations seem to work well inside the SNOWPACK model, despite the theoretical weaknesses that exist with them. However, we were not able to distinguish (for Crocus) if the errors come from the parameterizations (water retention curve, conductivity), other Crocus routines (compaction, metamorphism), or how they interact with each other. Since there are some theoretical problems with the parameterizations and they are the parts of the Richards routine which are part of the feedback mechanism, we cannot exclude the possibility that the parameterization used is the dominant source of error.

5 To address the issue, a study on microstructure is needed, either expanding the data set that the parameter sets are based on, or investigating the rates of wet snow metamorphism and compaction. Both of these experiments are outside the scope of this study.

We do not feel that our model can reproduce the results that were demonstrated in several recent publications using the SNOWPACK model applying the Richards equation. Therefore we feel the Richards routine as implemented in the SURFEX/Crocus framework has limited applicability in its current state.

The sentence in question is: "We show that the new routine has been implemented in the Crocus model, but due to amplification of parameter uncertainties through a number of feedbacks, meaningful applicability is limited until new and better parameterizations of water retention is developed for different snow types."

We do feel that this sentence should not single out the water retention curve and was changed, see below.

15 "We show that the new routine has been implemented in the Crocus model, but due to feedback amplification and parameter uncertainties meaningful applicability is limited."

### 3.3

10

The discussion section is nicely written and provides an interesting introspective discussion about the uncertainties and potential feedback mechanisms in water percolation modelling. Note that, however, many of the feedbacks are hypothesized

- 20 or based on results of other studies. The manuscript itself does not present material supporting or quantifying the strength of those feedbacks (no validation or sensitivity study). It would be good if the discussion could be made stronger. For example, the authors may want to discuss how water retention curves for crusts potentially look like, and how strong this influences LWC distributions or snowpack runoff?
- The Crocus model is not in a state where it works well with the Richards routine. However, we discuss this somewhat unexpected behavior and pinpoint the major sources of uncertainty. We demonstrate that due to the discussed feedbacks, even small structural differences (as for instance between Crocus and SNOWPACK) can be amplified leading to very different results. Furthermore, we outline potential future improvements to avoid these problems. Altogether, we think this is a contribution worthy being reported to enable future scientific progress. However conclusions can still be drawn and supported from the work presented. Much of the discussion pertains to reinterpreting (other researcher's) experimental studies in the context of modeling, which was not done in many of the original experimental studies.
  - See section 3.10 (of this document) for discussion about crusts layers.

p4, section 2.1: Maybe explicitly state that the working of the bucket scheme in Crocus is very similar to the SNOWPACK model. p4,19: Is the bucket size always fixed to 5% of pore space? The sentence following this sentence is a bit confusing, as if there are additional constraints. Should the sentence "For Crocus, ..." not better read "This makes the holding capacity

- 5 proportional to the density of the snow layer, \*but\* independent of snow grain type or surrounding environment." It it also not clear what is meant by "surrounding environment" and how it could potentially influence the holding capacity? There are no additional constraints on the "bucket size". This is stated because it is important that the reader understands that the bucket routine does not account for grain type, or the surrounding environment (layers above or below layer in question, soils water condition etc.). The Richards routine accounts for both of these (unless free flowing boundary at bottom of snow
- 10 pack is used).

We have added that 5% is a default value and gave example of surrounding environment.

"The "bucket size" or holding capacity has been defined as 5% of a layers pore spaces as default, however this can be adapted if needed. (Vionnet et al., 2012). For Crocus, the holding capacity is proportional to the density of the snow layer but is independent of snow grain type or surrounding environment (adjacent snow layers, soil, ect)."

#### 15 **3.5**

p8,114: please provide a bit more detail on how the amount of evaporation is determined. Atmospheric forcing only provides the latent heat flux, which needs to be partitioned in evaporation and sublimation. How is Crocus doing it? Note that a reason for numerical problems with Richards equation can be when the prescribe evaporation flux exceeds the available water. For this reason SNOWPACK employs a system where the evaporation cannot exceed the amount of water available in the upper

20 element plus the amount of water that can be advected from below given the hydraulic conductivity there. Similar for influx, although typically unrealistic large rainfall rates (>> 200 mm/hr) are necessary to exceed the absorption limit in snow of liquid water. In reality melt ponds form in snow only when liquid water cannot leave the snowpack below, not because the water input rate exceeds the snow absorption capacity.

The evaporation is described in Vionnet et al 2012 section 3.7 "Surface fluxes and surface energy balance". The evaporation 25 is calculated before the percolation routine with the use of two routines SNOWCROBUD and SNOWCROFLUX. Vaporization/condensation can occur when the top snow layer is wet, otherwise mass flux is in a solid state (deposition/sublimation). We did not find problems with fluxes being too high. Evaporation should not affect the Richards routine in the current set up of the model, and rain rate never reaches a value close to 200 mm/ hr.

3.6

**30** p13,120: "such that the criteria to enter the percolation routine has been met." This is very confusing at it is for the first time mentioned that there are criteria whether or not to enter the percolation routine. Which criteria are meant here?

We added a sentence describing the criteria in Sec. 3.3 in the revised manuscript (Implementation of Richards routine in Crocus).

There are 2 criteria,

- 1. Number snow layers  $\geq 3$ , currently bucket routine is used for melt out. (we do not reach melt out in this study)
- 5

2. The snowpack has to contain > pre-wetting amount of water, or have a rain rate of  $> 10^{-10}$ 

"To reduce unnecessary computations the following 2 conditions need to be satisfied before entering the Richards routine:

1. There must be a snowpack. If there is < 3 layers of snow the bucket model will be used for water percolation.

2. There must be liquid water. If  $\theta < \theta_{min}$ , and the rain flux (over the time step of 15 min)  $< 10^{-10}$  m.

If one of these two conditions are not satisfied Crocus will be run without calling the Richards routine"

10

#### 3.7

p14,113: Many examples can be found to show that preferential flow has a much smaller typical spatial scale. See for example Fig. 2 in Techel and Pielmeier (2011), or Fig. 1a in Würzer et al. (2017). Many other examples can be found in literature. The purpose of this sentence was to show that there is spatial variability that will affect water flow on a scale >1m. Therefore

15 we have taken out the reference for preferential flow and adapted the sentence.

"Hydraulic conductivity has been determined by Calonne et al., (2012) on small snow samples therefore it is possible that the measurements do not represent conductivity at a higher spatial scale because processes that affect the density distribution, grain metamorphism and pore space differ on a meter to several meter scale (Birkeland et al., 1995)."

20

#### 3.8

p15,l2-3: "this claim needs validation": I think it depends on the application. During the first wetting, grain shape will probably play a very important role. New snow getting wet probably retains much more liquid water initially than the water retention curve developed for melt forms will provide. For wet snow avalanche prediction, the first-wetting is often considered of crucial

25 importance and I think improvements in the description of water flow in new snow and faceted snow (generally less shear strength) are required. On the other hand, for many hydrological applications, often the runoff behaviour during a melt season is important, for which the assumption of melt forms is justified.

The sentence in question is P15 11 (original manuscript): "This negative feedback on snow grain type could mean the melt forms are the only crystals that need a modeled water retention curve, but this claim needs validation"

This is a matter of wet snow metamorphism speeds, which should be validated experimentally (via microstructure experiment, or a model sensitivity study). We agree that studies using a time scale of "melt season" melt forms should be sufficient. However if the rate is very fast (~30 min), melt forms may be justified for applications which use a shorter time scale.

The reviewer brings up a good point here. The bucket model has been shown to provide reliable results for runoff behavior for

5 longer periods (Brun et al 1989 (fig 9), Brun et al 1992, (fig, 6)). Motivation to add the Richards routine to Crocus come from a desire to better simulate the first wetting of the snowpack, and the distribution of water over the snow layers. Improvements on longer scale application are welcome, but a long term goal is to develop snowpack models to a point where first wetting can be modeled. The work done for this manuscript, does not reach this point but it is a necessary first step, from switching from the empirical routines to physical ones.

#### 10 **3.9**

p15,119: This is a bit confusing wording, as principally, I would say that snow layers are initialized with the "pre-wetting" amount. But here, it is probably meant initialization when the routine is being called during a Crocus time-step P 15 119 "However, 83% of snow layers were initialized in the Richards routine with a LWC< 10%"

We changed it to "...83% of the snow layers entered the Richards routine..."

#### 15 **3.10**

p15,l26-28: Although I agree with the statement, it cannot be considered a conclusion of \*this\* work. It has not been demonstrated that the water flux over the crust is over- or underestimated (no validation done), neither has it been shown that the simulations are sensitive to the hydraulic parameters for crusts (no sensitivity study done)

p2, 117 we state results from Jordan (1995), that shows that waters behavior around crust layers is not well understood, some

- 20 crusts promote flow and others prevent it. Therefore, the water retention curve has to have both high and low suctions when compared to surrounding snow layers. Regardless of waters behavior we are certain that the grain size used in the parameterization of the retention curve and the conductivity function is wrong, since crusts don't have individual snow grains. Because theory breaks down when it comes to crust layers there is no amount of quantifiable validation that can justify that crust are modeled in a physical way with the current parameterization. If the model is not sensitive to this error is a different question that should be validated/quantified. As far as we know this concern has not been addressed in other studies.
- 25 question that should be validated/quantified. As far as we know this concern has not been addressed in other studies.
  Our justification for using this parameterizations in the Richards routine is that there are no other parameterizations for ice

#### 3.11

crusts available.

Fig. 5: This figure is only mentioned once in the manuscript, and is not discussed at all. Please discuss the agreement betweenmodel and observation, or remove the snow profile.

We removed the figure.

# 3.12

I think the manuscript should not only show results for LWC distributions inside the snowpack, but also snowpack runoff



Soil Wetness Index1

# 5 Figure C Top soil layers water content for the synthetic data set, red is bucket routine, blue is Richards routine. Black arrow shows timing of 2<sup>nd</sup> snow event.

Figure C shows a plot of the top soil layers LWC, which is not snowpack runoff but a result of snowpack runoff. The synthetic data set was designed to highlight differences between the routines over a wide range of water input rates (melt in this case). Therefore, it is not expected that the bucket routine and the Richards routine have similar flux to the soil with the synthetic data set.

This plot shows that the Richards routine is able to move water from the snowpack to the soil column. The timing of the soil wetness increase agrees well with the timing of water percolation in Fig. 9A (black arrow shows time of  $2^{nd}$  snow event).

15

10

#### **3** Technical corrections / minor comments:

• General: note that Calonne et al. (2012) determined permeability, which can be related to conductivity. But in principle they did not publish conductivity experiments.

We have corrected this in the revised manuscript.

General: please mention somewhere the CPU time needed to run the simulations, compared to the bucket scheme.
 There are many factors that affect the run time for simulations. Using our "default" settings for this manuscript:
 Convergence

head error < 1e-3 m theta error < 1e-5 unitless

10 mesh bal <1e-4 m

Crocus time step of 900 s

\*Output saved 900 s

\* Normal Crocus default saves output every 3 hr. or 10800 s. With Richards routine the plots look like they have randomly high pixels when the plot resolution is 3 hr. Saving the output so frequently is a major contributor to the run time.

15

The synthetic simulation with Richards took 9m 38s where with the bucket it took 8m 46s. Adapting the pre-wetting amount, convergences criteria (mesh\_bal limit), time step and saving output resolution has a major influence over the runtime. We think it is not useful and misleading to report on the runtime of Crocus in this manuscript because many of the variables will likely change with further development of the Crocus model.

