

## Authors response to comments by Christiaan Van Dallum on gmd-2020-242 by Veillon et al.

Reviewer comments are in black. Author response in blue and proposed changes in the manuscript in **bold blue** or in latex fonts. Page and line numbers refer to the first version of the manuscript.

This study presents a new and numerically fast way to determine the snow albedo for use in climate models. The spectral albedo model TARTES together with SBDART are used to determine the energy absorbed for various snowpacks. By using kernel functions, the absorbed energy can be interpolated between tie points, which allows the absorbed energy to be calculated for a wide range of wavelengths. The authors also investigate the impact of various processes and find that the optical depth and LAP content are the most important variables.

The algorithm that the authors present is a clever way to determine the absorption of energy in snow and is also within the scope of this journal. However, I had to read the manuscript several times to properly understand the method and there are still several parts not entirely clear to me. Although VALHALLA is potentially a useful model for the community, the manuscript does not provide an adequate description on how to implement it, hindering the actual implementation in climate models that may be done by others. Consequently, I think that some parts of the manuscript should be reformulated and/or expanded on. The following comments should help with solving most issues, with, for example, P1 L1 meaning page 1, line 1.

AC: The authors are very grateful to Christiaan Van Dallum for the time spent on reviewing the manuscript and for the very comprehensive and relevant comments. Point by point answers are provided below along with proposed changes in the manuscript.

### General comments

1. The most pressing concern is that the method section is hard to follow and misses some information in my opinion. As this is a vital part of the manuscript, it is hard to interpret the results if the methods are not clearly defined. For example, it took a while before I realized that VALHALLA models absorption and not albedo. I especially miss a part about how the implementation would look like in a climate model. I would suggest to rewrite or restructure most of the method section to take away the confusion. The authors may use the following structure, breaking Sect. 2 in 3 parts:

2.1) Existing models

2.1.1) TARTES,

2.1.2) SBDART

2.2) VALHALLA description

2.2.1) Theoretical considerations (currently 2.3). Including a) a discussion why a tie-point method is a clever way to go. b) Explain why the authors choose to model the absorption curve and not the spectral albedo curve.

2.2.2) Interpolation method (currently 2.4). Furthermore, some steps, choices and variables in Sect 2.3 and 2.4 are poorly explained and could be expanded upon. More details can be found in the specific comments.

2.2.4) Reference situation selection (current 2.5.2 – 2.5.4)

2.3) Implementation considerations. It is unclear how VALHALLA can be embedded in a climate model. VALHALLA has a list of insolation situations and a list of snow states, but how do you connect the VALHALLA snow states to the actual snow state in a model? Concerning the incoming radiation, one could simply feed broadband downwelling radiation to VALHALLA, but that is ignoring the spectral radiation available from radiation modules within atmospheric modules? Why should you do that? Furthermore, what input parameters are required, which parameters are then calculated using what equations, are there lookup tables involved, what input parameters are required, what do you do for cases with a SZA larger than 80 degrees, etc. This would be in my opinion a vital subsection and should take away the confusion.

AC: Thanks a lot for this suggestion. The entire method section has been rewritten and restructured according to your comments. We, however, believed that the proposed section 2.3 would fit better in the discussion section. For this purpose, we added a section implementation considerations in the discussion section. The proposed modifications are reported below.

[Modification in the methods :](#)

## 75 2 Method

The VALHALLA method relies on the accurate calculations of the solar radiation absorbed by the snowpack for a small number of selected wavelengths, named tie points (*tps*) in the following. The number of tie points is kept as small as possible to limit the computing resources. Between these tie points, the VALHALLA method interpolates the absorbed radiation based on kernel functions that reflect the main spectral variations of the absorbed radiation across the solar spectrum. The general reasoning of  
80 the method consists in assuming that the spectral variation between tie points can be approximated using the refractive index of ice. The calculation of the absorbed radiation at the tie points can be performed with any radiative transfer model. In the following, we selected the Two-stream Radiative Transfer in Snow (TARTES, Libois et al., 2013) for the snowpack and the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART, Ricchiuzzi et al., 1998a), for the atmosphere.

### 2.1 Radiative transfer models

#### 85 2.1.1 Radiative transfer in snow, TARTES

TARTES calculates spectral albedo in a multilayer snowpack when the physical properties of each layer and the angular and spectral characteristics of the radiation are known (Libois et al., 2014) and is embedded in the detailed snowpack model Crocus (e.g. Tuzet et al., 2017). TARTES is based on the Kokhanovsky and Zege (2004) formalism for weakly absorbing media to

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describe the single-scattering properties of each layer and the delta-Eddington (Joseph et al., 1976) approximation to solve the radiative transfer equation. TARTES represents the snowpack as a stack of horizontal homogeneous layers. For calculation, physical properties of the snowpack (e.g., grain radius, grain shape, density, thickness, type of LAPs, LAPs concentration) and SZA for direct radiation (for diffuse radiation, SZA is fixed at 53°) are used as inputs. The grain size is characterized by the snow specific surface area (SSA; expressed in  $\text{m}^2 \text{kg}^{-1}$ , defined as the ratio between the surface of the air-ice interface  $S$  and the ice mass volume  $V$ ):

$$95 \quad \text{SSA} = \frac{S}{V \rho_{\text{ice}}} \quad (1)$$

with  $\rho_{\text{ice}}$ , the volumetric mass of ice ( $917 \text{ kg m}^{-3}$ ).

We used two shape parameters that are relevant for the optical properties of snow : the asymmetry parameter  $g$  (dimensionless) and the absorption enhancement parameter  $B$  (dimensionless, Libois et al., 2013).  $g$  quantifies the amount of radiation that is scattered forward for a snow grain and  $B$  quantifies the lengthening of photon paths inside a snow grain due to internal multiple reflections.

In Tuzet et al. (2017) and later studies, TARTES was used for calculations of radiative transfer with a spectral resolution of 20 nm. This resolution is the best compromise between the accuracy of radiation and calculation time, which is still very important, and makes this model configuration computationally expensive.

### 2.1.2 Radiative transfer in the atmosphere, SBDART

105 The model Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART, Ricchiuzzi et al., 1998b) is used for radiative transfer calculation in clear-sky and cloudy conditions in the atmosphere. SBDART uses Discrete Ordinate Radiative Transfer (DISORT, Stamnes et al., 1988) to solve the radiative transfer equation in the atmosphere vertically homogeneous. This model is organized to permit up to 65 atmospheric layers and 40 radiation streams. The main input parameters used in this study are the aerosol optical depth (AOD), the cloud-layer optical depth ( $\tau$ ), the boundary layer aerosol type selector (IAER) and SZA. 110 With these parameters, SBDART calculated direct and diffuse irradiance ( $\text{W m}^{-2}$ ) for each wavelength between 0.320 and 4.000  $\mu\text{m}$ . This atmospheric radiative transfer model was chosen since it provides accurate simulations of solar irradiance in snow covered areas (e.g., Tuzet et al., 2020) and offers a large number of parameters to set for the atmospheric properties.

