Response to Referee #1 (Richard Essery) comments

This paper provides exhaustive (and quite exhausting!) documentation of Crocus, historically and still currently one of the most important models of snow on the ground. I have never before reviewed a manuscript with so few figures or so many nested braces! The authors do not follow the GMD encouragement that "Examples of model output should be provided, with evaluation against standard benchmarks, observations, and/or other model output", but they do review other published evaluations and applications. The documentation collates developments in several previous publications and corrects errors in some of them. As such, this is an essential reference for users of Crocus. I recommend that it should be published with minor changes. A table of all the options and their dependencies would be a useful addition.

We would like to sincerely thank Richard Essery for the time dedicated to this review, his positive appreciation and very useful remarks. We are fully aware that the length of the model description and the number of equations make the review process especially difficult. We highly appreciate the accuracy of the comments which testifies the great attention paid to reading the manuscript.

In addition to our review of existing model evaluations and applications, and accounting for a similar comment of Anonymous Referee 2 and following GMD recommendations, we added a new Appendix in the revised version of the manuscript with an overview of simulation results at the 10 ESM-SnowMIP reference sites corresponding to the published code version. This can be considered as a benchmark of the model skill that can be useful to assess the impact of future model developments.

As suggested, we also added a table summarizing all options and dependencies (Table 1).

Specific comments:

70

Parametrizations which do not make this assumption that the diffuse fraction depends on solar zenith angle only are available. How much difference does using this parametrization make in simulations when data are available?

In the extreme case where the sky is fully overcast, the error of Equation 1 can obviously be high in terms of diffuse / global radiation ratio as the direct component can be close to 0 regardless the value of the solar zenithal angle. In many cases, only global radiation data are available and it is unfortunately not possible to parameterize differently the diffuse/global ratio from cloudiness data or atmospheric optical depths. The impact in terms of error in the simulated broadband albedo is an underestimation of about 0.07 for fully overcast sky, from literature comparing snow albedo in different cloud conditions (Gardner and Sharp, 2010, Fig. 9). This error would be more or less of the same magnitude than ignoring the dependency of the solar zenithal angle in clear sky conditions, but with a lower impact in the snow energy balance as the incoming energy is generally lower in cloudy conditions. For these reasons, forcing the model with direct and diffuse components should be preferred when the data are available from measurements or from radiative transfer modelling in the atmosphere.

The text of the manuscript was adjusted to make the readers aware of this limitation when the diffuse / global ratio has to parameterized.

95

At atmospheric pressures, should T0 not be the melting point of water rather than the triple point?

Thanks for pointing out this detail. Indeed, T_0 represents the melting point temperature at atmospheric pressure. In SURFEX, it has always been assumed to be equal to the triple point value (273.16 K) and this assumption was kept for Crocus for the consistency between the different components of the land surface model. Although this inaccuracy of 0,01 K is not expected to have a significant impact on simulation results, the revised manuscript now explicitely mentions this approximation.

264

Why are values 3 and 5 not included here in "occurrence of depth hoar at any time since the layer creation"?

Indeed, the sentence has been changed as all odd values (1, 3, 5) correspond to the occurrence of depth hoar at any time since the layer creation.

469

For vertical heat transport between layers, the harmonic weighted mean to add conductivities in series seems more natural.

486

What is the justification for now using the harmonic mean between the bottom snow layer and the ground?

Since the origin, arithmetic means have been used in Crocus to compute the thermal conductivity at the interface between snow layers while harmonic means were used in other components of SURFEX (ISBA-ES snow scheme or ISBA-DIF soil scheme). The choice of Vionnet et al., 2012 was to maintain the arithmetic means when Crocus was implemented within SURFEX. However, as suggested by Richard Essery, the literature now tends to converge towards harmonic means expected to make the numerical schemes converge more quickly. Moreover, as also mentioned by Richard Essery, this arithmetic mean is inconsistent with the thermal conductivity used at the soil-snow interface and also with the computations of MEB. Therefore, following this remark, we decided to modify the code and the paper by using harmonic means. A new release referred as Crocus3.0.1 is provided with this modification. The impact on simulations was found to be very low in our test cases, except for some transient events where a thin snow layer only stays a few hours on the ground.

737

SOF and HAR are not explained.

These acronyms refer to soft and hard, and the discrimination is based on a threshold on the maximum penetration resistance (Table H1). This is added in the revised manuscript.

1026

The Clausius-Clapeyron equation gives de_{sat}/dT. Equation (F6) is an approximate integral of the formula.

Absolutely, we corrected this inaccuracy in the text.

1040

Is there any justification for adjusting the Richardson number for slope? Atmospheric stability adjustment has bigger issues on slopes than the component of gravity.