# • General: there is a change of tense sometimes, compare for example section 4.3 with 3.4.

We have corrected this in the revised manuscript.

• General: sometimes "Figure" and sometimes "Fig." is used to refer to figures.

We follow the rule of GMD, Fig. should be used unless at the start of a sentence where Figure is used.

• Abstract: "this routine is based on". Why the wording "based on"? I would write here: "this routine solves Richards equation".

25 We have changed this in the revised manuscript.

• p2,12-3: note that simulations using Richards Equation have already been used for the assessment of wet snow avalanche activity (Wever et al., 2016a) and for determining the initial conditions for wet snow avalanche dynamics simulations (Vera Valero et al., 2016). Given that the authors discuss this topic in particular, they may consider citing these studies here. Below sentence with citations have been added.

30 "A physically based water percolation model has been used along with weather station data to improve forecasts of wet snow stability (Wever et al., 2016a), and for determining initial conditions for simulations of avalanche dynamics (Vera Valero et al., 2016)." • p2,116: This would not be the way I would explain the precondition for flow fingering, but I also have not the evidence to object against it. Maybe verify with DiCarlo (2013)? I think this is a more up-to-date citation that may be cited here aswell. The sentence in question (below) was not changed in the modified manuscript.

5 "Pressure gradients acting against the gravity may induce the formation of preferential flow channels, as flow channels in soil occur where capillary pressure gradient opposes the waters flow direction (Philip, 1975)."

The reference suggested DiCarlo (2013) is a detailed review of finger flow in sand and soil with a strong focus on characterizing finger flow behavior for modeling. Since the Richards routine does not account for finger flow we do not think it is necessary

10 to described flow fingers in such detail. The sentences purpose is to state that finger flow occurs and probably has a connection with suction (were pressure gradients oppose gravity).

We believe this is similar to the criteria used by Würzer et al. (2017) for initiating finger flow in the snowpack. However, we are unsure if the term "pressure head" in Würzer et al. (2017) refers to, pressure head or suction (negative pressure head).

15 • p3,l3: "Greenland Ice Sheet" (capitalized)

We have corrected this in the revised manuscript.

• p3,l8: "ice crusts": in line with the International Classification (Fierz et al., 2009), this should be "layers". The mentioned study concerned more with ice layers than with ice crusts. Similar p3,l4: lenses are discontinuous ice layers. In this case, I think it should be layers rather than lenses.

20 We have corrected this in the revised manuscript.

• p6,119: "kr" should be kr.

We have corrected this in the revised manuscript.

• p7,117: Here and elsewhere: I prefer "conductivity of snow"

We have changed this in the revised manuscript.

**25** • p7,eq 13: I assume the second equation should read  $\Delta zbot$ 

We have corrected this in the revised manuscript.

• p7,l14: I assume the reference should point to Eq. 13 instead of 11.

We have corrected this in the revised manuscript.

- p7,l24: citation style of Celia et al. is wrong (without parenthesis)
- 30 We have corrected this in the revised manuscript.

• p8,l3: "computation step" is a vague term. I think this refers to the iteration level k+1? Maybe write: "the pressure head h at iteration level k+1.".

#### We have corrected this in the revised manuscript.

• p8,129: maybe specify: "Air temperature become as cold ..."

We have corrected this in the revised manuscript.

• p9,114-15: please rewrite sentence

We have corrected this in the revised manuscript.

• p10,12: wrong figure reference

5 We have corrected this in the revised manuscript.

• p11,110: "there is a complicated one-to-many relationship ..." Actually it seems to be very simple: below 2x10-5 there seems to be almost no effect, so the prewetting should just be below this value...

This figure and sentence have been taken out of the revised manuscript.

• p11,l14-15: I understand what is meant here, but it may be unclear for readers without a strong snow modelling background.

10 I would explain the remeshing procedure in the model description.

"The alternating dry wet pattern appears before the second snow event when  $T_{Crocus} = 60$  sec. The pattern smooths out during the second snow event, probably due to rearranging of the snow layer sizes."

These two sentence have been removed because the figure no longer shows this effect due to the head based pre-wetting and

15 the free flowing boundary condition.

• p12,l10: typo: "witch"

We have corrected this in the revised manuscript.

• p12,l21: "simulated data sets simulation" I suggest "synthetic data sets simulations"

This sentence has been removed, because results show free-flowing bottom boundary.

• p13,117: "and but does not have" please reformulate

This whole section has been changed.

• Appendix A: This time stepping is method is very similar to the one I used, and I based it on the work by Paniconi and Putti (1994). Maybe give them credits by citing their work?

We added this citation.

25 • p14,119: "on visual grain size measurements"

We have corrected this in the revised manuscript.

• p15,l7: "where, " —> ", where"

We have corrected this in the revised manuscript.

• p15,l11: "grain" —> "grains"

30 We have corrected this in the revised manuscript.

• p16,19: "is used to deal"

We have corrected this in the revised manuscript.

• p16,l24: "criteria are met"

We have corrected this in the revised manuscript.

• p16,l28: "within"

We have corrected this in the revised manuscript.

• p17: eq. A1 is not numbered as such

We have corrected this in the revised manuscript.

5 • p17,113: "lower density snow that found": please reformulate.

Changed to "For use in the Richards routine this parameter set would have to be applied to lower density snow than used to create it."

• p17,l17: "density not included"

We have corrected this in the revised manuscript.

10 • p17,119-20: please reformulate. This sentence cannot start with "while".

# While has been taken out.

• Appendix B.3: Note that it should read "Daanen" and not "Dannen".

We have corrected this in the revised manuscript.

• References: a few still point to discussion papers, where final papers have already been accepted and published, for example:

15 Avanzi et al. (2015) and Wever et al. (2016). Please provide DOIs consistently when available.

References have been updated as needed.

• Fig. 5: Specify here also from which date the snow profile is.

Figure removed. See section 3.11 of this document.

• Fig. 7: subfigure B is wrongly labelled C

20 We have remade most of the figures and made sure they had correct titles and labels.

Brun, E., Martin, E., Simon, V., Gendre, C. and Coleou, C.: An Energy and Mass Model of Snow Cover Suitable for Operational Avalanche Forecasting, J. Glaciol., 35(121), 333–342, doi:10.3198/1989JoG35-121-333-342, 1989.

25 Brun, E., P. David, M. Sudul, and G. Brunot. "A Numerical Model to Simulate Snow-Cover Stratigraphy for Operational Avalanche Forecasting." Journal of Glaciology 38, no. 128 (January 1, 1992): 13–22. doi:10.3198/1992JoG38-128-13-22.

Birkeland, K. W., K. J. Hansen, and R. L. Brown. "The Spatial Variability of Snow Resistance on Potential Avalanche Slopes." Journal of Glaciology 41, no. 137 (1995): 183–190.

30

Jordan, R.: Effects of Capillary Discontinuities on Water Flow Retention in Layered Snow covers, Def. Sci. J., 45(2), 79, 1995.
Paniconi, Claudio, and Mario Putti. "A Comparison of Picard and Newton Iteration in the Numerical Solution of Multidimensional Variably Saturated Flow Problems." *Water Resources Research* 30, no. 12 (1994): 3357–3374.

5 Tinet, A. J., L. Oxarango, R. Bayard, H. Benbelkacem, Guillaume Stoltz, M. J. Staub, and J.-P. Gourc. "Experimental and Theoretical Assessment of the Multi-Domain Flow Behaviour in a Waste Body during Leachate Infiltration." *Waste Management* 31, no. 8 (2011): 1797–1806.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E. and Willemet, J.-M.: The detailed snowpack
scheme Crocus and its implementation in SURFEX v7.2, Geosci Model Dev, 5(3), 773–791, doi:10.5194/gmd-5-773-2012, 2012.

Würzer, Sebastian, Wever, Nander, Juras, Roman, Lehning, Roman, and Jonas, Tobias, "Modelling Liquid Water Transport in Snow under Rain-on-Snow Conditions-Considering Preferential Flow." Hydrology and Earth System Sciences 21, no. 3:

15 1741, 2017

Wever, N., Fierz, C., Mitterer, C., Hirashima, H. and Lehning, M.: Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model, The Cryosphere, 8(1), 257–274, doi:10.5194/tc-8-257-2014, 2014.

20 Reply to review 2

# **Response to review:**

We would like to thank the reviewer for the comments.

# **Response to comments:**

For this section the authors response are shown in black, where the reviewers comments are in blue. Quotes ("") and *italic font* 

25 show changes to the manuscript.

Overall, this is an interesting modeling paper that describes the improvements in the Crocus(V7) snowpack model. The current modification improves the modeling of the water storage in the snowpack, and once further validated, could be an invaluable contribution to the state of art in snowpack modeling. Below I have a couple questions and minor suggestions, most of which

30 are editorial.

Abstract L15. Pendular and funicular regime (scientific jargon). Need to explain that first.

We added to the abstract to further explain the jargon.

"Snow layers often reached a point where the ice crystals surface area is completely covered by a thin film of water (the transition between pendular and funicular regimes), where feedback is expected to be nonlinear.."

5

Section 2. First paragraph. I am confused. Is it a three models coupled system (SURFEX, ISBA, and Crocus)? If yes, then title should be changed.

The Crocus model has been developed as a standalone model. However, Crocus is often run coupled with two other models (SURFEX and ISBA). Crocus was coupled to "Interactions between soil, biosphere and atmosphere" (ISBA), for a wider range

10 of bottom boundary conditions (Vionnet et al 2012, Noilhan and Planton, 1989). ISBA is coupled to SURFEX for a similar reason regarding the upper boundary.

Because the changes are all contained in the Crocus model we feel the title should include Crocus, but have added SURFEX to the title. We have adapted the 1<sup>st</sup> paragraph on section 2 of the revised manuscript to make connections between the models more obvious

15 more obvious.

The current formulation of the Richards equation 1 does not account for presence of ice and air in snowpack. How do authors think the results would change by introducing them in the equation 1?

The Richards equation does account for ice, air and water in the snowpack via the water retention curve and the hydraulic

20 conductivity. Both of these parameterizations are based on the snow layers dry density (ice vs air) the snow grains size (distribution of ice and air) and  $\theta$ , the water content.

# P4. L30. h should it be H?

25 Equation 2. shows the relationship between H and h.

"H is the hydraulic head, which is the sum of the pressure head (h) and the elevation (z), which is negative because z is positive downward (Eq. 2)."

H = h - z

Equation 2

#### 30

P5. L2,5. The notation is confusing pressure head (h), and retention curve h(theta)?

We took out  $h(\theta)$ , to avoid confusion. The water retention curve relates head values (h) to water content values ( $\theta$ ) and vice-versa.

### P5. L10. Equation 3. If it is water retention curve function then should be h(theta)

Equation 3 shows  $\theta(h)$  which is the inverse function of  $h(\theta)$ . We use the relations  $\theta(h)$  and  $h(\theta)$  in our routine. The Van Genuchten (1980) (VG) parameterization is used for the relation between water content and pressure head which can be seen in Fig.2. Figure 2 shows for a given grain size and snow layer density there is a one to one relation between h and  $\theta$ . We now use only " $\theta$ " and "h", to make notation clearer.

5

15

25

When water percolates through the snow layer and freezes at the bottom. The pressure and volume at the bottom grid cell increases due to ice formation. How does the model handle the increase in pressure due to ice formation?