## 2.2 The VALHALLA method

### 2.2.1 Theoretical basis

115 The spectral direct albedo, also called directional-hemispherical reflectance,  $r$  of a homogeneous, optically infinite snowpack can be approximated by the following relationship (Libois et al., 2013; Dumont et al., 2017; Kokhanovsky et al., 2018) :

$$r(\lambda) = \exp\left(-u(\mu_0) \sqrt{\frac{64\pi}{3\rho_{\text{ice}} \text{SSA}(1-g)} \left(\frac{2n(\lambda)B}{\lambda} + 3 \frac{\rho_{\text{ice}}}{\rho_{\text{LAP}}} c_{\text{LAP}} C_{\text{abs}}^{\text{LAP}}(\lambda)\right)}\right), \quad (2)$$

where  $u(\mu_0) = \frac{3}{7}(1 + 2\mu_0)$ ;  $\mu_0$  is the cosine of the solar zenith angle,  $n(\lambda)$  is the imaginary part of the ice refractive index at the wavelength  $\lambda$ ,  $c_{LAP}$  is the light absorbing particles concentration,  $\rho_{LAP}$  is the volumetric mass of the light absorbing particles, and  $C_{obs}^{LAP}(\lambda)$  is the absorption cross-section of LAPs.

When neglecting the spectral variations due to the presence of LAPs in Eq. 2, the first order of spectral albedo variations can be approximated as

$$r(\lambda) \sim \exp(-J\sqrt{\frac{n(\lambda)}{\lambda}}), \quad (3)$$

where  $J = u(\mu_0)\sqrt{\frac{128\pi}{3\rho_{ice}SSA(1-g)}}B$ .  $J$  is constant with  $\lambda$  and depends only on illumination and snow physical properties.

The fraction of absorbed energy in the snowpack with respect to the incoming energy,  $f_p$ , is thus related to the spectral albedo by the following relationship :

$$f_p(\lambda) = 1 - r(\lambda), \quad (4)$$

For the atmosphere, we use the Beer-Lambert law to express the first order spectral variations of the incoming solar radiation. The Beer-Lambert's law establishes a relationship between the radiation transmitted through a given medium  $I$  and the incident irradiance  $I_0$  at the wavelength  $\lambda$ . Let  $L$  be the thickness of the media and  $c_a$  the absorption coefficient. Then :

$$I(\lambda) = I_0(\lambda) \exp(-c_a(\lambda)L), \quad (5)$$

$c_a(\lambda)$  is varying with the atmospheric profile, i.e. with the aerosols properties, the properties of gas in the atmosphere (water vapour, ozone, ...), the solar zenith angle and the cloud properties. Here we assume that the spectral variations of the solar irradiance at the surface can be written:

$$I(\lambda) \sim E_{ref}(\lambda) \exp(-D\sqrt{\frac{n(\lambda)}{\lambda}}), \quad (6)$$

where  $E_{ref}$  is the total incident energy at the wavelength  $\lambda$  for a reference atmospheric profile and  $D$  is constant with wavelength. In other words, this means that for instance, for a given location, we assume that changes in the atmospheric solar irradiance with time can be modelled using Eq. 6, i.e. main spectral changes are driven by the water vapour (assuming that the refractive index of water vapour is close to  $n(\lambda)$ ).

As a consequence, we assume that the absorbed energy by a snowpack for a given wavelength  $E_{abs}(\lambda)$  can be approximated by :

$$E_{abs}(\lambda) \sim E_{ref}(\lambda) \exp(-D\sqrt{\frac{n(\lambda)}{\lambda}}) f_p(\lambda). \quad (7)$$

### 2.2.2 Interpolation method

The VALHALLA method is based on precise calculation of the absorbed energy at the tie points ( $tps$ ), and on the interpolation between these wavelengths based on the general shape of the spectrum given in the equation above (Eq. 7). The method

calculates the absorbed energy since this is the variable directly used in the energy budget of the snowpack. The snow albedo can be directly diagnosed from the absorbed energy (e.g. Eq. 4).

The method uses a reference irradiance profile with a spectral resolution of 1 nm,  $E_{ref}$ . For each SZA value (varying between 10 and 80 degrees), a reference irradiance profile is calculated with SBDART. In total, 16 reference profiles were used (one set for clear-sky and partially cloudy conditions and the other one for full overcast conditions; see Section 2.5.2). These profiles are used to calculate a coefficient  $C$  between the broadband reference irradiance  $E_{ref}$  (integral of the reference profile) and narrow or broadband irradiance  $E_{exp,i}$  given by an atmospheric model for each narrow or broad spectral band  $i$ :

$$C_{b_i}^{b_{i+1}} = \frac{E_{exp,i}}{\int_{b_i}^{b_{i+1}} E_{ref}(\lambda) d\lambda}, \quad (8)$$

where  $b_i$  and  $b_{i+1}$  are the max and min wavelengths of the bands in which the atmospheric model is providing the solar incident radiation.  $C_{b_i}^{b_{i+1}}$  thus represents the scaling factor between the incident radiation provided by the atmospheric model and the reference irradiance for each narrow or broad spectral band of the atmospheric model. In the following, we use  $b_i = 320$  nm and  $b_{i+1} = 4000$  nm. Thus we assume that the broadband incident radiation only is available from the atmospheric model.

For each  $tp$ , the absorbed energy and irradiance are calculated using TARTES-SBDART and used for determining the values of variables  $D$  and  $J$ .

Between two tie-points  $tp_n$  and  $tp_{n+1}$ , we assume that the absorbed energy can be approximated by :

$$E_{abs}(\lambda_{tp_n}^{tp_{n+1}}) = C_{b_i}^{b_{i+1}} E_{ref}(\lambda_{tp_n}^{tp_{n+1}}) \exp(-D_{tp_n}^{tp_{n+1}} \sqrt{\frac{n(\lambda_{tp_n}^{tp_{n+1}})}{\lambda_{tp_n}^{tp_{n+1}}}}) (1 - \exp(-J_{tp_n}^{tp_{n+1}} \sqrt{\frac{n(\lambda_{tp_n}^{tp_{n+1}})}{\lambda_{tp_n}^{tp_{n+1}}}})). \quad (9)$$

To determine these variables, which take into account all snow and illumination properties, an optimization by the least-square method is used. Indeed,  $D$  and  $J$  are mutually dependent.

