Response to RC1 :

General comments:

a) This paper introduces the updated detailed snowpack model Crocus, which now calculates the deposition and the evolution of light-absorbing impurities (LAI) such as black carbon (BC) and dust in the snowpack. Although the previous version of Crocus that incorporated the TARTES radiative transfer model can consider effects of SSA (specific surface area of snow) and LAI on snow albedo explicitly, the present update allows model users of Crocus to simulate more realistic energy exchanges between the atmosphere and the snowpack as well as temporal evolution of snow physical conditions.
Overall, this paper is well written and I found there is potential that the present study can provide deepened knowledges of snow modelling; however, model validation works are not sufficient to demonstrate effectiveness of the present update. Model performances in terms of snow depth and snow water equivalent are almost the same between the present updated version and the reference version that calculates snow albedo by a relatively simple empirical approach. Therefore, I think readers will find it difficult to assess whether the present update successfully worked or not. At least, I think the authors should present model performance in terms of shortwave (broadband) albedo at Col de Porte in the same manner as Table 2.
—–
The authors are grateful to the reviewer for reviewing our manuscript and for the suggestions concerning the model validation. Indeed there are no real improvement in terms of snow water equivalent and depth but it is important to keep in mind that the “relatively simple empirical approach” used in the reference Crocus version was calibrated at Col de Porte. This simple approach is consequently expected to give satisfying results at Col de Porte and significant improvements were not expected there by improving the physics of the snow model, given that the performance of the model is already virtually as good as it can be measured, given all the uncertainties at play (meteorological observations, snow measurements, model errors – see Lafaysse et al., 2017). We are satisfied that the more sophisticated model has similar performance than the default version. This is discussed in more detailed p16 in the revised manuscript.
However, the empirical scheme of snow darkening used in the reference version can not be applied as such to areas where LAIs contamination levels are significantly different from Col de Porte (or the parameterization should be manually adjusted otherwise spurious results are obtained, see e.g. Jacobi et al., 2015 or 2016). The new scheme using LAI deposition fluxes as inputs of the model is expected to be more transferable to other sites, as long as appropriate deposition fluxes are available. Moreover, the recent developments make it possible to numerically investigate LAI-snow interaction processes.

The evaluation of daily shortwave albedo has been added as detailed in response to comment f).

Specific comments:

b) P6 L30- P7 L2: Is there a reference paper for the description of “The parameterization implemented in Crocus considers that the dry deposition affects the near-surface with an exponential decay to take into account wind pumping which buries a fraction of the dry deposited particles by circulating air into the uppermost snow layers.”? An observation-based evidence for this description would be needed.

The authors consider that wind pumping might be a process affecting the redistribution of dry-deposed LAIs in the near-surface snowpack. However we have no observation-based evidence to provide in support of this intuition. Hence, we used a low value for the e-folding depth of the dry deposition distribution (5 mm) providing similar LAI distribution than affecting all the deposition to the topmost layer (basic parameterization of dry deposition) as explained in the manuscript p 7L10.

In addition, as detailed in the paper, the value is in accordance with experimentally measured depth for which wind pumping has an effect.

c) P8 L14-16: The authors state that "In the present study, the default value of BC scavenging coefficient is set to 20% according to the values provided in Flanner et al. (2007) and assessed by Doherty et al. (2013) and Yang et al. (2015)."; however, BC scavenging ratios listed in Table 1 (note that scavenging ratios for BC and dust listed in the table are inverted) are set to 0 % for most of the settings. Please explain why.

The default value of BC scavenging in our study is set to 0% with just one configuration implementing the BC scavenging value of 20% provided in Flanner et al. (2007). The corresponding paragraph has been modified.

The mistake in the table has been corrected.

The legend of Figure 2 has also been modified accordingly (p27): Simulated BC concentration evolution at the end of 2013/2014 snow season at Col de Porte. The upper panel corresponds to a simulation without scavenging whereas the lower panel corresponds to a simulation using the value of 20% for BC scavenging.