This behavior described by the reviewer can be seen in the Filefjell results (Fig. 6 D of the revised manuscript). In the Filefjell case the ice layer at the bottom of the snowpack becomes very dense. The model will eventually crash due to extreme values 10 of the suction and conductivity if the density becomes too great.

I assume "increase in pressure" means increase in suction (negative pressure), since this model does not deal with positive pressures (no pooling of water). Regardless of the terminology it is the pressure gradient (dh/dz) what matters for water percolation. It is not obvious what will happen when one layer becomes denser. The hydraulic conductivity and the water

retention curve will both be affected by the change in density and also the change in  $\theta$  because the pore spaces decrease.

In general it is not well understood how water interacts with crust layers it has been reported to act as a barrier layer but also a conduit (Jordan, 1995). Better parameter sets are needed for crust layers as stated in section 6.5.

20 We feel very dense layers will not be problematic if new parameter sets for crusts are developed and feedback from the snow compaction routine is updated for high water contents.

#### It would be interesting to plot pressure head changes with time on Figures 8 and 9.

The saturation (S defined in equation 6) is the major factor in a snow layers pressure head. This can be seen in Fig. 2. Snow density and grain size have a smaller effect on the pressure head of the snow pack.

- Because the pressure changes so drastically with regards to S (or  $\theta$ ), we feel it is better to show how  $\theta$  changes with time and the density evolution instead of changes in h. The histogram in Fig. 2 shows how pressure head acts at different water contents, this is particularly interesting to see that the saturation is always < 20% for the simulated forcing.
- Section 6.6. Authors are referring to the different routines, like 'C13' and so on. It is confusing to read those notations and 30 have no idea where they come from. For clarity, I suggest to make a chart including all the important routines. C13 and B92 are parts of the SNOWCROMETAMO routine shown in figure 1. We make this clearer in section 6.5 by describing the relationship between C13, B92 and the routine SNOWCROMETAMO. We also refer to figure 1.

"The water retention curve and hydraulic conductivity functions are not designed for use on crust layers. Furthermore, Crocus' snow metamorphism routine (SNOWCROMETAMO, Fig. 1) does not work well for crust layers, because dense crusts do not have individual grains, but rather a solid ice layer with bubbles. There is a choice of routines in SNOWCROMETAMO, the

5 B92 (Brun et al. 1992) and the C13 routines. The B92 routine uses sphericity and dendricity. The C13 routine uses optical diameter, which is used as an approximation for visual grain size in the Richards routine."

There are figures, like Figure 11, which have the same legend. I suggest to make one legend, and put A) and B) as a subtitle or place the text inside the figure

10 Figure 11 (Fig. 9 in revised manuscript) has been updated with A and B and the time step duration printed inside the plot area.



15 Figure 9: Water percolation in the simulated data set scenario with different time steps: A)  $T_{Crocus}$ = 900 s (15 min), B)  $T_{Crocus}$ = 60 s both plots use the free-flowing bottom boundary with pre-wetting set to  $\theta_{min}$  = 10<sup>-5</sup>. The 60s simulation has water at the bottom of the snowpack 4 days before the 900 s simulation. "

# References

Brun, E., David, P., Sudul, M., and Brunot. G.: A Numerical Model to Simulate Snow-Cover Stratigraphy for Operational Avalanche Forecasting. J Glaciol 38(128), 13–22. doi:10.3198/1992JoG38-128-13-22., 1992

5 Jordan, R.: Effects of Capillary Discontinuities on Water Flow Retention in Layered Snow covers, Def. Sci. J., 45(2), 79, 1995.

Noilhan, J. and Planton, S.: A simple parameterization of land surface processes for meteorological models, Mon. Wea. Rev., 117, 536–549, 1989

10 Van Genuchten, M. T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44(5), 892–898, 1980.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E. and Willemet, J.-M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geosci Model Dev, 5(3), 773–791, doi:10.5194/gmd-5-773-2012, 2012.

# **SECTION 3: Author's changes in manuscript**

# Implementation of a physically based water percolation routine in the 20 Crocus/SURFEX (V7.3) snowpack model

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**Abstract.** We present a new water percolation routine added to the 1D snowpack model Crocus as an alternative to the empirical bucket routine. This routine is based onsolves the Richards equation, and which describes flow in an of water through

30 unsaturated porous <u>mediumsnow</u> governed by capillary suction and hydraulic conductivity of <u>the</u> snow layers. We tested the Richards routine on two data sets, one recorded from an automatic weather station over the winter of 2013-2014 at Filefjell, Norway, and a simple synthetic data set. Model results using the Richards routine generally lead to <del>thinner and denser simulated</del> erust layers compared to the bucket routine. Wet snow<u>higher water contents in the snow layers.</u> Snow layers often reach reached a point where the ice crystals surface area is completely covered by a thin film of water (the transition between the pendular and funicular regimes, with 17), where feedback is expected to be nonlinear. With the synthetic simulation 17.5% of snow layers obtaining obtained a saturation of >10% and 4.30.45% of layers hadreached saturation of >15% for the synthetic

- 5 data set.%. The Richards routine had a maximum liquid water content of <u>167.3173.6</u> kg m<sup>-3</sup> where the bucket routine had a maximum of 42.1 kg m<sup>-3</sup>. To express We found that wet snow processes, such as wet snow metamorphism and wet snow compaction rates, are not accurately represented at higher water contents. These other routines feedback on the parameterization used by the Richards routines, which rely heavily on grain size and snow density. The parameter sets available in literature do not represent all the snow types that can be found in a natural snowpack. The parameterization of the water
- 10 retention curve and the hydraulic conductivity of snow layers, the Richards routine heavily relies on accurate density and grain size estimations. We found the Richards routine was sensitive to the chosen modelling time step. The time step dependency is a result of feedback between the water percolation routine and the snows compaction and metamorphism routines.poorly represent crust layers. We show that the new routine has been implemented in the Crocus model, but due to feedback amplification of and parameter uncertainties through a number of feedbacks, meaningful applicability is limited until new and
- 15 better parameterizations of water retention. Updating/adapting other routines in Crocus, specifically the snow compaction routine and the grain metamorphism routine, is developed for different snow types.needed before Crocus can accurately simulate the liquid water content within the snowpack using the Richards routine.

#### **1** Introduction

Knowledge about the process of water percolation in the snowpack is necessary for improving many applications such as flood forecasting, river and reservoir management, slope stability and avalanche forecasting. Measuring liquid water content (LWC) of snow layers is not practical because it is time consuming and, LWC has the ability to dramatically change over the timescales, that are considerable shorter than those of observations (Techel and Pielmeier, 2011; Wakahama, 1975). When water is introduced to a snowpack, snow stability is able to change rapidly, because cohesion strength depends on the amount of water saturation (Ambach and F. Howorka, 1966; Brun and Rey, 1987; Hartman and Borgeson, 2008). Because LWC of a

- 25 snowpack can change quickly, avalanche forecasters, mountain guides, researchers and rescue workers, have reported that they do not fully trust classical snow stability tests (e.g. Rutschblock and extended column tests) when performed in wet snow (Techel and Pielmeier, 2009). To improve flood and avalanche forecasting capabilities, detailed snowpack hydraulic information on fine spatially and temporally scales is required. One way to achieve a detailed view of snow hydraulics is to supplement meteorological and hydrological observations with physically based percolation modeling. <u>A physically based</u>
- 30 water percolation model has been used along with weather station data to improved forecasts of wet snow stability (Wever et al., 2016a), and for determining initial conditions for simulations of avalanche dynamics (Vera Valero et al., 2016).

Vertical water flow through a layered snowpack can occur in two different modes, matrix flow and preferential flow. Matrix flow is a diffusive flow through the pore space of the snowpack, which sets up a uniform water front. Preferential flow, also called finger flow, is when water quickly flows in channels to deeper layers (Marsh and Woo, 1984). A combination of both flow schemes occurs in a snow layer; often preferential flow will initiate wetting a dry snow layer, followed by an expansion

5 of flow paths that will end up in matrix flow (Williams et al., 2010). As water percolates through an isothermal snowpack, preferential flow paths are created, and water transport through the snowpack becomes very efficient (Colbeck, 1979). Using multi-color dye tracer experiments, Schneebeli (1995) has shown that the preferential flow channels in an isothermal snowpack can migrate over time.

Gravity and capillary forces govern water movement in unsaturated snow (Colbeck, 1972; Jordan et al., 1999). Capillary forces

- 10 arise from adhesion and surface tension of liquid water inside the pore space of the snowpack. Snow layering produces vertical gradients since capillary pressure has an inverse relationship to pore size, (Wankiewicz, 1978). Pressure gradients acting against the gravity may induce the formation of preferential flow channels, as flow channels in soil occur where capillary pressure gradient opposes the waters flow direction (Philip, 1975). Two common textural barriers are crust layers and neighboring snow layers with sharp grain size differences. Assessing the hydraulic conductivity of textural barriers is not
- 15 straightforward, because layers behavior may vary greatly; such as crusts which can act as an impermeable layer or act similar to vertical conduits (Jordan, 1995). Fine-grained snow layered above coarser grains give rise to flow barriers due to capillary pressure gradients opposing gravity. An area of high saturation can be found above such barriers and lateral water flow due to suction, terrain slope and water pooling are a common result (Colbeck, 1974b; Williams et al., 2010).
- Physically-based models of water percolation through snow were first developed to describe gravitationally driven flow through isotropic isothermal snow neglecting capillary effects(Colbeck, 1972). Model complexity evolved and snow layering was introduced (Colbeck, 1974b, 1975), and heterogeneous flow where water is routed to deeper layers via flow channels (Colbeck, 1979). Model development on percolation in a cold snowpack was addressed by including thermodynamics to percolation models (Bengtsson, 1982; Colbeck, 1976; Illangasekare et al., 1990). Capillary forces were introduced in some early models despite the deficiency in parameter sets (Colbeck, 1974a; Jordan, 1983; Wankiewicz, 1978). Wankiewicz (1978)
- 25 concluded that more information on snow microstructure is needed to improve modeling of water percolation through a layered snowpack. Some recent models include gravity and suction driven preferential flow in isothermal snow layers (Hirashima et al., 2014; Katsushima et al., 2009).

Measuring the hydraulic conductivity and water retention of snow layers is a time consuming task performed in a cold lab and so far cannot be conducted in the field or even deployed as an autonomous recording system. Yet, new parameterizations of

30 the retention curve (Yamaguchi et al., 2010, 2012) and permeability, which relates to hydraulic conductivity (Calonne et al., 2012) have been developed recently. These developments have been taken advantage of in percolation models based on Darcy's law (Hirashima et al., 2010) and the Richards equation (Wever et al., 2014, 2015). Hydraulic conductivity and water retention of snow layers give insight on how the snowpack may evolve in regards to LWC. For instance, the 2012 surface runoff anomaly from the Greenland ice sheetIce Sheet can be explained by the reduced hydraulic conductivity of near surface

firn and ice layers. Growth of near surface ice <u>lenseslayers</u> prior to the 2012-melt-season caused a low hydraulic conductivity between surface layers and deep firn and ice layers. This effectively sealed off the available pore space in deep, cold firn which usually absorbed a large part of meltwater, thereby causing an increased amount of early season runoff (Machguth et al., 2016). Although having important consequences, few models are capable of adequately simulating the formation of ice layers or

- 5 lenses and their hydrological impact. A dual domain Richards based model has begun explaining preferential flow paths, which can reproduce some of the ice <u>crustslayers</u> present in the snowpack (Wever et al., 2016). The Richards equation when applied to snow describes water percolation through a porous ice matrix considering the water retention curve and the hydraulic conductivity of snow layers. A one-dimensional Richards equation solver was recently added to the detailed snow model SNOWPACK (Wever et al., 2014, 2015). We added a similar physical water transport routine to the snowpack model Crocus.
- 10 This paper will discuss the parameterization, sensitivity of the new routine and compare difference in water percolation with the bucket routine for two data sets.