In the context of optimization, variable  $D$  is written in :

$$G_{tp_n}^{tp_{n+1}} = \exp(-D_{tp_n}^{tp_{n+1}} \sqrt{\frac{n(tp_n)}{tp_n}}), \quad (10)$$

with :

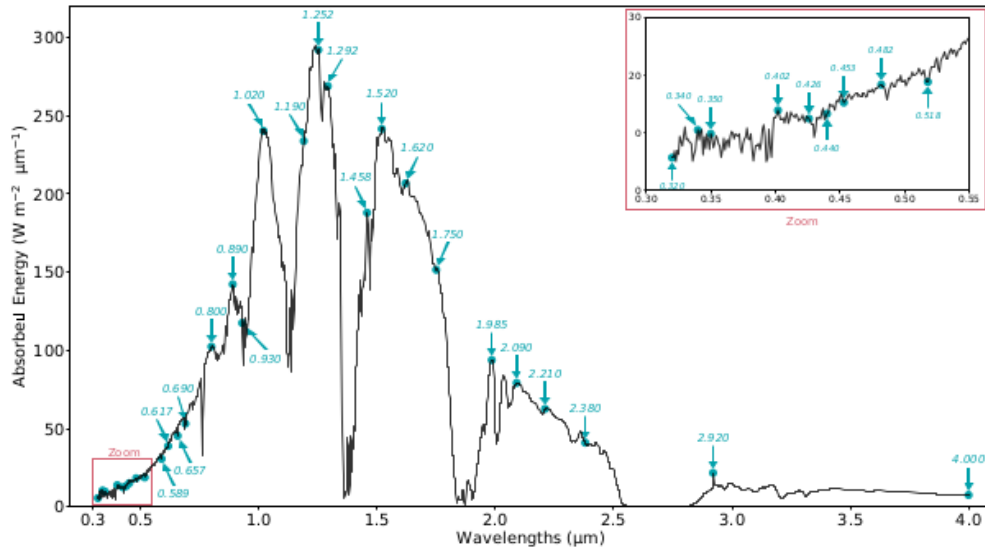
$$D_{tp_n}^{tp_{n+1}} = -\log(G_{tp_n}^{tp_{n+1}}) \sqrt{\frac{tp_n}{n(tp_n)}}, \quad (11)$$

and  $J$  :

$$J_{tp_n}^{tp_{n+1}} = -\log\left(1 - \frac{E_{abs_{tp_n}}}{C_{b_i}^{b_{i+1}} E_{ref_{tp_n}} G_{tp_n}^{tp_{n+1}}}\right) \sqrt{\frac{tp_n}{n(tp_n)}}. \quad (12)$$

The optimization is realised on the variable  $G_{tp_n}^{tp_{n+1}}$  and uses absorbed energy  $E_{abs}$  and total irradiance  $E_{ref}$  for  $tp_{n+1}$ .

$$\Delta_{tp_n}^{tp_{n+1}} = E_{abs_{tp_{n+1}}} - C_{b_i}^{b_{i+1}} E_{ref_{tp_{n+1}}} G_{tp_n}^{tp_{n+1}} (1 - \exp(-J_{tp_n}^{tp_{n+1}} \sqrt{\frac{n(tp_{n+1})}{tp_{n+1}}}}). \quad (13)$$



**Figure 1.** Spectral positions of  $tps$  on an example of absorbed energy profile by a snowpack without LAPs.

Namely, an optimization method is used to solve Eq. 9. The optimization algorithm is finding the value of  $G_{tp_n}^{tp_{n+1}}$  for which  
 175  $\Delta_{tp_n}^{tp_{n+1}}$  is the closest to zero,  $\Delta_{tp_n}^{tp_{n+1}}$  being the difference between the left and the right sides of Eq. 9.

### 2.2.3 Numericals settings

#### Selection of the tie points

The tie points,  $tps$ , are the reference wavelengths for absorbed energy and total irradiance. For all types of snow and cloud  
 cover, a total of 30  $tps$  are selected as a compromise between accuracy and computational time (Fig. 1). The  $tp$  has been  
 180 selected as the local maxima and minima of absorbed energy after several optimization tests (not shown).

#### Reference irradiance profiles

To account for a representative set of atmospheric conditions, different reference irradiance profiles depending on SZA and  
 cloud cover are chosen. These profiles are calculated by SBDART simulations with a spectral resolution of 1 nm for two cloud  
 cover types. For simulations of clear-sky and partly cloudy conditions, reference irradiance profiles with values of  $\tau$  equal to  
 185 0.5 are calculated. For simulations of full-overcast conditions, these profiles are calculated with a value of  $\tau$  equal to 10 (Table  
 1).

### 4.3 Comparison to other existing methods

Gardner and Sharp (2010) developed an snow broadband albedo parameterization accounting for changes in the snow and atmospheric properties. The computational cost of such albedo parameterization is very small and the accuracy is around 0.01 for the broadband albedo (compared to reference calculations at 10 nm resolution). This accuracy is depicted in Fig. 6 by the grey dotted horizontal lines. The accuracy of VALHALLA is roughly an order of magnitude lower. However, the albedo parameterization of Gardner and Sharp (2010) and VALHALLA fulfil two different goals since VALHALLA requires accurate snow and atmosphere radiative transfer calculation for the *tps*. The computational cost of Gardner and Sharp (2010) is thus lower than the one of VALHALLA.

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The SNOWBAL coupling scheme from Van Dalum et al. (2019) described in the introduction of our study provides albedo calculation with an accuracy better than 0.01. Thanks to the physics of the snow radiative transfer model TARTES, SNOWBAL accurately calculates the vertical distribution of the absorbed energy in the different snow layers. This is also the case for VALHALLA when using the method with TARTES for the *tps* points or with any other multilayer radiative transfer model for snow (e.g. SNICAR, He et al., 2018). SNOWBAL used 14 representative wavelengths (RWs) for which accurate snow radiative transfer calculations are performed. The number of RWs depend on the number of narrowbands available for the solar radiation. For VALHALLA, the accurate snow and atmosphere radiative transfer simulations are performed for 30 *tps*. When using 15 *tps*, our method fails to converge to a good representation of the broadband albedo (increasing the error by a factor of 10 to 15). The use of more *tps* (30) is therefore necessary for an improved representation of the broadband albedo. *tps* and RWs are not directly comparable, since the number of RWs depends on the number of narrowbands available and it is not the case of the number of *tps*.

VALHALLA and SNOWBAL fulfill two different niches. SNOWBAL indeed required accurate snow radiative transfer calculation and accurate atmospheric conditions (cloud water content, direct-to-diffuse irradiance ration, ...). VALHALLA requires both snow and atmosphere radiative transfer calculations for the *tps*. This difference together with the need for more than 15 *tps* implicates that the computational cost of VALHALLA is higher than the computational cost of SNOWBAL. However, the accuracy of the SNOWBAL methods depend on the number and range of the narrowband solar radiation available. SNOWBAL accuracy increases when the sub-band spectral variability is reduced. Here, we used the VALHALLA method with broadband solar irradiance inputs, i.e. the worst case. The method was also tested with narrowband solar radiation inputs (from AROME (Seity et al., 2011), not shown) providing similar accuracy on the absorbed energy than the one presented with broadband inputs.