Page 8 Lines 14-16 have been modified accordingly: In the present study, we disabled scavenging by default, implying that the default value of BC scavenging coefficient is set to 0%. However in order to assess the impact of BC scavenging we run a configuration implementing a BC scavenging coefficient of 20% according to the values provided in Flanner et al. (2007) and assessed by Doherty et al. (2013) and Yang et al. (2015).

d) P10 L4: Lateral boundary forcing of meteorological conditions of the ALADIN-Climate model is given from ERA-Interim. How about lateral boundary forcing for BC and dust? In case an emission inventory is used in the parent model (boundary forcing), it should be mentioned here as well.

P10 L4 has been modified accordingly: For aerosols, no data are available at the lateral boundaries. Aerosol lateral boundary forcing is set to 0 because ALADIN-Climate domain is considered to be large enough to include all the aerosol sources affecting the area. For instance, the domain includes the whole Saharan desert.

e) P10-11 Sect. 3.3: The ALADIN-Climate-calculated LAI deposition fluxes were checked by referring to in-situ measurements obtained at Italian Alps. I think the authors should also check validity of the ALADIN-Climate-simulated precipitation rate at Col de Porte. This validation would reveal whether the ALADIN-Climate model could simulate wet deposition realistically or not.

In this study, the precipitation rate comes from in-situ measurements at Col de Porte. The wet deposition fluxes from ALADIN-Climate are only activated if there is in-situ measured precipitation. Dry deposition is active all the time. These details were missing in the first version of the manuscript, and are now added to the revised manuscript.

Page 10- line 7 has been modified : '...(Di Mauro et al., 2015). Wet deposition is only activated when there is measured precipitation. '

Modifications have been performed in the discussion : page 15 – line 29 :
"Lastly, it must be underlined that the wet deposition fluxes from ALADIN-Climate are only taken into account in the simulations when in-situ precipitation is measured. Consequently, any mismatch between ALADIN-Climate and measured precipitation occurrence may lead to errors in simulated wet deposition. "

f) P12 Sect. 4: Please add a subsection where validation results for shortwave albedo at Col de Porte are presented as mentioned above.

Additional evaluations were performed to address this suggestion.

Albedo measurements are available from two sensors at Col de Porte: daily broadband albedo described in Morin et al., 2012 since 1993 and spectral albedo measurements for the snow season 2013-2014 described in Dumont et al., 2017.

First, the simulated daily broadband albedo was evaluated using broadband albedo calculated from daily averaged downwelling and upwelling shortwave broadband radiation fluxes, hourly measured at Col de Porte. Measurements were discarded during snowfall events or when measured fluxes are too low: lower than 20 W m^{-2} for the incoming radiation and than 2 W m^{-2} for the reflected radiation (Lafaysse et al. 2017, Morin et al. 2012). If less than 5 hourly data can be used for calculation daily albedo were discarded .

The daily broadband albedo was computed using model results for each configuration (discarding the same data as for measurements). The results presented a significant bias of around -0.1 (Figure and table bellow).

Figure 1: Daily broadband albedo measured and simulated with our different model configurations

Configuration	Shortwave albedo
	RMSE(bias) from 05/11/13 to 01/05/14
C0	0.100(-0.081)
C1	0.144(-0.112)
C2	0.110(-0.075)
C3	0.113(-0.078)
C4	0.111(-0.077)
C5	0.106(-0.072)

Table 1: RMSE and bias between measured and simulated daily broadband albedo

A similar bias between daily albedo and broadband albedo derived from spectral measurements (Dumont et al., 2017) was noticed in Lafaysse et al. 2017 (Figure 1). A possible explanation for this systematic bias is the slope of the snow surface under the sensor.

Secondly, the evaluation was thus restricted to broadband albedo values derived from spectral measurements (Dumont et al., 2017). These values have indeed been corrected from slope effect and a value of broaband albedo of a perfectly flat surface can be derived. The evaluation with respect to this dataset has been added to the manuscript as detailed in the following.

Data & Methods section : P10 L1

Hourly albedo at noon were calculated using spectral reflectance measurements described in Dumont et al., 2017.
Measured spectral reflectance were first converted to spectral reflectance for a flat surface using Eq. 8 in Dumont et al., 2017.
Lastly the spectral reflectance values were integrated over the wavelength range 350-2800 nanometers , weighted by the incoming spectral irradiance, in order to provide broadband albedo.
The same data have been used in Lafaysse et al., 2017 (Figure 1).