# 2 SURFEX, ISBA and Crocus description

<u>Crocus is a standalone snowpack model, however Crocus is often run coupled to the SURFEX and ISBA models for dynamic</u> boundary conditions at the snow/atmosphere and snow/ground interfaces. **SURFEX is an atmosphere to surface coupling** 

- 15 model, with ISBA (Interactions between Soil, Biosphere, and Atmosphere) being the land surface scheme (Noilhan and Mahfouf, 1996). The Crocus model (Brun et al., 1989) is the most detailed of three snowpack models embedded in the ISBA routine. It was classified in the group of "most complex snow models" by the Snow Models intercomparison project (Etchevers et al., 2004). Crocus is a one-dimensional multi-layer model that describes the snow microstructure evolution based on environmental conditions. This model simulates the snowpack from the first snow to melt out, by calculating mass and energy
- 20 fluxes between snow layers and its interface with the underlying ground and overlying atmosphere. Processes that act on and in the snowpack are summarized in Vionnet et al. (2012), which are represented in Crocus by routines (shown in Fig. 1). These routines run in a sequential manner. This paper will discuss a new option for the water percolation routine for the Crocus model but does not consider aspects of coupling between Crocus and other components in ISBA and SURFEX. For a detailed description of the implementation of Crocus in SURFEX and a detailed description of Crocus see Vionnet et al. (2012).
- 25 The SURFEX/ISBA-Crocus default time step is 15 minutes denoted (T<sub>Crocus</sub>), but in this study, T<sub>Crocus</sub> will be varied to examine sensitivity-and degree of coupling to the soil. Crocus requires the following forcing variables; air temperature, humidity, wind speed, incoming shortwave and longwave radiation, solid and liquid precipitation rate and atmospheric pressure (Vionnet et al., 2012). FocingForcing data is generally provided by highly instrumented test-sites, output from numerical weather prediction models (Vernay et al., 2015) or an assimilation/combination of the two (Durand et al., 2009).
- 30 The water transport and refreezing processes are expressed in the SNOWCROREFREZ routine (Fig. 1). Feedbacks exist between the liquid water transport (SNOWCROREFREZ) and other processes such as snow compaction

(SNOWCROCOMPACTN) and metamorphism (SNOWCROMETAMO). It is important to realize that changes to the amount and timing of water percolation will feedback to other routines and affect other snowpack variables.

# 2.1 The bucket approach

To describe water percolation in snow, Crocus has been using an empirical based routine, the so-called bucket routine that has

- 5 been calibrated using long time series of lysimeter data (Morin et al., 2012) and drainage experiments on the irreducible water content (Coleou and Lesaffre, 1998). The bucket routine uses a holding capacity, defined by a percentage of the snow layers pore space. A snow layers "bucket" is filled up with water when water is introduced via rain or melt. Once the bucket is full, overflow occurs to fill up the subsequent snow layer's bucket, restricting water motion to downward direction. <u>Crocus-The</u> "bucket routine usessize" or holding capacity has been defined as 5% of a snow-layers porespore spaces volume as the holding
- 10 capacity or "bucket size" as default, however this can be adapted if needed (Vionnet et al., 2012). For Crocus, the holding capacity is proportional to the density of the snow layer andbut is independent of snow grain type or surrounding environment-(adjacent snow layers, soil, etc.). The size of the "buckets" is not agreed upon in literature, which is discussed in detail in Lafaysse et al. Sec. 3.7 (2017). Singh et al. (1997), found water holding capacity to be 6.8% of a snow layers volume (note this is total volume not just pore space). However, when an impermeable layer was set beneath it, the holding capacity rose to the space of the space of the space.

15 14.2%, showing that the surrounding environment has an effect on LWC of a snow layer, at least for a short time period.

#### **3** Implementation of Richards routine in Crocus

Richards routine describes motion of water through an unsaturated porous matrix considering capillary driven and gravity driven flow. Recent developments in parameterizing snowsthe conductivity of snow and snowpack water retention allow for the implementation of Richards equation in layered snow pack models. In contrast to the bucket model, the Richards routine

- 20 allows for upward motion of water if capillary pressure conditions are suitable.
- A Richards solver has recently been implemented in the SNOWPACK model (Wever et al., 2014). A comparison between the bucket percolation and Richards percolation in the SNOWPACK model showed that Richards routine performed better than the bucket routine for a sub-day time scale when compared to lysimeter data (Wever et al., 2014, 2015). However, Avanzi et al. (2015) found speed of water transport with the Richards equation over a capillary barrier to be underestimated when compared to experimental results, but the model reproduces an increased LWC above barriers.
- This paper discusses the implementation of a similar routine in the Crocus model. The new routine SNOWCROPERCO\_RCH represents an alternative to the SNOWCROPERCO routine (bucket) (Fig. 1). We use the snow layer discretization in <u>CorcusCrocus</u> as a mesh for solving the Richards equation.

Richards equation (eq. 1) is a non-linear partial differential equation describing the water mass balance of snow with water 30 fluxes expressed using a generalized Darcy law taking into account the dependence of hydraulic conductivity with water content. Its main variables are the pressure head (h) and the volumetric liquid water content ( $\theta$ ).

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z} \left( K(\theta) \cdot \frac{\partial H}{\partial z} \right) \tag{1}$$

 $K(\theta)$  is the hydraulic conductivity which is a function of the volumetric water content ( $\theta$ ), and t and z denote time and depth (positive downward). H is the hydraulic head, which is the sum of the pressure head (h) and the elevation (z), which is negative because z is positive downward (Eq. 2).

(2)

5 
$$H = h - z$$

The water retention curve  $h(\theta)$  and the hydraulic conductivity function needs to be expressed for each snow layer.

# 3.1 Water retention curve

10

20

30

Using the Van Genuchten (1980) parameterization, the water retention curve can be expressed with Eq. (3) if four parameters ( $\alpha$ , n,  $\theta_r$ ,  $\theta_s$ ) are known. Where  $\alpha$  and n are the Van Genuchten fit parameters (see Eq. 4) and  $\theta_s$  (Eq. 5) and  $\theta_r$  (Eq. 7) are the saturated water content and the residual water content, respectively.

$$\theta = \theta_r + (\theta_s - \theta_r) \cdot (1 + (\alpha \cdot h)^n)^{-\left(1 - \frac{1}{n}\right)}$$
(3)

Recent experiments (Yamaguchi et al., 2010, 2012) and theoretical estimates based on prior experiments (Daanen and Nieber, 2009) propose parameter sets for these four variables. This paper utilizes the Yamaguchi et al. (2012) parameter set (we also provide options in Crocus to use two alternative parameter sets, see Appendix B).

15 
$$\alpha = 4.4 \times 10^6 \cdot \left(\frac{\rho_{snow}}{D \cdot 1000}\right)^{-.98}$$
  
 $n = 1 + 2.7 \times 10^3 \cdot \left(\frac{\rho_{snow}}{D \cdot 1000}\right)^{0.61}$ 
(4)

Where  $\rho_{\text{snow}}$  is the dry density of the snow, D is grain size diameter and P is porosity (volume of pore space).

$$\theta_{\rm s} = 0.9 \times P \tag{5}$$

Yamaguchi et al. (2012) performed a drainage experiment to obtain the Van Genuchten fit parameters. The gravitational drainage experiment assumed that the saturated hydraulic conductivity  $\theta_s$  for snow to be 90% of the pore spaces. This is due to small air bubbles that become trapped in the pores between the snow grains as the snow saturates. One should note that

Yamaguchi's study examined samples of melt form and small rounded grains with a density range of 361- 636 kg m<sup>-3</sup> and grain size range of 0.05 mm to 5.8 mm. Columns of snow were saturated with 0°C water and left to drain. The study found a parameter set for melt form crystals and concluded that rounded crystals could not be represented with the same parameter set

as melt forms.

The Van Genuchten parameterization being applied is adopted from soil science for flow in an unsaturated soil matrix. The residual water content in snow presents specific challenges that are not present when applied to soil. Snow is often completely dry via phase transform, where soil is assumed to always have a small amount of liquid water.  $\theta_r$  is defined as the amount of water that remains in the porous medium with infinite suction being applied. It corresponds to disconnected water patches entrapped in the pore system. Following Yamaguchi et al (2010), a residual water content  $\theta_r = 0.02$  is adopted. However, the

LWC of a snow sample can further 'dry out' via evaporation and freezing, resulting in a negative saturation (S) (Eq. 6).

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$
 Where  $\theta_r < \theta < \theta_s$ 

Negative saturation (where  $0 \le \theta < \theta_r$ ) is physically possible with phase change, but causes numerical problems. Therefore, saturation needs to be restricted between 0 and 1. To overcome this limitation we use a continuous piecewise function to keep  $\theta > \theta_r$  (Eq. 7).

$$5 \quad \theta_r = \begin{cases} .02 & if \quad \theta > .02 \\ .75 \cdot \theta & if \quad \theta < .02 \end{cases}$$
(7)

To avoid infinite values of the hydraulic head (Fig. 2), and hydraulic conductivity (Fig. 3, Sec. 3.2) of 0 when approaching LWC=0 a small amount of water needs to be added to snow layers that are completely dry. In this study we call this added water 'pre wetting' or  $\theta_{min}$ . Pre wetting of volumetric water content  $\theta_{min} = 10^{-6}$  (unitless) (as default, but a sensitivity study varies this amount) is added to layers that have  $\theta < \theta_{min}$  to keep the hydraulic conductivity value numerically different from

- 10 zero. To conserve mass and enthalpy of the snow pack the water added to a dry ( $\theta < \theta_{min}$ ) layer is melted from the layers ice/snow, keeping the density of the layer unchanged. When this is done the snow layers temperature is cooled according to the amount of latent heat required to melt ice corresponding to  $\theta_{min}$ . This means that in this step, our implementation allows the existence of liquid water, even at temperatures below 0°C. Nevertheless, this is a technical maneuver to avoid runaway head values and conductivity values approaching zero for dry snow layers, and after the water motion is described, the water
- 15 balance is closed again by refreezing  $\theta_{\min}$  if required by temperature conditions. Water is added to the dry layers in a way where all dry layers start with the same pressure head, which corresponds to the minimum pressure of the dry layers, with  $\theta = \theta_{\min}$ . In this study we call this added water 'pre-wetting'. The default value of  $\theta_{\min} = 10^{-6}$  (unitless) was chosen however we varied the value of  $\theta_{\min}$  in a sensitivity test.