### 4.4 Implementation considerations

The VALHALLA method has been developed to provide accurate calculation of the solar energy absorbed by the snowpack at low computational cost compared to full spectral calculation. The VALHALLA method requires accurate calculation of the spectral absorbed energy for the *tps*. In the study, this is based on TARTES and SBDART models but any other radiative model could be used (e.g. SNICAR for snow (He et al., 2018), Bird and Riordan (1986) for the atmosphere). The overall accuracy of the calculation depends on the choice of the radiative transfer model for snow and for the atmosphere. We believe that the VALHALLA method is an especially efficient compromise between accuracy and computational cost when only broadband (or large narrowbands) solar irradiance value are available from the atmospheric model. This is the case for example for the detailed snowpack model Crocus in the land surface model SURFEX (Tuzet et al., 2017), this is also the case when surface simulations are performed offline (not coupled), i.e. using atmospheric reanalysis or measurements as inputs.

2. The comparison with Van Dalum et al. (2019), mentioned in the introduction and discussion, is inadequate. The authors have to realize that SNOWBAL and VALHALLA fulfil a different niche. SNOWBAL is a coupling scheme, which is built to couple a spectral albedo model like TARTES with a narrowband radiation scheme as is available in RACMO2. This does not only allow for the physics of TARTES to be directly implemented in a climate model, but also allows for an absorption profile on every timestep for each (sub)surface snow layer and for each narrowband, hence allowing internal heating. VALHALLA, on the other hand, as far as I could tell, does not directly couple TARTES, but is an albedo parameterization, as it approximates the total amount of energy absorbed in the snowpack. It reduces the computational time and applies the physics of TARTES indirectly into a climate model, but loses the information of internal absorption of energy. Hence, it is comparing apples with oranges.

AC: Thanks for your thoughts on this point. We are sorry that the first version of the manuscript does not perfectly reflect the ability of SNOWBAL. The introduction part on SNOWBAL was rewritten according to your comments (see proposed modifications in the response to your comment above).

Comparing the number of *tps* used with the number of RWs is also not a valid comparison, as RWs are not used to determine a kernel function. Also, the number of RWs that are used in SNOWBAL are determined by the number of narrowbands available in the climate model to couple. The uncertainty of SNOWBAL would lower if more narrowbands are available, as the sub-band variability is then reduced. At the contrary, the computational costs of SNOWBAL-TARTES would increase, while it remains the same for VALHALLA. In conclusion, I would suggest to revise or (partly) remove the comparison with SNOWBAL.

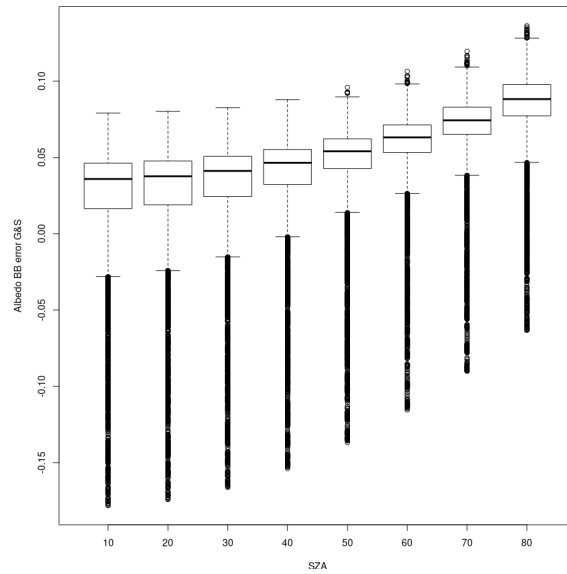
AC: The comparison with SNOWBAL and the difference between SNOWBAL and VALHALLA has been fully rewritten in two sections in the discussion (comparison with existing methods and implementation consideration). The two proposed sections are reported in the response to your general comments 1/ and 3/. Please see also response to Joseph Cook comments.

3. In my opinion, the manuscript would benefit if some analysis is done by comparing VALHALLA with existing albedo parameterizations (like the parameterization of Gardner & Sharp (2010)). It would allow the authors to illustrate the importance of VALHALLA with respect to previous work and validate its necessity. This could also be used to further highlight what processes are now captured properly and could answer some questions. For example, how well does VALHALLA perform on real cases, or alternatively, on snow layers as produced by climate models. Such models typically have many thin but distinctive layers, so how well does it perform then? How would VALHALLA treat ice lenses close to the surface? Adding a short comparison would improve the manuscript.

AC : Thanks for the suggestions. We performed the comparison with Gardner & Sharp parameterization even though the later parameterization and VALHALLA also fulfill different niches since VALHALLA relies on exact multilayer radiative transfer calculations for snow (TARTES in our study). We first compared

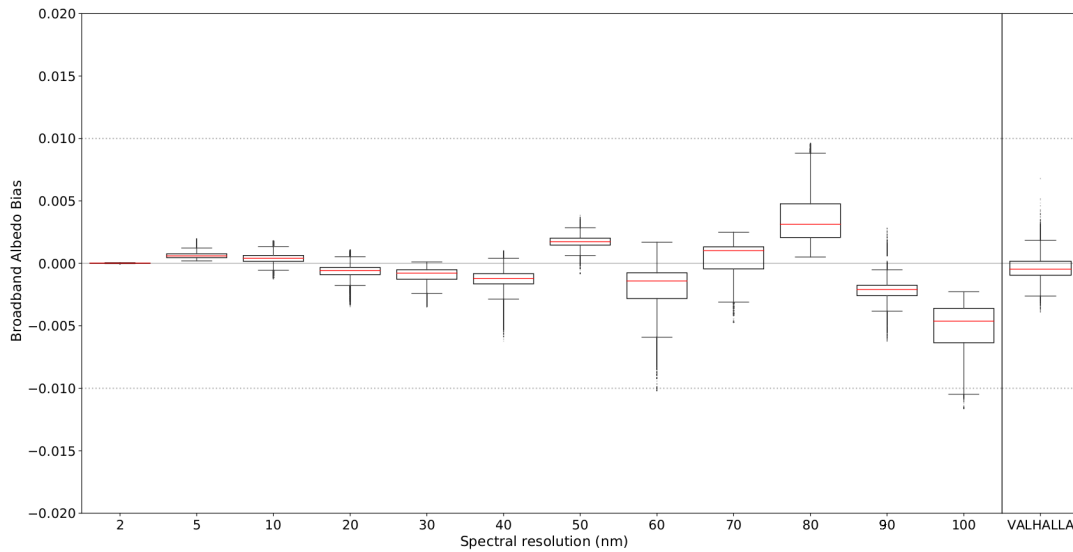


the results of the Gardner & Sharp parameterization to SBDART-TARTES calculation at 1 nm spectral resolution. The figure below shows the results obtained for all our atmospheric and snow profiles.