Model Set-up : P11 L24:

3.4 Shortwave albedo evaluation

Lafaysse et al. 2017 have shown that Crocus broadband shortwave albedo features a large bias (up to 0.1 depending on the configuration) compared to Col de Porte albedo measurements described in Morin et al., 2012. In order to investigate the origin of this bias we run an additional computation with an offline version of TARTES radiative transfer model, using impurity content simulated with C5 and SSA values retrieved from spectral albedo measurements from Dumont et al., 2017. This simulation is only used in the Section 4.4 and is referred to as "C5(SSA)".

Similarly to the measurements, we only consider broadband albedo computed at noon from downwelling and upwelling broadband radiation fluxes simulated by Crocus. For C0 configuration we use broadband downwelling and upwelling shortwave fluxes at noon to compute the albedo. For the other configurations, we integrate the spectral downwelling and upwelling shortwave fluxes on the shortwave range (300-2800nm) to compute the broadband albedo.
Measured and simulated broadband albedo are then compared for days when the simulated snow depth is higher than 0 in all of our simulations and automated spectral albedo measurements are available (46 days in total).

Result section: P14 L9

4.4 Shortwave albedo computation

Figure 5 shows the evolution of the simulated and measured broadband albedo at noon.

The last column of Table 2 provides albedo bias and RMSE resulting from this comparison. Those results are consistent with RMSE/bias values obtained in Lafaysse et al. (2017) ensemble simulation. Except for C5(SSA), C0 outperforms the other configurations in terms of albedo. Equivalent scores are obtained for C5 configuration and the difference between C1 and C2,3,4 shows that accounting for LAI largely improve the albedo simulations over a simulation neglecting the impact of impurities.
Albedo bias for C5 simulation is significantly reduced by using measured SSA values instead of the simulated ones, suggesting that the albedo bias is partly explained by the bias in SSA.

Configuration	Shortwave broadband albedo at noon
	RMSE(bias) from 15/02/2014 to 01/05/14
C0	0.059(+0.049)
C1	0.121(+0.094)
C2	0.078(+0.060)
C3	0.078(+0.061)
C4	0.081(+0.063)
C5	0.067(+0.054)
C5(SSA)	0.044(+0.020)

Discussion section P17 L6**:**

Shortwave albedo computations

Section 4.4 highlights that shortwave albedo computation features a significant bias for all the configurations, also noticed by Lafaysse et al. (2017) regardless of the albedo scheme employed.
Snow albedo is not only dependent on snow LAI contents but also largely depend on SSA values, which have been shown to exhibit a 4 m^2 kg^{-1} bias for near-surface snow. The additional computation run using optimized SSA values indicate that most of the albedo bias is due to the bias in SSA (last column of table 2). Modifications of other Crocus parameterizations (such as the SSA evolution laws) would therefore be required to significantly improve shortwave albedo computations.

Section 4 also points out that our recent developments do not improve the albedo computation compared to the reference version (C0 compared to C2, C3, C4 and C5). However, these developments are expected to improve Crocus shortwave albedo computations if they were applied to regions with different contamination levels of LAIs compared to the Col de Porte (e.g: Colorado, Arctic, Antarctic...) where the reference empirical albedo scheme calibrated for Col de Porte poorly performs.

Finally, as underlined in Lafaysse et al. (2017) the improvement of one parameterization does not necessarily lead to the improvement of the overall snow simulations. For example, snow depth evolution at Col de Porte is simulated reasonably despite a strong shortwave albedo overestimation. This albedo bias is compensated by other parameterization biases; correcting this bias would hence lead to a degradation of snowpack simulation if the other parameterizations stay untouched (e.g C5 compared to C2, C3 and C4).