#### 3.2 Hydraulic conductivity

20 Hydraulic conductivity (K) is a function of water content ( $\theta$ ) see Eq. (8), as a snow layer gets wetter the conductivity will increase (Fig. 3).

$$K(\theta) = k_r(\theta) \times K_{sat}(D, \rho_{snow}) \tag{8}$$

The Van Genuchten-Mualem equation (Van Genuchten, 1980 and Eq. 9) is used to calculate the relative permeability  $k_r$ . It is implemented as a function of h (using Eq. 3 for the relation between h and  $\theta$ ):

25 
$$k_r = \left(1 + |\alpha \cdot h|^{\frac{1}{1-m}}\right)^{\frac{-m}{2}} \cdot \left(1 - \left(1 - \left(1 + |\alpha \cdot h|^{\frac{1}{1-m}}\right)^{-1}\right)^m\right)^2$$
 (9)

Hydraulic conductivity reaches a maximum when the snow matrix is saturated, known as conductivity at saturation ( $K_{sat}$ ). Since conductivity at saturation is dictated by snow structure, which is a complex system it is described by a simple statistical model in both parameters sets available. It should be noted that both  $K_{sat}$  (Eq. 10) and  $k_r$  (Eq. 9 through  $\alpha$  and m) are dependent on the dry density of the snow and the grain size.

30 Calonne et al (2012) used 3D images of snowsthe microstructure of snow to derive the permeability (conductivity) from different snow types and densities ranging from <100 kg m<sup>-3</sup> to ~550 kg m<sup>-3</sup>, seen in Eq. (8). Equation 8 is the preferred

parameter set due to the range of snow types and densities that went into deriving the equation (other alternatives <u>are</u> described in appendix B).

$$K_{sat} = 3.0 \cdot \left(\frac{D}{2}\right)^2 \cdot exp(-0.013 \cdot \rho_{snow}) \cdot \left(\frac{G \cdot \rho_{water}}{\mu_{water}}\right)$$
(10)

G is gravity 9.816 m s<sup>-2</sup> and  $\mu_{water} = 0.001792$  kg m<sup>-1</sup> s<sup>-1</sup> the dynamic viscosity of water at 0°C.

# 5 3.3 Solving Richards equation

15

To reduce unnecessary computations the following 2 conditions need to be satisfied before entering the Richards routine:

- 3. There must be a snowpack. If there is < 3 layers of snow the bucket model will be used for water percolation.
- 4. There must liquid water. If  $\theta \le \theta_{\min}$ , and the rain flux (over the time step of 15 min)  $< 10^{-10}$  m, the percolation routine is skipped.

# 10 If one of these two conditions are not satisfied Crocus will be run without calling the Richards routine.

To solve Richards equation, we utilize the following strategy: A finite volume discretization is applied taking each snow layer as integration volume. The average pressure head of each snow layer (corresponding to its LWC) is supposed to apply in the center of the layer.

The water fluxes ( $\Phi$ ) are computed at the interface between layers. Counted positive when entering a snow layer, the flux at the top and the bottom are computed respectively as:

$$\Phi_{i,top}^{t+1} = K_{top}^{t+1}(\theta_i^{t+1}, \theta_{i-1}^{t+1}) \left( \frac{h_{i-1}^{t+1} - h_i^{t+1}}{\Delta z_{top}} + 1 \right)$$

$$\Phi_{i,bot}^{t+1} = K_{bot}^{t+1} \left( \theta_{i,}^{t+1}, \theta_{i+1}^{t+1} \right) \left( \frac{h_{i+1}^{t+1} - h_i^{t+1}}{\Delta z_{bot}} - 1 \right)$$
(11)

Where *i* is the index <u>for of each</u> snow layer (layer 1 at top of the snow pack). Values on the interface between two snow layers are indicated with *top* and *bot* (bottom) <u>subscriptsubscripts</u> respectively.

20  $K_{top}$  and  $K_{bot}$  are the hydraulic conductivity of the upper and lower boundary interfaces of layer *i*, respectively. To compute  $K_{top}$  and  $K_{bot}$  the arithmetic mean was used as an estimate of the conductivity at snow layers interfaces; shown in Eq. (10).

$$K_{top} = \frac{K_{i} \Delta z_{i} + K_{i-1} \Delta z_{i-1}}{\Delta z_{i} + \Delta z_{i-1}} \qquad K_{bot} = \frac{K_{i} \Delta z_{i} + K_{i+1} \Delta z_{i+1}}{\Delta z_{i} + \Delta z_{i+1}}$$
(12)

 $\Delta z_{bot}$  and  $\Delta z_{top}$  is the distance between layer mid points as described below in Eq. (4413).

$$\Delta z_{top} = \frac{\Delta z_i + \Delta z_{i-1}}{2} \qquad \qquad \Delta \overline{z_{top}} z_{bot} = \frac{\Delta z_i + \Delta z_{i+1}}{2} \tag{13}$$

- 25 Averaging conductivity of two adjacent snow layers with a simple arithmetic mean as an estimate for the interface value may be over simplifying the <u>snows</u>-conductivity <u>of snow</u>. Snow grain size, density and crystal types often have sharply defined boarders. These parameters would have great influence on the snow hydraulic conductivity. It could be argued that a piecewise function comprised of individual snow layer's conductivity better describes the vertical pattern of conductivity in the snow pack (Szymkiewicz, 2009). However, when a piecewise function was tested, "dry layers" (with 0<sub>min</sub>-that needed pre-wetting)
- 30 caused impermeable barriers and caused numerical problems for the simulation. Other options for combining conductivity

values of snow layers to estimate the interface are possible, but more research is needed to understand how the interface conductivity <u>at the interface</u> behaves.

The time discretization is a Crank-Nicolson finite differences scheme, which is second order accurate in time. The non-linearity of the equation is then dealt with the iterative methodology proposed by (Celia et al., (1990)). It approximates  $\theta_i^{t+1,k+1}$  by a truncated Taylor series Eq. (14).

$$\theta_i^{t+1,k+1} = \theta_i^{t+1,k} + \frac{d\theta}{dh} \Big|_i^{t+1,k} \left( h_i^{t+1,k+1} - h_i^{t+1,k} \right)$$
(14)

Where the superscript *k* refers to the evolution of the iterative process.  $\frac{d\theta}{dh}\Big|_{i}^{t+1,k}$  is the derivative of the retention curve (Eq. 3) computed analytically for  $\theta_{i}^{t+1,k}$  (or  $h_{i}^{t+1,k}$ ). The final discretized form of Richards equation (Eq. 1) including the Crank-Nicholson scheme with Celia decomposition reads as:

$$10 \quad \frac{\theta_{i}^{t+1,k} + c_{h}^{t+1,k} \left( h_{i}^{t+1,k+1} - h_{i}^{t+1,k} \right) - \theta_{i}^{t}}{\Delta t} \Delta z_{i} = 0.5 \left( \Phi_{i,top}^{t+1,k+1} + \Phi_{i,bot}^{t+1,k+1} \right) + 0.5 \left( \Phi_{i,top}^{t} + \Phi_{i,bot}^{t} \right)$$
(15)

The system of discretized equations is solved with respect to the pressure head h at each computation step.iteration level k+1. The three-diagonal linear system is solved with the direct LU Thomas algorithm. The value of the volumetric content is then updated until the convergence criterion of the Picard iterative process is reached (see appendix A).

15 The Richards equation is solved on a variable time step denoted with a  $\Delta t$  (see appendix A for how time step varies). The SURFEX/Crocus model <del>runruns</del> on a fixed time step T<sub>Crocus</sub>, which is set to 15 minutes unless otherwise specified. Snow layer properties such as grain size and snow density and snow layer temperature are updated on each T<sub>Crocus</sub>. The variable time step segments T<sub>Crocus</sub> are split up into smaller steps as needed, until  $\Sigma \Delta t = T_{Crocus}$ . Outflow to soil and liquid water content of each layer are updated in the main Crocus routine when the time steps join. Finally, density, snow temperature and liquid water 20 content are updated and the Crocus routine is finished.

#### 3.4 Boundary conditions

5

The rain rate and evaporation rate are imposed as a flux for the upper boundary condition. For the snow-atmosphere interface rain/evaporation rates replace  $(\Phi_{i,top}^{t+1,k+1}, \Phi_{i,top}^{t})$ .  $\Phi_{i,top}^{t+1,k+1}$  and  $\Phi_{i,top}^{t}$ . Both rain and evaporation fluxes are provided from the meteorological forcing.

25 <u>There are two options for the bottom boundary, one uses soil properties from the ISBA soil routine, the other is a free-flowing bottom boundary.</u>

# 3.4.1 Bottom boundary with soil properties

The lower boundary is the soil snow interface. Properties from the upper most soil layer are imported from the <u>SurfexSURFEX</u>/ISBA soil routine, which also uses the Richards equation for unsaturated water flow. Interfacial conductivity

between the soil and bottom snow layer  $K_{bot}$  is calculated with Eq.12 using the top soil layer hydraulic conductivity and thickness. The top soil layers pressure head and thickness are used in Eq. 10 to calculate flux to soil  $\Phi_{i,bot}^{t+1}$ . Both the soil properties and flux at snow pack surface remain constant over the <u>routineroutine's</u> inner time steps and are updated on the time step (T<sub>Crocus</sub>). The bucket model

# 5 3.4.2 Free-flow bottom boundary

A free flowing bottom boundary has been added where the pressure gradient of the last two snow layers is applied at the bottom boundary. The hydraulic conductivity of the last snow layers is used for melt out, when there is less thanat the snow soil interface. Water flux is restricted downward. If the pressure gradient of the bottom two snow layers is upward, the pressure at snow-soil interface is set to 0.05 m of snow. All plots shown in this manuscript use the free flowing boundary.

# 10 4 Forcing data / experiments

The Richards routine was tested on two data sets: one from Filefjell, Norway (61.178231 N, 8.112925 E) recorded at an automatic weather station by the Norwegian Water and Energy Directorate (NVE) and the other is a synthetic data set.

### 4.1 Filefjell

The Filefjell data set was recorded at hourly steps over the 2013-2014 winter at a flat field at 956 m a.s.l. Filefjell is located
about 200 km North West of Oslo. Despite being 30 km inland from the end of a fjord, Filefjell is considered to have a continental snow climate, which has an averagesaverage precipitation of 603 mm year<sup>-1</sup> and large annual temperature variation shown in Fig. (4). Continental snow climates are characterized by thin snow covers, cold temperatures and few rain on snow events during the winter months (McClung and Schaerer, 2006). TemperaturesAir temperatures become as cold as -28.3 °C and after January, there is a long cold spell where temperatures stay well below zero for about a month. The surface incident shortwave radiation is low during winter, where maximum daily values are below 300 W m<sup>-2</sup> from October 18, 2013 to February 19, 2014, due to the high latitude. The first large rain on snow event occurs on March 7, 2013, with a second event on April 6 & 7, 2013. Early winter rain on snow events occurred before January, which is not typical for continental climates. Unfortunately, no manual snow pit measurements at the field site have been conducted during the winter of 2013-2014. However a snow pit observation was recorded March 19, 2014 approximately 3 km away on a 24° south east facing slope (Fig. 5) (Solemsli, 2014).

# 4.2 Synthetic

Figure 65 shows the 90-day synthetic data set. The peak radiation values for this data set are low and increase linearly from 100 to 200 W m<sup>-2</sup>. Temperature has a linear increase from 265°K to 276°K. The temperature and radiation patterns set in the synthetic data set were chosen to induce a modest melt rate early in the simulation that is ramped up to a heavy melt rate at the

end of the simulation. The synthetic data set is designed to test the new routines for a large range of water supply rates. This data set has two large snow events the first one starts on day 3 and deposits 2.6 m over five days. The second event occurs on day 60 after the first snow event had a chance to settle down to 1.1 m and the diurnal radiation cycle has a chance to form a melt freeze crust at the surface. The second snowfall, did not only buryburied the old surface crust under 1.8 m of snow (for

5

Richards routing, 1.9 for bucket routine) of). The second snow, which is fall was deposited with density variations that result from, an effect of the radiation cycle. The synthetic data set allows for a simple comparison between the Richards routine and bucket routine without complicated snowpack structures, over a wide variety of melt intensities.