*Figure 1 - Mean calculated broadband albedo errors between Gardner & Sharp, 2010 and SBDART-TARTES albedo computed from 1 nm spectral resolution calculation. The broadband albedo error is represented versus the sun zenith angle in degree.*

The Gardner & Sharp parameterization depicts a small positive bias consistent with figure 11 in Van Dallum et al., 2019. To avoid unnecessary complexity, we decided to report the standard error given in the text of Gardner & Sharp, 2010 (0.01) in Figure 6. The new figure 6 is now :



We also detailed the comparison with Gardner & Sharp in the discussion section (section 4.3 Comparison to other existing methods, see proposed text in the response to general comment 1).

Regarding the comments on the snow layering, the accuracy of VALHALLA depends on the accuracy of the multilayer snow RT model used for the tie points (TARTES here). For ice lenses, since the spectral variations are still highly dependent on the refractive index of ice, when the RT model is able to do a correct calculation at the tie points, then we believe that the accuracy of VALHALLA won't change.

These points are now detailed in the new sections in the discussion (section 4.3, see above and section 4.4 Implementation considerations - see the proposed text in our response to your general comment 1/).

4. Can the authors say something about or show why they do not deem it necessary to make a distinction between liquid and ice water clouds and why they keep the water vapour content constant?

AC: We guess that the comments on water vapour content being constant is for the reference profiles (Table 2). The choice to keep the water vapour content constant was guided by the fact that method (Eq. 9) accounts for the effect of the water vapour in the atmosphere (not accurately since we used the refractive index of ice and not the one of water vapour, see eq. 6). Separate reference profiles could also be calculated for liquid and ice water clouds, but we did not test it in the study.

The details on the clouds properties have been added in section 2.2. In the discussion we also add a sentence about it : **“The reference profiles can also be adapted to the cloud types (liquid water or ice droplets, droplets radius) when this information is available together with the solar radiation.”**

5. The authors state that VALHALLA could also be used to determine narrowband albedos. However, I am not convinced yet. How well does the method do for small narrowbands, in which, for example, only one or two *tps* are located? Can the authors say more about applying VALHALLA to a narrowband scheme?

AC: We guess this comment refers to former lines 335-336. We added more information for the results obtained for narrowband inputs in section 4.3 (please see proposed text in response to your general comment 3.). We chose not to detail the results with the narrowband input, since one of the advantages of the method is that it can run for broadband input. This is now explained in sections 4.3 and 4.4 (see proposed text in the response to the general comment 1/).

6. Some parts of the manuscript would benefit from more interpretation. See specific comments for more details.

AC: All specific comments below have been accounted for. See below for a point by point answer.

I also have some specific comments that I would like to see addressed.

### **Specific comments**

P1 L16: Please add a reference to this statement.

AC: We add a reference to Warren, 1982 to justify the statement.

P1 L17: Shortly define the albedo here.

AC: The sentences were modified as follows: **“The albedo, defined as the fraction of reflected solar radiation, is very high** for fresh snow **and** limits energy absorption by the snowpack. Darker or old snow and glacial ice absorb more **solar** energy \citep{warren1982optical, gardner2010review}.”

P2 L35-37: “This is usually ... and ice surfaces.” Climate models are also often limited to narrowbands, so spectral fluxes are not available and consequently the albedo has to be determined for narrowbands or broadband.

AC: Right, the paragraph was changed as follows :

“In addition to the above-mentioned requirements, accuracy in the estimation of the energy absorbed at the snow surface can be achieved through spectral calculation of the albedo but remains numerically expensive. **This also requires spectral calculations of the solar irradiance that are most of the time not available in climate models.** This is usually overcome in most global and regional climate models by computing broadband or narrowband albedo to estimate the energy budget at the snow and ice surfaces. The broadband albedo is defined as the ratio between total reflected and total incident solar energy integrated across the entire solar spectrum, whereas the narrowband albedo is integrated **over a limited range of the solar spectrum.** These integrations however lead to a bias in the calculation of the snowpack albedo, which ultimately propagates in the computation of the surface energy and mass budgets.”

P2 L38: This might be a bit confusing, as the narrowband albedo is usually defined as the albedo of a spectral band, not over several spectral bands. AC: [This has been changed. Please see the modifications above.](#)

P2 L47: Van Dalum et al. 2019 calculate RWs for the first 12 of the 14 bands of RRTMsw.

P2 L48: It is also important to note that with using the RWs computed with SNOWBAL, Van Dalum et al. 2019 actually couple TARTES with RACMO2. This does not only allow for the calculation of a narrowband albedo, but also provides the absorption of solar radiation in every modeled snow layer for each narrowband.

P2 L53-L56: Although SNOWBAL has been used for RACMO2, it is not true that it is not applicable for other models. RWs can be determined for models with a different set of narrowbands just as easily, as long as the SZA, cloud content and water vapour content are available.

AC: The paragraph was rewritten according to the 3 above comments and now reads :

To overcome these uncertainties while maintaining an adequate calculation time to remain competitive, new methods are developed. One of them, recently developed by (Van Dalum et al., 2019), effectively couples a snow spectral albedo model with a narrowband atmospheric radiation scheme. This method (Spectral-to-NarOWBand ALbedo module; SNOWBAL) allows the coupling of the radiative transfer model TARTES (Two-streAm Radiative TransfEr in Snow, Libois et al., 2013) with the European Centre for Medium-Range Weather Forecasts (ECMWF) radiation McRad scheme based on the shortwave Rapid Radiation Transfer Model (RRTMsw) embedded in RACMO2 (Mlawer et al., 1997; Clough et al., 2005; Morcrette et al., 2008; ECMWF, 2009). They used the first 12 of the 14 predefined representative wavelengths (RWs, for every 14 bands of RRTMsw) dependent on irradiance distribution and albedo within a spectral band to calculate the narrowband albedo and radiation absorption in each (sub)surface snow layer. To determine the 12 RWs, a limited number of properties of the atmosphere are selected using a look-up table (LUT). They demonstrate that RWs primarily depend on the SZA, cloud content and water vapour. This method is tested on different types of snow and for clear-sky and cloudy atmospheric conditions, and represents broadband snow albedo with low uncertainties ( $<0.01$ ). In van Dalum et al. (2020a, b), the SNOWBAL module is evaluated in RACMO2 over the Greenland ice sheet. This method can therefore be used on large surfaces while accurately representing the albedo of snow and ice. The impact of snow properties on the RWs are not accounted for in the LUTs since it is negligible in the case tested in Van Dalum et al. (2019). This might be a limitation when the narrow bands of the atmospheric model are too large. The use of this method with another model than RACMO2 will require a recalculation of the LUTs for a different

P3 L69-73: For me it is not clear why Crocus is introduced here. It is not mentioned in the introduction and as far as I could tell also not used in the remainder of the manuscript. So it might be better to remove this part.