The Richardson number is defined as the ratio between buoyancy and flow shear. As buoyancy is a vertical strength, it is natural to project the vector perpendicular to the slope to characterize turbulence over a tilted surface. However, we fully agree that numerous other uncertainties are involved in the case of slopes and not accounted for in this parameterization, for instance the wind speed profiles associated with catabatic and anabatic winds.

1049

Letter gamma is used on this page for both slope angle and psychrometric constant without distinction.

We apologize for this inconsistency in notations. Slope angle was replaced by letter Theta as in Vionnet et al., 2012 to remove this ambiguity, as the psychometric constant is always symbolised by letter gamma. To avoid confusion with grain type referred as Theta_i in the preprint, we now use letter Psi for grain type.

Minor corrections:

48 delete "make"

Corrected

160 "is split"

Corrected

307 "dependence on snow microstructure"

Corrected

372 Start a new line before "where".

Corrected

373 "volumetric mass" is more commonly called density.

Corrected

394 "The last modification is"

Corrected

411 "at Col de Porte"

Corrected

430 "a homogeneous repartition is applied"

Corrected

432 "the highest integer such that"

Corrected

434 "not inconrporated in"

Corrected

441 Strictly, q_sat is also a function of pressure.

We replaced q_sat(T) by q_sat(T, P_s) everywhere.

531 “This allows representation of”

Corrected

558 “cannot”

Corrected

567 missing)

Corrected

578 “either by the heating energy or by …”

Corrected

598 “either by the layer colling after diffusion or by …”

Corrected

640 “accounted for by adding”

Corrected

695 “a shear resistance R_{s_i} is diagnosed”

Corrected

709 “for slope angle \gamma”

Corrected

714 and throughout “indice” should be “index”

Corrected everywhere

786 “it can vary significantly from one domain to another”

Corrected

812 “an independent package called snowtools with full user documentation”

Corrected

851 “discrepancies”

Corrected

883 “adequation” is a very uncommon word in English. I think that the simplest fix would be “to reproduce the properties of …, or complex remote sensing signals”

Corrected

904 “make the application of a number of data assimilation algorithms to this model challenging”

Corrected

921 “discrepancies”

Corrected

946 “are repeated here”

Corrected

967 “cannot”

Corrected

968 “between dendritic and non-dendritic cases”

Corrected

1036 “The derivative”

Corrected

1092 “preventing the vectorization”

Corrected

1096 “prevents vectorization”

Corrected

Response to Anonymous Referee #2 comments

Referee comments in grey italics, our response in blue.

I agree with referee #1 that the format of the paper is a little odd in that the only evaluation of the model is showing the computational efficiency of the different modules using "default physical options" (Section 4.2). I think this information is valuable but for it to be the only results shown was a little puzzling.

We sincerely thank Anonymous Referee #2 for his careful review that helps improve this article.

As noticed by Richard Essery (Referee #1), although our initial manuscript did not provide simulation results, it provides a detailed and unprecedented review of the abundant literature providing simulation results with this model. This review provides a more comprehensive description of the capacities of the model than what can be done in this article. However, to account for the remark of the Referee, we added a new Appendix in the revised version of the manuscript with an overview of simulation results at the 10 ESM-SnowMIP reference sites corresponding to the published code version. This can be considered as a benchmark of the model skill that can be useful to assess the impact of future model developments.

If this is purely a paper synthesizing recent advancements of the physical formulas and parameters used in Crocus and referencing the specific studies they come from, I think a schematic diagram for what Crocus does (e.g. Vionnet et al., 2012 Fig. 1) and which processes are relevant to this current study would be helpful. It could even be something like Figure 1. I would have liked this to be referenced earlier to provide some context about what was traditionally incorporated in the Crocus model and what's been added.

Figure 1 provides a comprehensive description of the processes represented in the model. Following, the suggestion of Anonymous Referee #2, we added labels « NEW » and « UPDATED » on this Figure to emphasize changes compared to the previous reference paper (Vionnet et al., 2012) and the revised manuscript refers earlier to this Figure in the introductive paragraph of Section 2.

Some other general comments include; grammatical errors, and unclear wording, and many of the provided equations are never actually referenced in the text (e.g. 135 and 136).

We apologize for the grammatical errors and unclear wording. They were carefully corrected in the revised manuscript following both reviewers recommendations. Eq. 135-136 (137-138 in the revised manuscript) are now referenced in the text. We believe that it is not always necessary to reference equations in the text when they come directly after a clear introductive sentence.

Specific comments:

Lines 10-12: confusing as written.

The sentence was split into two parts and reformulated in the revised manuscript to make it easier to understand.