# 4.3 SURFEX configuration of the model runs

The C13 routine was used for snow metamorphism in the presented simulations, which routine SNOWCROMETAMO (Fig.

- 10 <u>1)</u> uses optical diameter and sphericity to describe snow microstructure the C13 routine from (Carmagnola et al., <u>(</u>2014). The soil layer sizes have been modified from the default values to allow for convergence during periods of intense water input. For the Filefjell simulation the top soil layers was 1m thick and the simulated data set had a 0.3m soil layer. Thickness of the top soil layer was adjusted as needed to allow for convergence during periods of high water flux between snow and soil. as the default metamorphism routine, although other options exist. The C13 routine uses optical diameter and sphericity to
- 15 describe the microstructure of snow. The free flowing boundary was used for the bottom boundary condition in the Richards routine. The default time step (T<sub>Crocus</sub>) was used unless otherwise specified. Every 900 s the prognostic and diagnostic variables were saved despite duration of T<sub>Crocus</sub>.

# **5** Results

# 5.1 Filefjell Simulation

- Simulation results for the Filefjell data set are presented in Fig. (76) with the top (76 A & B) showing amount of liquid water and snow layer density from the simulation run with the bucket routine and bottom (76 C & D) with the Richards routine. These simulations used T<sub>Crocus</sub>=15 min, but the resolution of Figure 7 is 3 hours. The snowpack thickness reaches just over 1 m (1.1 m for Richards routine and 1.2 m for bucket routine) at its maximum in March before a fast melt out. The difference in snow thickness between the two routines is due to the wet snow compaction that relies on the LWC. The majority of the snowpack wetting occurs during the April melt. The wetting front reaches the bottom of the snowpack at approximately the same time independent of which routine was used (Fig. 56 A and C). The three rain/melt events that occur early season (23/24)
- Oct., 15 Nov. and 26 Nov.) pass water to the soil layers for both percolation routines. The two melt/rain events that occur after the cold period in January (7 Mar. and 6/7 Apr.) wet the snowpack's surface before it is inreaches an isothermal state. These two events are more pronounce and reach deeper snow layers in the simulation using Richards routine. The event on Mar 7
- formed a layer with density ~300 kg m<sup>-3</sup>(at 0.7 m to 0.9 m) when run with Richards routine, which is missing from simulations using the bucket routine (see Fig. 76 B & D).

The density evolution according to the bucket routine (Fig. 7<u>6</u> B) shows formation of a dense crust at the bottom of the snowpack of about 375 kg m<sup>-3</sup>, where the Richards routine (Fig. 7<u>6</u> D) creates a much thicker and denser layer of  $\frac{500 \text{kg}}{600 \text{kg}}$  m<sup>-3</sup>. The Richards routine makes a slightly denser pre-isothermal snowpack and a much denser snowpack during periods of enhanced water transport. The bucket routine allows easy transmission through crust layers because high density layers yield

5 low pore volumes resulting in "small bucket size". The bucket routine does not represent crust layers well because they develop too thick and not dense enough.

### 5.2 Synthetic data set's simulation

The synthetic data set's results are presented in Fig. (87) illustrating simulations utilizing the bucket routine and Fig. (98) showing simulation using the Richards routine. Figure 87 C & 98 C are zoomed in on the second snow event-with a finer plot

- 10 resolution of 15min (same as T<sub>Crocus</sub>): The percentage of pore space that is filled by water is the measure used to calculate "bucket size" which makes it an intuitive way to view water content for the bucket routine. The results of the bucket simulation show a uniform wetting front that features a stepped pattern (Fig. <u>87</u> A). The stepped pattern arises from the diurnal cycle of water input at the surface. With the Richards routine, water percolates during the high and low phase of the diurnal radiation cycle, which results in a faster water front progression and a lack of the stepped pattern (Fig. <u>98</u> A). There is also a big variance
- 15 in the percentage of pore space filled with water throughout the simulation. Effects of the diurnal cycle are visible in the Richards routine's results, in the form of percolation fronts that move down the snow layers. The percolation front passing thought the second snow event (Fig. 9 C) is delayed by layers that were deposited with different densities, which is not seen with the bucket model.

A pattern emerges after melt water from after the second snow event reaches the bottom snow layer (Fig. (98 A & C)) where

- 20 <u>yellow and red stripes appear</u>, (also seen in Fig. 7C6C and 8C but less pronounced). The bottom snow layer remains dry throughout the simulation, and everyEvery second snow layer remains very wet between 10-1512% pore volume corresponding to a water content of 60-80 kg m<sup>-3</sup>. Before water percolates to the bottomFigure 8C shows interesting behavior of the snowpack somemany newly wet snow layers quickly drain to less than 5% saturation after the water front has percolated to deeper layers.
- 25 The bucket routine run with the synthetic forcing (Fig. <u>\$7</u> B), produces a thick crust layers that does not exceed a density of about 400 kg m-3. There is no delay in the water front's movement as it passes the melt freeze crust in Fig. <u>8B.</u><u>7B.</u> The Richards routine produces a melt freeze crust that is thicker and more dense (about 500 kg m<sup>-2</sup>) than the bucket routine.

# 5.3 Sensitivity of pre-wetting and time step

The temperature development of the snowpack for both the Richards and bucket routines lead the wetting front. However,

30 changing the amount of pre-wetting in the snowpack (Fig. 10) or length of  $T_{Crocus}$  (Fig. 149) will change the timing of the warming and water front. A sensitivity study was performed on The amount of "pre-wetting-using the simulated data", is set. The by  $\theta_{min}$ . The temperature evolution of the snow pack drastically changes when  $\theta_{min} > 10^{-6}$ , however, the timing of the fronts

were recorded when 3 of the bottom 5 snow layers became 0°C for warmingpercolation front or LWC >  $\theta_{min}$  for and the wetting front. The criteria distribution of 3 out of 5 of the bottom layers reacting was chosen because it is unclear just how much of an affect the soils thickness has on the ground heat flux which can prematurely warm and wet the bottom layer. The timing between water in the snowpack reaching an isothermal state and the water front percolating to the bottom of is not affected

5 much. When too much water is used for pre-wetting the snowpack increase as pre-wetting amount increases. Fig. (becomes isothermal when the surface becomes wet (Fig. 10) shows a trend that the less water used to pre-wet the snowpack the longer it takes for both fronts to propagate to deep layers. However, there is a complicated one-to-many relationship between pre-wet amount and timing of the warming and water fronts.).

The time step also affects the timing of the warming and water front, which can be seen in Fig. ( $\frac{1+9}{2}$ ). When T<sub>Crocus</sub> is reduced

10 the warming and wetting front is able to percolate much faster. The alternating dry wet pattern appears before the second snow event when  $T_{Crocus} = 60$  sec. The pattern smooths out during the second snow event, probably due to rearranging of the snow layer sizes.

# **6** Discussion

Figures 8 AComparing Fig. (7 A) and 9(8 A-show) shows that the Richards routine creates an isothermal snowpack and water percolation to deep layers earlier in the simulation than the bucket routine. However, the timing of the warming- and waterfronts depends on many variables. The following sections discuss some of the parameters that we have found to have influence over the timing and amount of water flow and some of the limitations and assumptions used in the routine.

#### 6.1 Liquid water content magnitude

- The bucket routine has a LWC upper limit of 5% pore space. There are two wetness states that are frequented in the bucket routine, the dry state and wet state at holding capacity. A snow layer spends little time over the course of a snow season in the transition between dry and at holding capacity, which can be seen in Fig (7-C<u>6 B, 7C</u>). Routines such as the compaction and grain metamorphisms were developed using the bucket routine and rely on a nearly binary water content configuration.
- Using Richards routine, we obtain much higher LWCs, which constantly vary between time steps (Fig. 76 C & 98 A). Richards routine is capable of wetting snow layers to the transition between pendular and funicular regimes as defined, by Denoth (1980)
- where 17% of the simulated data sets snow layers that entered the percolation routine had > 10% of their pores filled with water. This study did not investigate how other routines in Crocus (e.g. the compaction routine) that are affected by the LWC are affected by high LWCs in snow layers. However, it is expected that wet snow compaction and wet grain metamorphism are non-linear functions with feedback on LWC in the transition between pendular and funicular, since the physical distribution of water is held differently in the snow's pores with respect to snow crystals surfaces (Denoth, 1982).

### 6.2 Bottom boundary

The bottom boundary is an area of concern because it feeds the soil water percolation routine with meltwater and differences. <u>Differences</u> in pore structure over the snow-soil interface will often create at textural barrier, which can lead to pooling or accelerated flow. Figure 7 C & 9 A, show the bottom snow layer remaining drier than then second bottom snow layers after

5 the snowpack is fully wet. The advantage of running the Crocus model coupled with SURFEX and ISBA is that boundaries in the Crocus model (atmosphere and soil) are better represented and dynamic. The free-flowing boundary does not take advantage of the coupling between Crocus and ISBA, but shows better results in the models current state. We recognize the bottom boundary as a part of the routine that needs more development, so the Richards routine can take full advantage of being run with SURFEX and ISBA.

# 10 6.2.1 Bottom boundary with soil properties

The performance of the bottom boundary when soil conditions are used is not realistic, the LWC of the snowpack becomes too high, which can cause numerical problems. The flux to the soil remains lower than when the free-flowing boundary is used. The result of this (not shown) is higher saturations in all the snow layers after the bottom snow layer becomes wet. The higher LWCs make for stronger feedback from the other Crocus routines, which creates an even stronger "yellow/red striped

15 pattern" (seen in Fig. 8 A).

The hydraulic conductivity of the bottom soil layer and the suction of the soil layer are imported to Crocus from the soil routine. These values are held fixed for the time step  $T_{Crocus}$ . The hydraulic conductivity of the bottom interface is the arithmetic mean (harmonic mean can be used) of the bottom snow layer and the top soil layer's thickness and hydraulic conductivity. Snow layers are able to move water between them on the internal time step (t), which can be as small as a fraction of a second.

- 20 Snow layers suction and conductivity are altered on the internal time step (t). However, the <u>soilssoil's</u> suction and conductivity remains constant until  $\Sigma t=T_{Crocus}$  witchwhich means the snow-soil interface has a less dynamic conductivity and suction because half the values making up the K<sub>snow/soil</sub> are constant on  $\underline{T}_{erocus}\underline{T}_{Crocus}$ . One way to force the bottom interface to be more dynamic is to reduce  $T_{Crocus}$  (Sect. 5.3). A second way is to increase the top soil layers thickness, then the snow layer will dominate in the weighted average used for conductivity at the snow-soil interface. However, increasing the size of the soil
- Ideally, the snowpack and soil column would be solved as one continuous column (Wever et al., 2014). However, the snowpack is semi-implicitly coupled to the soil percolation routine on  $T_{Crocus}$ . Unfortunately, with the ISBA model the soil and snow routines are not coupled on the variable time step t. To solve the soil and snow as one continuous column of unsaturated porous media would take major reorganizing of the SURFEX model and was not feasible during this study, but should be

reduces the reliability of snow, soil thermodynamics routine, but that is beyond the scope of this study.