AC: We agree with the reviewer. The part on Crocus was removed and the entire Method section was rewritten according to the general comment 1/ (please see response to general comment for modifications in the manuscript).

P3 L79: Please be aware that SSA is usually the abbreviation of specific surface area. Also add a space between  $m^2$  and  $kg^{-1}$  and also apply this to all other units in the manuscript. AC: Modified accordingly and also in the rest of the manuscript and in all the figures.

Eq 1: 'SSA' and 'ice' should not be in italics. AC: This has been modified.

All Equations: As an equation is part of a sentence, punctuation is often required at the end of the equation. AC: This has been modified.

P3. L83-84: Please introduce grain shape and 'g' and 'B' a bit more.

AC: The sentences have been changed to : **"We used two shape parameters that are relevant for the optical properties of snow : the asymmetry parameter  $g$  (dimensionless) and the absorption enhancement parameter  $B$  (dimensionless, \citealp{libois2013}).  $g$  quantifies the amount of radiation that is scattered forward for a snow grain and  $B$  quantifies the lengthening of photon paths inside a snow grain due to internal multiple reflections."**

P4, Sect 2.2: SBDART should be described in more detail in my opinion. Also, why did you specifically use this version of DISORT?

AC: We believe SBDART is a useful tool to simulate spectral solar irradiance. It enables the use of a large number of parameters and has proven to be quite accurate in snow covered areas. The calculation is also not too time demanding even though faster alternatives can be found. The section 2.2 was updated as follows :

“This atmospheric radiative transfer model was chosen since it provides accurate simulations of solar irradiance in snow covered areas (e.g. \citealp{tuzet2020}) and offers a large number of parameters to set for the atmospheric properties.”

P4 Sect 2.3: A few introductory sentences are necessary in my opinion to illustrate that you will introduce the physical concepts of VALHALLA.

AC: We agree that this was missing. A full paragraph was added in the beginning of the new method section (please see also response to your general comments 1/).

This reads :

## 75 2 Method

The VALHALLA method relies on the accurate calculations of the solar radiation absorbed by the snowpack for a small number of selected wavelengths, named tie points (*tps*) in the following. The number of tie points is kept as small as possible to limit the computing resources. Between these tie points, the VALHALLA method interpolates the absorbed radiation based on kernel functions that reflect the main spectral variations of the absorbed radiation across the solar spectrum. The general reasoning of  
80 the method consists in assuming that the spectral variation between tie points can be approximated using the refractive index of ice. The calculation of the absorbed radiation at the tie points can be performed with any radiative transfer model. In the following, we selected the Two-streAm Radiative TransFER in Snow (TARTES, Libois et al., 2013) for the snowpack and the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART, Ricchiuzzi et al., 1998a), for the atmosphere.

### 2.1 Radiative transfer models

P4 L97: The use of the letter ‘r’ for the spectral albedo is unconventional and may cause confusion, as it is often used for grain radius.

AC: We believe ‘r’ is conventional for reflectance in optics. We thus did not change the letter, but added the word reflectance in the first sentence.

P4 L97: “... or an homogeneous, ...” --> “... or a homogeneous, ...” AC: modified

P4 L101-104: On L104 you define Lambda-tilde as  $\lambda/\lambda_0$ . This should be moved to L101. Also, where do you use the absorption coefficient of Eq. 3 and explain the Angstrom coefficient. Furthermore, what does ‘pol’ in Eq. 3 mean, pollution?

P4 L101: Can you describe the parameter ‘l’ in more detail? It is a bit vague, as it apparently represents both the size and shape of a grain.

AC: Line 101-107 were fully modified and simplified according to the two comments above. It now reads:

The spectral direct albedo, also called directional-hemispherical reflectance,  $r$  of a homogeneous, optically infinite snowpack can be approximated by the following relationship (Libois et al., 2013; Dumont et al., 2017; Kokhanovsky et al., 2018) :

$$r(\lambda) = \exp\left(-u(\mu_0)\sqrt{\frac{64\pi}{3\rho_{ice}SSA(1-g)}\left(\frac{2n(\lambda)B}{\lambda} + 3\frac{\rho_{ice}}{\rho_{LAP}}c_{LAP}C_{abs}^{LAP}(\lambda)\right)}\right), \quad (2)$$

where  $u(\mu_0) = \frac{3}{7}(1 + 2\mu_0)$ ;  $\mu_0$  is the cosine of the solar zenith angle,  $n(\lambda)$  is the imaginary part of the ice refractive index at the wavelength  $\lambda$ ,  $c_{LAP}$  is the light absorbing particles concentration,  $\rho_{LAP}$  is the volumetric mass of the light absorbing particles, and  $C_{abs}^{LAP}(\lambda)$  is the absorption cross-section of LAPs.

When neglecting the spectral variations due to the presence of LAPs in Eq. 2, the first order of spectral albedo variations can be approximated as

$$r(\lambda) \sim \exp\left(-J\sqrt{\frac{n(\lambda)}{\lambda}}\right), \quad (3)$$

where  $J = u(\mu_0)\sqrt{\frac{128\pi}{3\rho_{ice}SSA(1-g)}B}$ .  $J$  is constant with  $\lambda$  and depends only on illumination and snow physical properties.

P4 L104 and elsewhere: Units should not be in italics. AC: Modified everywhere in the paper and in all figures.

P4 L105: "... can be approximate as" --> "... can be approximated as" AC: Modified

Eq 4: Why can Eq 2 be approximated as Eq 4? Please explain. AC: we gave more details (please see modifications in the response to your comment on line 101).

P4 L107: Please use one symbol for the imaginary part of the ice refractive index, as a different symbol is used at L100. AC: Thanks for noticing it, this was modified, now only  $n$  is used everywhere.

P4 L107 and Eq 4: Is the parameter 'J' a tuning parameter of some sort? Please explain in more detail.

AC: This was modified and explained. The value of  $J$  according to equation 2 was also added in the text. See proposed modifications in response to your comment on page L101.

P4 L109: "The fraction of absorbed energy in the snowpack ..." --> "The fraction of absorbed energy with respect to the incoming energy...", or something similar. AC: Changed

P4 L112: "... through a given media..." --> "... through a given medium" . AC: Changed

Eq. 7: Similar to Eq 4, what did you assume to rewrite Eq. 6 to Eq. 7? Also similar to the parameter 'J' of Eq 4, what is parameter 'D' here?

AC: The description of  $D$  was wrong, sorry. This was changed to :

$$I(\lambda) = I_0(\lambda) \exp(-c_a(\lambda)L), \quad (5)$$

$c_a(\lambda)$  is varying with the atmospheric profile, i.e. with the aerosols properties, the properties of gas in the atmosphere (water vapour, ozone, ...), the solar zenith angle and the cloud properties. Here we assume that the spectral variations of the solar irradiance at the surface can be written:

$$I(\lambda) \sim E_{ref}(\lambda) \exp(-D\sqrt{\frac{n(\lambda)}{\lambda}}), \quad (6)$$

where  $E_{ref}$  is the total incident energy at the wavelength  $\lambda$  for a reference atmospheric profile and  $D$  is constant with wavelength. In other words, this means that for instance, for a given location, we assume that changes in the atmospheric solar irradiance with time can be modelled using Eq. 6, i.e. main spectral changes are driven by the water vapour (assuming that the refractive index of water vapour is close to  $n(\lambda)$ ).