P30: A new figure has been added (see Figure 2 below)

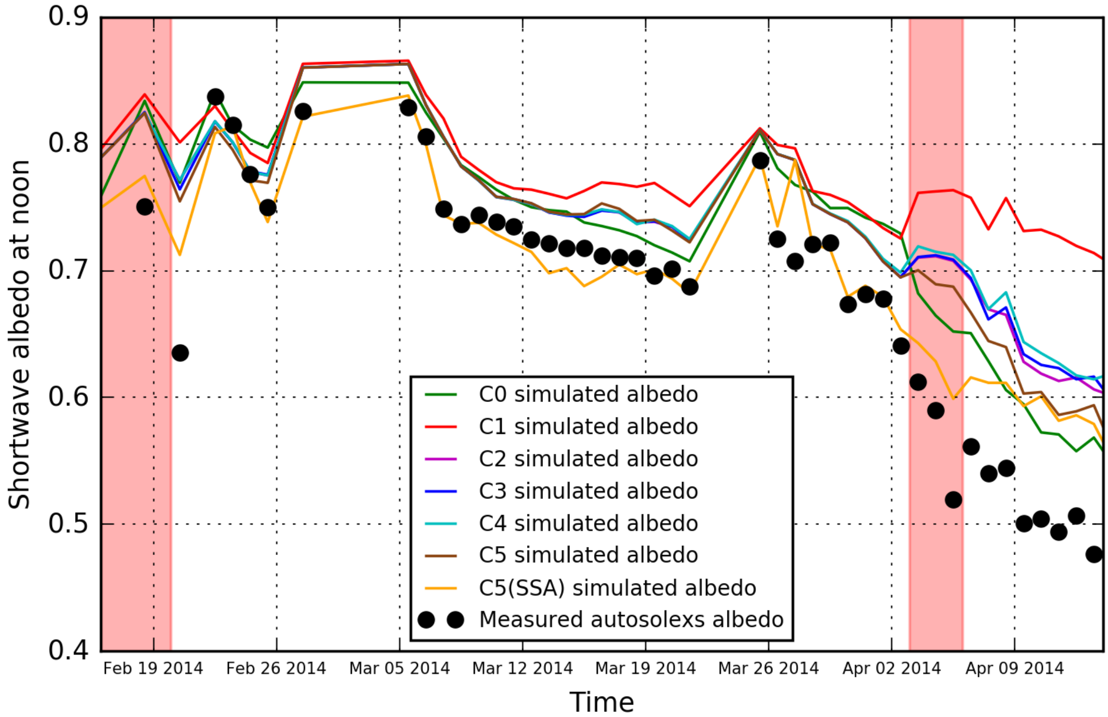

Figure 2 (added to the manuscript as Figure 5): Shortwave broadband albedo at noon. The colored lines correspond to simulated albedo while the black dots correspond to Autosolexs measured albedo (Dumont et al., 2017). The two major Saharan dust events are represented by the red shading.

g) P14 L3-8: During the period when simulated near surface SSA are increased (new snow exists near the snow surface), observation data for SSA are not available as seen in the lower panel of Fig. 4. The authors should explain the reason.

Near surface SSA are obtained via spectral albedo measurements. These measurements are less accurate or unavailable in case of snow falls as detailed in Dumont et al., 2017.
The following sentence was added page 10 line 22 :
"Near surface LAI content and SSA are generally not available during snowfall due to large uncertainties in the albedo measurement (Dumont et al., 2017). "

h) P14 L21-22: When discussing radiative forcings due to direct and indirect impacts quantitatively, I think it is better to use C5 configuration as a control run rather than using C2 configuration. It is because C5 configuration gives more realistic LAI deposition fluxes, and values for radiative forcings would become more reliable and meaningful.

In order to address this suggestion, the same method has been applied to C5 configuration. It appears that using C5 as a control run leads to the same temporal patterns as described in the manuscript discussion (Figure 3 bellow). However the distribution between direct and indirect impacts is slightly modified, with 14.1% of indirect impact against 15.3%. For the present study the default control run (C2) has not been changed but the results obtained using C5 as a control run are mentionned.