30 considered in the future.

25

During periods of high flux between the snow and soil, the convergence criteria will not be reached with a reasonable time step (t). It was found that increasing the size of the top soil layer allowed the convergence during high flux periods. However,

increasing the size of the soil reduces the reliability of snow, soil thermodynamics routine, but that is beyond the scope of this study. The size of the top soil layer was set to a value which allowed the simulation to converge in a reasonable amount of time. For the Filefjell simulation the top soil layer was 1.0 m and for the simulated data sets simulation the soil layer was 0.3 m.

# 5 6.2.2 Free-flow bottom boundary

The free-flowing bottom boundary does not require adapting the soil layers sizes. The drawback is that there is no feedback between the soil routine. The free flowing boundary can be applied for application that do not need soil conditions, however for many applications the flux from the snowpack to the soil is critical. The free flowing boundary was implemented as a work around for a poorly functioning bottom boundary condition.

#### 10 6.3 Coupling

T<sub>Crocus</sub> dictates the degree of coupling between SURFEX routines, including the coupling between the ISBA and Crocus and between routines in Crocus. The water percolations process is coupled to the soil percolation process and the energy balance of the snowpack, in Crocus these routines are run sequentially and are coupled via T<sub>Crocus</sub>. The energy balance is made up of many processes that are expressed through many of the<u>various</u> routines in Crocus (see Fig. 1). The temperature of the snow
15 layers is altered after the percolation routines (for both Richards and bucket) due to), latent heat release, is considered if refreezing occurs. Although, a sensitivity study on the link between temperature of snow layers and percolation would be relevant such a study was not possible because of other feedbacks in the model.

The histograms in Fig. (2 & 3) show the distribution of snow layer's saturation when they entered the Richards routine. The water content is often very low with 69.553.3% of the snow layers under 5% LWC, for the simulated data set. At low saturations, the hydraulic conductivity function and the retention curve are very sensitive to changes in density, grain size and saturation. It is important to note that a 1% change in saturation when very dry can affect both the hydraulic conductivity and the water retention curves by orders of magnitude. Figure 119 shows the simulated forcing when run with  $T_{Crocus} = 900$  sec and  $T_{Crocus} = 60$  seconds. Water moves through the snowpack earlier when  $T_{Crocus} = 60$  seconds because faster feedback between the percolation routine and routines alters layer density and layer grain size.

- 25 Similar to snow layers, a small change in saturation of soil layers should affect the hydraulic conductivity and the suction of the bottom boundary. However, the top soil layer is only coupled to the snowpack via T<sub>Crocus</sub>. Problems occur when too much water is passed from snowpack to soil in one time step (also discussed in Sec. 6.2). If T<sub>Crocus</sub> is large and the top soil layer is thin, the amount of water transfer from the snow into the soil would drastically change the conductivity and suction at the soil snow interface in a time span much smaller than T<sub>Crocus</sub> and the routine does not converge. Reducing T<sub>Crocus</sub> is a strategy that
- 30 will better couple the soil layers and snowpack. This strategy is not feasible however, since the Richards routine is sensitive to the duration of the time step ( $T_{Crocus}$ ), the approach of increasing the soil layers size is preferred.

### 6.4 Pre wetting amount

Water percolation and temperature development are sensitive to large values of  $\theta_{min}$  (>10<sup>-6</sup>), which is the amount of pre-wetting used. The pre-wetting is needed because the water retention curve approaches infinity and the hydraulic conductivity function approaches negative infinity when  $\theta$  approaches 0 (see Fig. 2 & 3). Figure 10 shows that the amount of pre-wetting used

- 5 strongly affects the timing of when the snowpack reaches an isothermal state, and but does not have a large effect on the water front movement. With  $\theta_{min} \ge 25 \times 10^{-6} \text{ (m}^3 \text{ m}^{-3})$  used for the pre wetting amount, the snowpack reaches an isothermal state quickly after the top layers of the snow have been introduced to a sufficient amount of melt water (day 39), such that the criteria to enter the percolation routine has been met. The water front does not show a pattern concerning  $\theta_{min}$ . The water front reached the lower snow layers on day 58 or 59 regardless of the  $\theta_{min}$  limit. Latent heat released in deeper snow layers from
- 10 the freezing process are an effective way of transporting energy through the snowpack. It is unlikely that there are long periods between the warming front and the wetting fronts movement in the snowpack.  $\theta_{min} = 10^{-6}$  was chosen as default because the two fronts started to reach deep snow layers together, where a larger value of  $\theta_{min}$  resulted in a warming front leading the wetting front by more than a day. The time between the warming front and water front reaching the lower layers of the snow pack constantly decreased as  $\theta_{min}$  decreases. The bucket routines results show that the warming and wetting fronts move
- 15 together down the snowpack.

Pre-wetting amount is based off a minimum pressure head value for dry layers with  $\theta_{\min} = 10^{-6}$  (default value). Figure 10 shows how the temperature evolution is affected by the magnitude of  $\theta_{\min}$ . If  $\theta_{\min}$  is too large the snow pack becomes isothermal quickly after the top snow layer becomes wet for the first time. However if  $\theta_{\min}$  is too low the simulation may not converge, or the simulation takes much longer to run because of the extreme pressure difference between wet and dry layers.

#### 20 **6.5 Conductivity through crusts**

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The Richards routine is able to produce <del>crustscrust</del> layers from melt water that the bucket routine cannot reproduce-, like the <u>melt freeze crust in Fig. (8 B)</u>. However, the thickness and density of crust layers are dependent on where the percolation routine moves water since refrozen liquid water is often the cause of crusts at the surface and inside the snowpack. The water retention curve and hydraulic conductivity functions are not designed for use on crust layers. Furthermore, Crocus' snow metamorphism routine <del>B92</del>(<u>SNOWCROMETAMO</u>, Fig. 1) does not work well for crust layers, because dense crusts do not have individual grains, but <del>rather</del><u>closer</u> to a solid ice layer with bubbles. <u>There is a choice of routines in <u>SNOWCROMETAMO</u>, the B92 (Brun et al. 1992) and the C13 routines. The B92 routine uses Sphericity and dendricity. The C13 routine uses optical diameter, which is used as an approximation for visual grain size in the Richards routine. The assumption that optical diameter is a sound approximation for visual grain size is questionable, especially for crust layers.</u>

30 Nevertheless the metamorphism routine calculates a grain size for all layers including crusts (see Sect. 6.6). Figure (9B)8B shows that the crust layer was able to develop into a thinner and denser crust compared with the bucket routine (Fig. 87 B). Since there is no literature available on water retention and hydraulic conductivity of crusts layers, crusts are treated like

normal snow layers in both percolation routines. The Richards equation is solved in one dimension normal to the snow surface. However, dye tracer experiments have shown that water transport <u>thoughthrough</u> snow is a two- (maybe three-) dimensional process (Williams et al., 2010). When the wetting front reaches a barrier such as a crust or capillary differences, the underlying snow layer probably will develop flow channels where a one dimension model does not suffice. Averaging the hydraulic

5 conductivity between a layers barrier suction with the flow channel suction is one way to express a two dimensional process in one dimension. Hydraulic conductivity has been determined (via permittivity) by Calonne et al., (2012) on small snow samples therefore it is likely that the measurements do not represent conductivity at a higher spatial scale because preferential paths have a spatial patternprocesses that affect the density distribution, grain metamorphism and pore space differs on a <u>5meter</u> to <u>7 mseveral meter</u> scale (WilliamsBirkeland et al-1999., 1995).

#### 10 **6.6 Grain metamorphism routine**

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# The C13 routine was used for snow metamorphism in the presented simulations, which uses optical diameter.

The hydraulic conductivity function <u>derived</u> from Calonne et al., (2012) utilizes the optical grain diameter and snow density. The hydraulic conductivity function pairs well with the C13 routine, because they both use optical grain diameter. However, the water retention curve (Yamaguchi et al., 2012) was based on <del>a visual grain size measurements and the use of optical grain diameter may hinder the performance of the water retention curve.</del>

- The pore shape and structure is important for the retention curve and the hydraulic conductivity. Small pores inside the snow layer create suction via capillary rise, and water travels through the voids in the snowpack. Both parameterizations could benefit from a better description of the pores structure. Density and grain size is not enough to describe the pore structure of a snow sample. We use optical diameter for parametrization but in nature, optical properties do not influence the snows
- 20 hydrological processes <u>of snow</u>. For the retention curve and the conductivity functions to be used at low saturations, pore shape and structure should be considered. Introducing a routine in Crocus that calculates pore shape could be beneficial for not only the water percolation routine but also the thermal conductivity (Riche and Schneebeli, 2013; Sturm et al., 1997). This would also require new parameterizations including a pore structure variable with the grain size and density.

# 6.7 Water retention curve

25 The Yamaguchi et al. (2012) water retention curve has been applied to melt forms crystal type and reported poor performance with rounded grains. It is expected that the retention curve does not represent precipitation particles, decomposing and fragmented precipitation particles, faceted crystals and depth hoar well. However, when water is present in a snow layer snow grain metamorphism will transform all snow crystals into MF (Colbeck, 1976; Shimizu, 1970). This negative feedback on snow grain type could mean the melt forms are the only crystals that need a modeled water retention curve, but this claim needs validation.

The residual water content is one of four parameters needed to define the water retention curve. The residual water content represents how dry a layer can get with maximum suction applied. A constant  $\theta_r$  was used for different grain types, sizes and densities but results from Adachi et al. (2012) suggest that  $\theta_r$  varies with grain size.

Hysteresis in the water retention curve stems from odd shape pores<sub>2</sub> where<sub>7</sub> pores can hold different amounts of water at the same hydraulic head depending on the initial LWC. In most cases, snow will go from a dry state (pore space filled completely with air) and become wet. The Yamaguchi parameters for the <del>VGVan Genuchten</del> model are derived from a drainage experiment, where the pore space was completely filled with water and allowed to drain. Adachi et al. (2012) showed that the shape of the water retention curve is affected more in fine textured graingrains then coarse grains.

Parametrization of the water retention curve based on a wider range of snow grain types and sizes are needed to represent natural snow pack conditions. For fine textured snow, parameter sets derived from wetting experiments would be beneficial, as the snow usually starts from a dry state.

# 7 Conclusion

20

We added a new<u>A</u> water percolation routine <u>that solves Richards equation was added</u> to the <u>snow pack model</u> Crocus <u>model</u> as <u>ana physically based</u> alternative to the empirical bucket <u>percolation</u> routine. <u>The performance of the Richards routine is not</u>

15 <u>sufficient for simulations of the snowpack, because further work is needed on other parts of the Crocus model that feedback</u> on the parameter sets used by the Richards routine.

The bucket model keeps snow layers in the pendular wetness regime. The Richards routine reaches LWCs much higher than the bucket routine, with <u>LWC-water filling>17% pore volume</u> for many snow layers, which lies in the funicular regime for all snow types. However, <u>8317.5</u>% of snow layers were initialized inentered the Richards routine with a <u>LWC-<10%-% of the</u>

- pore space filled with water (bucket routine has max 5%). With small changes in LWC (>1%) at low saturation the suction and hydraulic conductivity can change by orders of magnitude. The parameterization used to define the suction and the hydraulic conductivity is heavily reliant on the snow grain size and the density of snow layers.
- The wet snow metamorphism and wet snow compaction routines were implemented when the bucket model was the only option for water transport. There is a physical difference in the distribution of water inside the pores between pendular and funicular regimes. This difference is not accounted for in the snow compaction rate or wet snow metamorphism rates, which leaves the feedback to the new routine open to question.