P5 L125 – 126: “(varying between 10 and 80)”, missing units. [AC: units added](#)

P5 L129: What do you mean with ‘experience’ irradiance? [Please see the answer to the next comment.](#)

Eq. 9: It is not clear over what you are integrating, I suppose wavelength? If so, add ‘dy’. Also, why do you want to calculate ‘C’, what does it represent? Furthermore, what is ‘i’, please specify.

[AC: We agree that this was confusing, this has been clarified as follows :](#)

The method uses a reference irradiance profile with a spectral resolution of 1 nm,  $E_{ref}$ . For each SZA value (varying between 10 and 80 degrees), a reference irradiance profile is calculated with SBDART. In total, 16 reference profiles were used (one set for clear-sky and partially cloudy conditions and the other one for full overcast conditions; see Section 2.5.2). These  
 135 profiles are used to calculate a coefficient  $C$  between the broadband reference irradiance  $E_{ref}$  (integral of the reference profile) and narrow or broadband irradiance  $E_{exp,i}$  given by an atmospheric model for each narrow or broad spectral band  $i$ :

$$C_{b_i}^{b_{i+1}} = \frac{E_{exp,i}}{\int_{b_i}^{b_{i+1}} E_{ref}(\lambda)d\lambda}, \quad (8)$$

where  $b_i$  and  $b_{i+1}$  are the max and min wavelengths of the bands in which the atmospheric model is providing the solar  
 140 incident radiation.  $C_{b_i}^{b_{i+1}}$  thus represents the scaling factor between the incident radiation provide by the atmospheric model and the reference irradiance for each narrow or broad spectral band of the atmospheric model. In the following, we use  $b_i = 320$  nm and  $b_{i+1} = 4000$  nm. Thus we assume that the broadband incident radiation only is available from the atmospheric model.

Eq 13: I think there is an error in this equation. The ‘G’ term should be in the denominator. I quickly checked the VALHALLA code and it seems that it is correct there, but please verify this.

[AC: Thanks for spotting this error, yes ‘G’ should be in the denominator. This has been corrected in Eq. 13.](#)

P6 L147: This is a strange sentence, please rewrite and also explain in more detail what happens in Eq. 14. Do you do this optimization for all cases? Please also define the Delta term.

AC: The sentence was indeed strange, it has been rewritten as follows adding details about delta and Eq. 14 : **“Namely, an optimization method is used to solve Eq. \ref{eq:method}. The optimization algorithm is finding the value of  $G_{tp_n}^{tp_{n+1}}$  for which  $\Delta_{tp_n}^{tp_{n+1}}$  is the closest to zero,  $\Delta_{tp_n}^{tp_{n+1}}$  being the difference between the left and the right sides of Eq. \ref{eq:method}.”**

Sect. 2.5.1: It might be beneficial if this is told earlier, i.e. in Sect. 2.4.

AC: This information was moved earlier at the beginning of the method section (please see response to general comment for the proposed modifications).

P6 L150-151: “30 tps is selected” à “30 tps are selected”. AC: Changed

Fig 1: Can you explain why there is no tp at the major minima of the spectrum, like around 1200 and 1400 nm? Furthermore, the units should not be in italics.

AC: the units have been changed in all the figures. The major minima were not necessary (after test) to improve the accuracy of the method.

Sec. 2.5.2 and 2.5.3: These sections should be merged. Could you also specify for cloudy conditions if you use a liquid water or ice cloud and what its droplet radius is.

AC: In response to your general comment 1/, the two sections have been merged in a new section 2.2.3 Numerical settings. See response to the general comments 1/ for the modifications of the whole section methods.

We also add the information on the type of cloud and droplet radius in the new section, it reads:

**“The main SBDART input parameters used in this study are the aerosol optical depth (AOD), cloud-layer optical depth ( $\tau$ ), boundary-layer aerosol type selector (IAER) and SZA (Table \ref{table:2}). For the cloud properties, we used liquid water droplets with a radius of 8 microns.”**

P7 L161-163: “These parameters ... on model outputs”. I do not fully understand this.

AC: The two sentences were changed to : **“These parameters have been selected after a principal component analysis of the spectral absorbed energy. The principal component analysis aimed at obtaining a list of representative parameters with the most pronounced influence on the absorbed energy spectrum.”**

Table 2: “one fore full-overcast” à “one for full-overcast”. I also suppose that the Mid-latitude winter atmospheric profile is one of the AFGL standards, please specify.



AC: The caption of Table 2 was corrected and we added the information about the AFGL standards.

Table 3: Not all units are correct in this table and the last sentence of the header should be reformulated. AC: All the units have been corrected and the last sentence of the header was reformulated to: **“For layer 3, the values of all input parameters, besides soot and dust contents, are constant. For layer 4, all input parameters are constant.”**

Sect. 2.5.4: This section is hard to follow and some information is missing; it would be beneficial if it is rewritten. Furthermore, can you say why you consider these impurity concentrations? They seem very high to me. Similarly, the SSA of  $155 \text{ m}^2 \text{ kg}^{-1}$  for fresh snow looks very high.

Also, what grain shape did you assume (so what  $g$  and  $B$  in TARTES) and which refractive index data set did you use (e.g., Warren and Brandt (2008))? Please elaborate on this.

AC: Yes 155 for new snow is very high but has been measured (e.g. Domine et al., 2007). The sentence was rephrased since it was confusing. All the other informations and justifications about the range and values selected has now been added in the section that reads :

#### **TARTES settings**

195 The main TARTES input parameters used in this study are the surface specific area (SSA) of the first layer of the snowpack, the snow water equivalent (SWE) for each layer of the snowpack and the LAPs concentration. We consider a snowpack with 3 layers of varying thickness and density (Table 3). These layers represent at most the first 20 centimeters of the snowpack, whose physical properties largely determine the albedo of the snow. The principal parameters on albedo calculation are the SSA of the first layer, the SWE of the first layers and the LAPs concentration of two first layers of the snowpack. We selected  
200 a wide range of SSA values ( $2$  to  $155 \text{ m}^2 \text{ kg}^{-1}$ ) in order to cover most of the snow types found on Earth (Domine et al., 2007). SWE gives the mass of snow and is the product between thickness ( $t$ ) and density ( $d$ ). For pure snow (without LAPs), the SWE values are provided for the first three layers of the snowpack. For snow with LAPs, the SWE and LAPs concentration (for soot and dust) are provided for the first two layers of the snowpack. For layer 3 and layer 4, the values of all input parameters are fixed. The ranges of LAPs content for soot and dust have been selected to cover the wide range of conditions that can be  
205 encountered in the various regions of the world from almost pristine snow in Antarctica to highly polluted snow (see e.g. Table 2 in Tuzet et al. (2020) for soot and Sterle et al. (2013) for dust). As recommended by Libois et al. (2014), we set the shape parameters  $B$  and  $g$  to 1.6 and 0.85. The refractive index from Warren and Brandt (2008) was used.