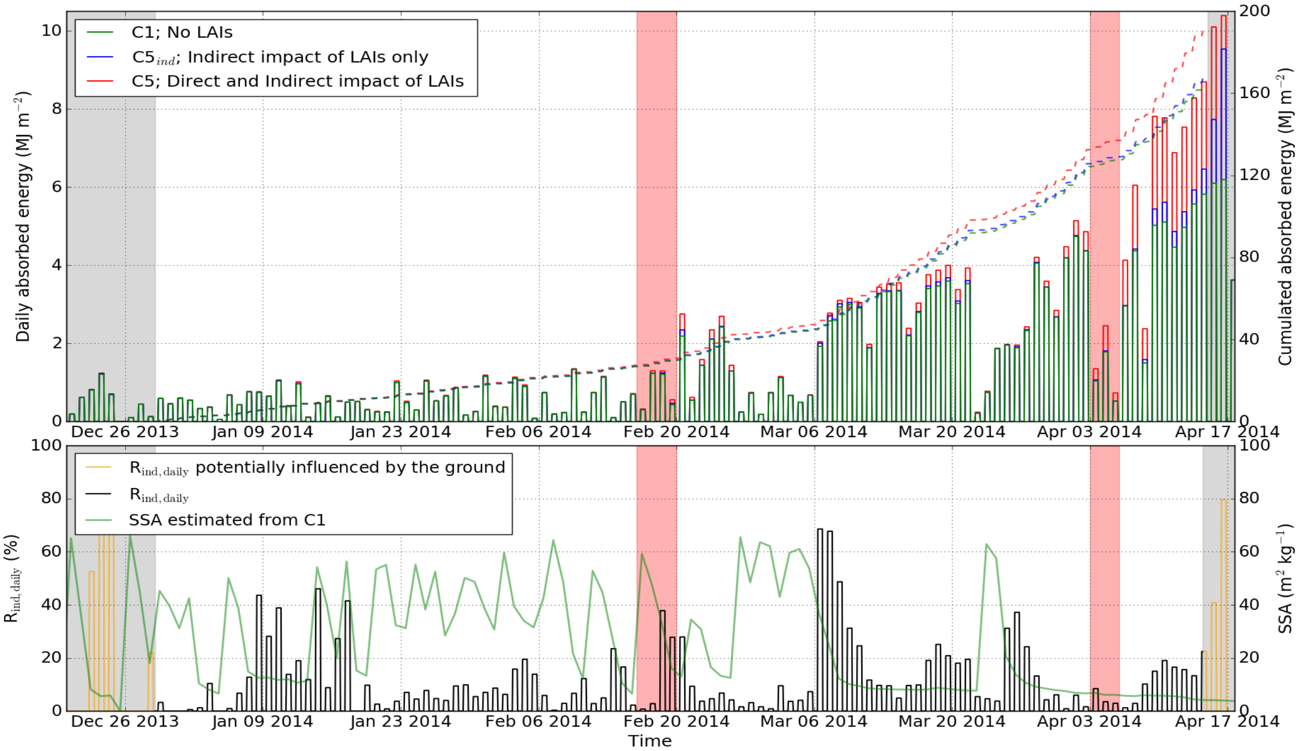

Figure 3: Same figure as Figure 6 in the original manuscript but using C5 as a control run instead of C2.

Energy absorbed by the snowpack during the season (upper panel); the full lines correspond to the daily amount of energy absorbed whereas the dashed lines corresponds to the cumulative energy absorbed over the study period. $R_{ind,daily}$ compared to near-surface SSA computed from C1 (lower panel); $R_{ind,daily}$ is the daily relative importance of LAIs in snow radiative forcing coming from the indirect impact. The dates during which the ground influences the energy budget have been masked (grey shading). The red shading represents two major Saharan dust events.

A note has been added P12 L13: Note that the same method can be applied by replacing C2 with C3,C4 or C5.

A paragraph on this additional result has been added in Section 4.5 Page 14 Line 27: Sections 4.2 and 4.4 highlight that C5 provides better results than C2 in terms of near-surface LAIs concentration and shortwave albedo. Given that radiative forcing is expected to be more accurate for C5, the same method has also been applied using C5 as a control run (instead of C2 on Figure 6). We obtain similar results in term of temporal evolution but the distribution between the average direct and indirect impacts is only slightly modified, with 14.1\% attributed to the indirect impact instead of 15.3 %, which we consider an insignificant variation.

—

Technical corrections:

i) P7 L7: When introducing zj and j, please explain the coordinate system considered by Crocus (e.g., positive direction).

Page 7 Line 7 has been modified accordingly: The layer number 1 is the topmost layer whereas the layer number N is the bottom layer

j) P7 L21: “Mo” and “SWE)o” are typos.