The parameterization used are heavily reliant on the snow grain size and the density of snow layers. New parameterizations for the hydraulic conductivity and the water retention curve that do not contain grain size are needed for dense crust layers.

30 The Richards routine in the current state treats crusts as a normal snow layer where grain size calculations are erroneous. The parameterization for the water retention curve was based on a small domain of densities, grain sizes and snow types, the domain

for this parameter set should be expanded for applicability in snow grains other than MF. New parameter sets should be based on wetting experiments for small grain sizes as hysteresis affects the Van Genuchten parameters ( $\theta_r$ ,  $\alpha$ , n).

The arithmetic mean was used to define the conductivity of interfaces between snow layers. By doing this, the stratified nature of the snow is smoothed. Different expressions for the conductivity at interfaces, yielded subpar results. The behavior of the

5 hydraulic conductivity at interfaces, is not well understood/expressed in current literature, but vital for calculating water transport through crust layers.

The snow-soil interface does not perform well during periods where large amounts of melt water should pass from the snowpack to the soil. The soils parameters (suction and hydraulic conductivity) are updated on a 15 minute time step, which is not fast enough during periods of high water flux. At the current state of the Crocus model, major structural changes are

- 10 needed in order to couple the soil and snow percolation routines. We identified the soil-snow interface as the source of numerical instabilities, when the top soil layer is small (< 0.3 m). This study did not investigate the effects the Richards routine has on the ISBA soil percolation routine, or the effects of a large top soil layer. On the variable time step used by the Richards routine. A free-flowing bottom boundary shows better results during high flux periods but does not take advantage of running Crocus in SURFEX coupled with ISBA.
- 15 Because of the number of areas of concern in the validity of the Richards routine, we did not attempt a validation experiment. In order to further develop the Richards routine, improvements and updates are needed in other Crocus routines (mostly melt, compaction and grain metamorphism) and/or the parameters sets used by the Richards routine, which is beyond the scope of this study.

# 8 Code and data availability

- 20 The SURFEX/CrocusV7 with Richards routine can be download via SVN by following instructions at <u>https://opensource.cnrm-game-meteo.fr/projects/snowtools/wiki/Install\_SURFEX</u>, and checking out the branch "damboise\_dev". A SVN account can be requested by following instructions given in link: <u>https://opensource.cnrm-game-meteo.fr/projects/snowtools/wiki/Procedure for new users</u>. <u>A walk through for running the model can be found in this link: https://opensource.umr-</u>
- 25 <u>cnrm.fr/projects/snowtools/wiki/Basic\_functioning\_of\_SURFEX\_without\_the\_s2m\_tool\_from\_snowtools</u> The Filefjell and simulated data set with the namelist needed for running the simulations are provided at, <u>www.norstore.no</u> (internal\_identifier\_AA4769C6-5277-4523-A3F0-7155B2DC39EC, & 2CEC0984-50A1-4A2A-B6C9-A83815EA50E8). Internal identifiers are used because the data set is in preparation, a doi reference will be provided when data set is published.

## **Appendix A - Picard iteration/convergence**

A Picard iteration is used to deal with the non-linear nature of the system of equations. There are three convergence tests that need to be satisfied to calculate the next internal time step (t). The three convergence criteria are on pressure head differences, volumetric water content differences and the mass balance (of individual snow layers) differences between two iterations must

5 be below  $10^{-4}$  m. Hence, there must be at least two iterations performed in order to test for convergence. If the current iterations deviation of pressure, volumetric water content and mass balance is smaller than the error-threshold that has been set then the convergence criteria is are met and the model proceeds to the next time step.

A set of rules are used to regulate the variable time step based on the number of iterations needed for convergence-, similar to <u>Paniconi and Putti (1994)</u>. A maximum number of iterations has been set to 15. If the calculations do not converge by the 15th iteration then the time step is reduced and calculations are preformed again, until the calculations converge within 15 time

10 iteration then the time step is reduced and calculations are preformed again, until the calculations converge within 15 time steps. The variable time step can range in time from about 400 seconds to fractions of a second withwithin a lower limit of 1E-10 seconds. Smaller time steps with in the Richards routine results in the model taking too long to run or convergence is not achieved. If convergence is reached in 4-7 iterations the time step is kept constant. Converging in less than 4 or between 8-15 iterations results in a longer or shorter time step respectively (Eq. A1).

$$15 \quad t^{i+1} = \begin{cases} t^{i} \cdot 1.5^{BS}, \ I < 4 \\ t^{i}, \ 4 \le I < 7 \\ t^{i} \cdot 0.5^{SS}, \ 7 \le I < 15 \\ back \ step, \ 15 < I \end{cases}$$
(A1)

Where I is the number of iterations and "back step" stops the calculation before convergence and reduces the t<sup>i</sup>. BS and SS are initialized at 1 and <u>isare</u> increased by 1 for the previous "bigger steps" or "smaller steps". BS and SS are reinitialized if the time step remains the same size ( $4 \le I < 7$ ).

#### Appendix B – Alternative parameter sets

20 The following sections describe alternative parameter sets for hydraulic conductivity (B.1) and water retention curve (B.2, B.3) that we implemented in the Richards routine, but not presented in this paper.

#### **B.1 Shimizu 1970**

25

Shimizu developed a statistical model for  $k_{sat}$  from the density and grain size of fine grained compact snow, Eq. (B1). Shimizu suggests that other snow grain types and densities may give different coefficients than those found in Eq. (17). The B1). For use in the Richards routine this parameter set has been would have to be applied to lower density snow that found capillary

pressure is related to pore structure (Jordan et al 1999). than used to create it.

Equation 17B1 relates snow density and grain size to conductivity at saturation (k<sub>sat</sub>).

$$k_{sat} = 0.077 \cdot \left(\frac{D}{2}\right)^2 \cdot exp(-0.078 \cdot \rho_{snow}) \cdot \left(\frac{G \cdot \rho_{water}}{\mu_{water}}\right)$$
(B1)

# B.2 Yamaguchi et al 2010

This parameter set was the prior work of the parameter set used in this study. Two major differences (when compared with Yamaguchi et al. 2012) for this parameter set are  $\alpha$  and n are functions of grain diameter (D) (and not density-not include) and the <u>.</u> The density range testedused in this studythe Yamaguchi 2010 parameterization is small, 545-553 kg m<sup>-3</sup>. While the The parameterization for the  $\theta_r$  and  $\theta_s$  are the same as in Yamaguchi 2012.

$$\alpha = 7.3 \cdot (D \cdot 1000) + 1.90 \tag{B2}$$

$$n = 15.68 \cdot exp(D \cdot 1000) \cdot (-0.46) + 1.00$$

#### B.3 Dannen Daanen & Nieber 2009

DannenDaanen and Nieber derived these relations based on measurements of liquid water content and water pressure from
 Marsh (1991). They assume snow crystals between 1mm and 0.1mm. However, descriptions of the measurements are not given in detail. DannenDaanen and Niebers study focuses on a framework of a coupled temperature and liquid water routine that does not focus on deriving the Van Genuchten fit parameters in a suitable way for different snow types, as all crystals are

$$\alpha = 30 \cdot (D \cdot 1000) + 12.00 \tag{B3}$$

15  $n = 0.8 \cdot (D \cdot 1000) + 3.00$ 

assumed spheres.

 $\theta_r = 0.05$ 

5

 $\theta_s = Porosity$ 

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Figure 1: Routines in the Crocus snowpack model with the water percolation routines highlighted in green.





Figure 2: Water retention curve using Yamaguchi (2012) in the Van Genuchten (1980) parameterization. Typical values for density and grain sizes of different snow crystals/grains were chosen to show the water retention curve for the spectrum of different snow layers it is applied to in the Richards routine. The density and grain size values were chosen from each crystal type from within a

5 reasonable range that may be found in nature. Background shows a histogram of the simulated data sets saturation with T<sub>Crocus</sub>= 900 s time step before entering the Richards routine. <del>Dark grey bars show the full 90 days. Light grey bars show the first 75 days</del> prior to the period of high flux between the snow and soil





Figure 3: Hydraulic conductivity curve <u>derived</u> from Calonne et al. (2012) using Yamaguchi et al. (2012) parameters. Typical values for density and grain sizes of different snow crystals/grains were chosen to show the hydraulic conductivity for the spectrum of different snow layers it is applied to in the Richards routine. The density and grain size values were chosen from each crystal type

5 from within a reasonable range that may be found in nature. Background shows a histogram of the simulated data sets saturation with T<sub>Crocus</sub>= 900 s -time step before entering the Richards routine. Dark grey bars show the full 90 days. Light grey bars show the first 75 days prior to the period of high flux between the snow and soil



Crystal ρ Form Size (mm) kg/m<sup>3</sup> 130 Т 120 + 3.0 110 1 1.0 100 1.0 90 80 1.0 70 2.0 1 0(0) 2.0 60 □(O) 2.0 50  $\wedge (\Box)$ 3.0 40 ∧(□) 3.0 30 20 10 ∧(□) 3.0 м 0 K 1F 4F F P I

Figure 4: Forcing data from an automatic weather station located in Filefjell, Norway for the period 01.09.2013 to 31.05.2014.





Figure 6


<u>Figure 5</u>: Simulated forcing data. Temperature (red) and net radiation (green) both linearly increasing creating low melt early in the simulation and high melt at the end of the data set.





Figure 7<u>6</u>: Crocus output from Filefjell, Norway, where top plots use the bucket routine and bottom plots use the Richards routine. Plots A and C show distribution of liquid water, and plots B and D show the density distribution.  $T_{\text{crocus}}$ =900 s (15 min) was the time step duration. For the Richards simulation (C + D) the bucket routine was used for melt out when snowpack was less than 0.1m (default is 0.05m).





Figure <u>87</u>: Crocus output for Neverland forcing using the bucket routine with  $T_{Crocus} = 900$  s (15 min), plotted every 3 hours, except plot C, which is plotted every 15 minutes. A) liquid water amount, B) snow layer density, C) % pore volume filled with water zoomed in on the second snow event, and D) temperature development of the snowpack.





Figure 9<u>8</u>: Crocus output for Neverland forcing using the Richards routine with  $T_{Crocus} = 900 \text{ s} (15 \text{ min})$ , plotted every 3 hours, except plot C, which). The bottom boundary is plotted every 15 minutes. With set to free-flow, with  $\theta_{min} = 10^{-75}$ . A) liquid water amount, B) snow layer density, C) % pore volume filled with water zoomed in on the second snow event, and D) temperature development of the snowpack.



Figure 10: Timing of warming/water front to reach bottom of the snowpack with different amounts of pre-wetting. T<sub>Crocus</sub>= 900 s was used to make this figure. Blue marks represent the timing the snowpack reached an isothermal state, where orange marks show when the water front reached the 3<sup>rd</sup> lowest snow layer. Red line is when the bucket routine's warming and wetting fronts reached

5 the bottom of the snowpack.



Figure <u>112</u>: Water percolation in the simulated data set scenario with different time steps: A)  $T_{Crocus}$ = 900 s (15 min), B)  $T_{Crocus}$ = 60 s both plots use  $\theta_{min}$  = 10<sup>-5</sup>. The 60s simulation has water at the bottom of the snowpack 4 days before the 900 s simulation.