Fig 2: The wrong section numbers are shown here: “... in Section 5.c) and 5.d) using ...” **Changed**

P8 L185-186. “Overall, the median error on the broadband absorbed energy calculated for all simulations decreases with increasing SZA”. Can you explain why?

AC: This is because the incoming (and thus the absorbed) energy is decreasing with increasing SZA. And p 8 L185-186 has been modified as follows : **“Overall, the broadband albedo biases vary little with SZA and the biases of the absorbed energy decrease with SZA. This is consistent with higher absorbed energy for lower SZA (higher incoming radiation and lower albedo).”**

P11 L203: There is a redundant dot here: “Figure 3a,b. show the...” AC: Modified

Fig 3: Not all units are correct and change “for all the simulations described 2.5.3 and 2.5.4 ...” into “for all the simulations described in Sect. 2.5.3 and 2.5.4...”. Please define ‘BB error’.

AC: Units in Figures 3, 4 and 5 have been corrected. The reference to the section has been corrected and BB error defined.

P11 L207: “More than 75% of the errors are positive”. Please add one time what you mean with ‘positive’ or ‘negative’ errors, to take away any possible confusion, i.e., that VALHALLA overestimates the absorption of energy for a positive error.

AC: Thanks, this has been modified to :“More than 75% of the errors are positive, meaning that VALHALLA overestimates the absorbed energy.”

P11 L217: “the majority of the errors are positive and...”, I think ‘positive’ should be ‘negative’ here.

AC : Yes, modified.

P14 L250: What do you mean with “the most important errors”?

AC: The sentence has been modified to : “LAPs being highly absorbent at the beginning of the spectrum (between 0.3 and 0.8  $\mu\text{m}$ , [citealp{warren1982optical}](#)), the highest spectral absolute errors are consequently located in this wavelength range.”

P14 L258: Typo AC: Modified

Fig 6: Can you be a bit more specific about what you mean with ‘Method’ in the right panel? Can you also state the meaning of the boxes, whiskers etc. or refer to a previous figure where you explained it.

AC: Method has been changed to VALHALLA in Figure 6 (see above for the new version of the figure). The caption has been changed :

**Figure 6.** Errors on the broadband albedo for different constant spectral resolutions (left) and comparison with the errors of our method (right). For these resolutions, the broadband albedo is computed by TARTES-SBDART and is compared to the one computed at 1 nm resolution. The red lines indicate the median (same as in Fig 2), the box shows the 25th to 75th percentiles and the whiskers show the 5th to 95th percentiles. The grey dotted lines correspond to an error of  $\pm 0.01$  as in Gardner and Sharp (2010).

Sect. 3.5: This part is hard to follow. For example, what do you mean with “the broadband albedo is calculated between 320 and 4000 nm and then between 327 and 4000 nm”? Furthermore, can you interpret Fig. 6 a bit more. For example, why does a higher resolution generally result in a negative bias? Why is the bias at a 72 nm resolution so much more negative than the bias of a bit lower and higher resolution? Please rewrite this section.

AC: The comparison between 320 and 327 nm was removed for more clarity and section 3.5 was fully rewritten to :

“In Figure \ref{fig:6} we compared the broadband albedo bias obtained with the VALHALLA methods to the bias obtained for varying constant spectral resolution. The comparison was performed using the simulations from section \ref{subsec:numerical}. For constant spectral resolution, the absolute bias generally increases with the spectral steps and tends to be more negative. This means that the bias on the absorbed energy tends to be more positive when the spectral steps increase. We believe that for large spectral resolution, the integration over the spectrum is missing the absorption bands leading the integral to be higher than for smaller spectral steps (see e.g. the spectrum in Figs. \ref{fig:3}-\ref{fig:5}). The VALHALLA method presents biases on the broadband albedo with absolute difference lower than 0.005 which are comparable to the bias obtained with resolutions lower or equal than 20  $\text{\si{\nano\meter}}$  (reference resolution used at MétéoFrance in research activities). The method uses 30  $\text{\tps}$  against 184 wavelengths for a calculation at 20  $\text{\si{\nano\meter}}$  resolution. However, for the same bias on the broadband albedo, the method thus uses six times fewer bands than a calculation at 20  $\text{\si{\nano\meter}}$  resolution.”

We hope this is clearer this way.

P16 L278-L280: “The irradiance provided by the method must, therefore, be as close as possible to the irradiance of the exact calculation to obtain a good representation of the absorbed energy.”. What does this mean if you apply your method into a climate model, as the irradiance is often not as close to the exact calculation in such model.

AC: The sentence was confusing and misleading and was consequently removed.

P17 L288-290: It is maybe also good to mention that although the absolute error decreases with SZA, the relative error generally increases for high SZA, as can be seen in Figures 3-5. Furthermore, for very high SZA (>85 degrees), what do you use then?

AC: yes, we agree. This was reformulated as follows :

“The associated absolute error evolves as a function of the amount of energy absorbed by the snowpack and is therefore driven by the absorbing factors such as the SZA and the SSA. The error on the absorbed energy, therefore, increases with a decrease in the solar angle and a decrease in the SSA value of the first layer of the snowpack. **Although the absolute error decreases with SZA, the relative error generally increases for high SZA, as can be seen in Figures \ref{fig:3}-\ref{fig:5}. For SZA higher than  $85^\circ$  (not tested here), the broadband albedo might be interpolated between the value at  $85^\circ$  and 1. The choice of an adequate reference irradiance profile for the simulation globally determines the accuracy of the absorbed energy error calculated by VALHALLA.** However, the choice of  $\text{\tps}$  is also a determining factor in a good estimate of the energy absorbed by the method.”

P17 L308-310: “The method presented ... in van Dalum et al. (2019)”. SNOWBAL is not only adapted to RACMO2, but can be applied to any narrowband climate model. Furthermore, SNOWBAL is also based on spectral albedo calculations. For P17 L305-314: As is stated in the general comments, comparing SNOWBAL and VALHALLA is like comparing apples with oranges in my opinion. AC: lines 305 to 314 have been fully rewritten according to your comments, please see the proposed text in response to general comment 3.

P18 L329-330: “For the other ... profile is inadequate.” This sentence is confusing, please reformulate. AC: The sentence was reformulated to : **“The use of reference profiles with an adequate value of SZA is necessary to the good accuracy of the method.”**