Lines 43: "to evolve"

We are sorry but we don't see where to implement this suggestion at this line.

Lines 49: It wasn't immediately clear to me what was meant by diagnoses

We added examples of diagnoses in this sentence to make this sentence easier to understand.

Lines 51-53: Confusing as written.

The sentence was split into two parts and reformulated in the revised manuscript to make it easier to understand.

Line 69 :"are set to zero"

We corrected the word « component » (singular) to make this sentence gramatically correct.

Line 82: "in an appendix."

Corrected

Line 85: might be helpful to describe LAP in more context. I think its actually defined later in the manuscript.

As suggested, we added a sentence to better introduce this paragraph : « *Light Absorbing Particles (LAP) are organic or mineral substances able to increase radiation absorption in snow.* »

The acronym LAP (Light Absorbing Particles) is also defined earlier in the manuscript (Line 71 of the preprint), as it is necessary to describe the forcing variables. Section 2.4.10 describes the evolution laws of LAP contents in the snow layers.

Line 132-133: confusing as written.

This sentence was split into two parts to make it easier to understand.

Line 136: "relatively" – "relative"

Corrected

Line 160: "When a layer i is split"

Corrected

Line 246-249: Confusing as written. Either .. either.

Corrected (either/or)

Line 252: "They depend on conditions of…"

Corrected

Line 258-260: Confusing as written.

The sentence was modified in the revised manuscript to make it easier to understand.

Line 348: "In addition, a threshold is applied on the mobility indice in case melt forms:"

Melt Forms corresponds to a grain type in the international classification of snow on the ground. However, we reformulated this sentence to remove any ambiguity :

"In addition, a threshold is applied on the mobility indice in case liquid water had been present at any time in the snow layer."

Line 394-395: "The last modification of absorption related parameters" ??

Replaced by *« The last modification about absorption of solar radiation »*

Line 513: "and G0 is the flux obtained by applying Eq. 95 with T1."

Corrected

*Line 530: "This allows **us** to represent" ??*

Corrected by *« This allows representation »* following Richard Essery's recommendation.

*Line 549: "…And to **solve** the linear system… modified **according** to the new values.*

We modified this sentence to avoid its separation into two parts by the equations and improve readability.

Line 558: "solving MEB"

Corrected

Figure 1: Reference earlier.

Figure 1 was already referenced before its position in the text (line 557 of the preprint). In the revised manuscript, as explained above, Figure 1 is now referenced much earlier at the beginning of Section 2, following Anonymous Referee 2 recommendations.

Line 578-579: Confusing as written.

We corrected the syntax of this sentence and added « available heating energy ». We believe this sentence now allows a clear introduction of Equation 120 (Equation 119 in the preprint).

Line 598-599: "Either… or" instead of "Either … either"

Corrected

Line 623-625: Confusing as written.

The sentence was modified in the revised manuscript to make it easier to understand.

Line 640: "removing" instead of "deleting"

Corrected

Line 644-645: Reads as somewhat conflicting. Crocus does not modify or update snow microstructure, yet you cannot track surface hoar buried underneath the snow?

We provide extended explanations in the revised manuscript to avoid any misunderstanding :
« Microstructure properties are not modified. Therefore, in case of deposition, the current Crocus snow model only increases the mass of the surface snow layer but it does not allow the formation of a dedicated layer with microstructure properties typical of surface hoar. As a result, it is neither possible to track the burying of surface hoar in the snowpack. »

Line 655-57: Does this mean model output variables that can be used for model evaluation and diagnostics? I think a little more of a description here and possibly in the introduction would be helpful.

Yes. We added in the text the following description : « *These diagnoses can be useful for model evaluation or interpretation in research or operational applications. »*

Line 695: "For understanding stability indices of the snowpack, shear resistance Rsi is computed for each layer i."

The shear resistance is actually a diagnostic which is necessary for the computation of stability indexes, and it is only computed for this reason. We prefer to maintain the meaning of the initial sentence, but we fixed the incorrect syntax.

Line 707-708: Confusing as written

The sentence was modified in the revised manuscript to make it easier to understand.

Line 709: typo – "values"

Corrected

Line 790: typo "then" – "that"

Corrected

Line 817: typo "spatialized" – "spatial"

Corrected

Line 848: typo "score" – "accuracy"

Corrected

Line 866-870: confusing as written

This sentence was split into two parts in the revised manuscript with extended explanations to make it easier to understand.

Line 903-905: could be written clearer.

We now explain that the variable size of the state vector (as formulated with the vocabulary of data assimilation) is linked to the variable number of layers in Crocus (which is clearly explained in the article).