Done.

k) Figure 1: Please explain definitions for red and black circles explicitly.

The red circles represent mineral dust and the black circles represent black carbon. The definitions had not been put explicitly on the figure because the model can easily account for other types of LAIs. As the other types of LAIs are not accounted for in this study, the figure has been changed.

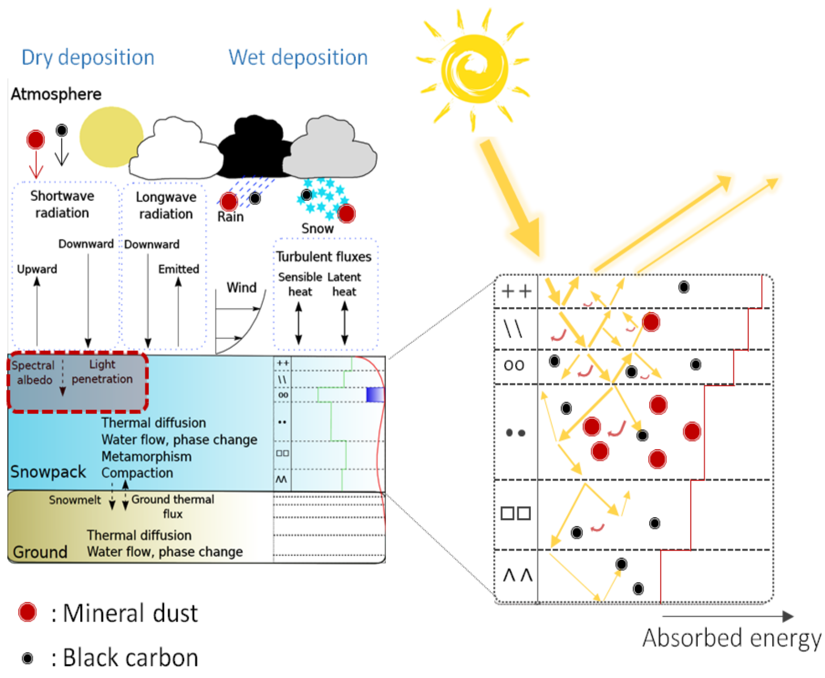

Figure 4 (Modified in the manuscript): Description of the detailed snowpack model Crocus including an explicit representation of LAIs deposition and evolution.

References:

Dumont, M., Arnaud, L., Picard, G., Libois, Q., Lejeune, Y., Nabat, P., Voisin, D., and Morin, S.: In situ continuous visible and near-infrared spectroscopy of an alpine snowpack, The Cryosphere, 11, 1091–1110, doi:10.5194/tc-11-1091-2017, http://www.the-cryosphere.net/11/ 1091/2017/, 2017.

Flanner, M. G., Zender, C. S., Randerson, J. T., and Rasch, P. J.: Present-day climate forcing and response from black carbon in snow, J.30 Geophys. Res., 112, D11 202, doi:10.1029/2006JD008003, 2007.

Jacobi, H-W., et al. "Black carbon in snow in the upper Himalayan Khumbu Valley, Nepal: observations and modeling of the impact on snow albedo, melting, and radiative forcing." *The Cryosphere Discussions* 9 (2015): 1685-1699.

Jacobi, Hans-Werner, et al. "Chemical processes in the atmosphere-snow-sea ice over the Weddell Sea, Antarctica during winter and spring." *EGU General Assembly Conference Abstracts*. Vol. 18. 2016.

Lafaysse, M., Cluzet, B., Dumont, M., Lejeune, Y., Vionnet, V., and Morin, S.: A multiphysical ensemble system of numerical snow modelling, The Cryosphere, 11, 1173–1198, doi:10.5194/tc-11-1173-2017, http://www.the-cryosphere.net/11/1173/2017/, 2017.

Morin, S., Lejeune, Y., Lesaffre, B., Panel, J.-M., Poncet, D., David, P., and Sudul, M.: A 18-years long (1993 - 2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325 m alt.) for driving and evaluating snowpack models, Earth Syst. Sci. Data, 4, 13–21, doi:10.5194/essd-4-13-2012, 2012.