Author response to reviewer comments on gmd-2020-442 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.

Comments by Joseph Cook

This paper aimed to describe a new method for estimating full-resolution spectral albedo from calculation at a subset of reference wavelengths. The rationale for this is that models with lower numerical load than full RTMs are required for regional climate models. Current models that do this are subject to biases because the regimes used to interpolate between reference wavelengths lead to biases.

In my estimation, the paper succeeds in demonstrating the new algorithm and the subject matter is well within the scope of GMD. Overall, they have clearly described their method, provided a transparent report of its performance relative to TARTES and identified an optimal configuration that balances computation time and accuracy. Therefore, I support this manuscript being published in GMD.

AC: The authors are very thankful to Joseph Cook for the time spent on reviewing the manuscript and for the positive feedback. Point by point answers are provided below along with proposed changes in the manuscript.

The areas that I think could be improved are:

a) it took me a few reads to really understand what benefit the new model provides to the community – I think just reworking the introduction slightly to make it crystal clear why this is useful might be helpful.

AC: We agree that this was not sufficiently clear in the first version of the manuscript. In the revised version the end of the introduction was fully rewritten and two sections were added in the discussion to discuss the pros and cons of VALHALLA compared to other existing methods. The modifications proposed are reported below :

Introduction

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.

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-NarrOWBand 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

set of narrowbands. The accuracy of the method is also expected to increase if more narrowbands are available, reducing the sub-band spectral variability.

Here, we describe a novel method for calculating accurately the solar energy absorbed by the snowpack based on the determination of spectrally fixed radiative variables. The method is named VALHALLA for Versatile ALbedo calculation metHod based on spectrALLy fixed radiative vAriables (version 1.0). This method maintains adequate accuracy of absorbed energy values while reducing calculation time irrespective of the radiative transfer scheme used for the atmosphere. While VALHALLA as SNOWBAL is a coupling scheme, VALHALLA fulfills a different niche than SNOWBAL since it allows accurate calculation when only broadband atmospheric inputs are available and accounts for the snow properties variations. SNOWBAL requires accurate snow radiative transfer calculations for a limited number of wavelengths and an adequate representation of the atmosphere, i.e., cloud content, water vapour, sza, direct-to-diffuse irradiance ratio. VALHALLA requires accurate radiative transfer calculations for both snow and atmosphere for a limited number of wavelengths. The proposed method takes advantage of the spectral characteristics of incident radiation and optical snow properties, based on the analytical approximation of the radiative transfer within the snowpack provided by Kokhanovsky and Zege (2004). The accuracy of the methods is assessed using accurate calculation at a spectral resolution of 1 nm. The sensitivity of the albedo calculations to the atmospheric and snow properties is also assessed. The results are compared with reference albedo calculations at different spectral resolutions and with other existing methodologies (Van Dalum et al., 2019; Gardner and Sharp, 2010). Implementation considerations in climate and land models are finally discussed.

2 Method

Discussion

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.

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 VAHLALLA, 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 atmophere 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 radiatiave 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.

b) the comparison with the 14 tps model used by van Dalum et al. (2019) was very informative. Given that the 15 tps version of VALHALLA failed to give a good representation of the albedo, and presumably there is a computational cost associated with adding tps, can you clarify the argument for using VALHALLA in its 30 tps form in a regional climate model in preference to SNOWBAL?

AC: A discussion on the pros and cons of the different methods (including VALHALLA and SNOWBAL) has been added in the discussion (see proposed text in the response to your comment a) above). Please see also answers to Christiaan Van Dallum general comments 1, 2 and 3.

c) Is there a physical explanation for the relationship between model bias and SZA/SSA?

AC: Yes there is a physical explanation. Figures 3,4 and 5 show that the error in absorbed energy is increasing with decreasing SSA and decreasing SZA. This is due to the fact that the higher absorbed energy is found for low SSA (lower albedo) and for low SZA (lower albedo + higher incoming solar energy). This was explained for SSA p13 lines 236-237. This was also explained for impurities p14 lines 253-254, but the explanation was missing for SZA.

In the new version of the manuscript, this was added p 8 L185-186 : "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).**"

d) Can you give any more detail about the "systematic error" at 400 nm? This seems like it could be a significant issue, but is not explained in much detail in the manuscript. Is this the same as what is referred to in the discussion lines 283-285?

AC: Yes this is the same as what is discussed in lines 283-285. This error appears in the presence of light absorbing particles. Since the method is based on the refractive index of ice, e.g. Eq. (10) in the paper, the interpolation is not really successful when the refractive index of another material is in play (e.g. snow with light absorbing particles in the visible wavelengths). As a consequence, adding more tie points in the visible helps but does not fully remove the errors (Fig. 5c,d).

This is now detailed P14 line 250:

"LAPs being highly absorbent at the beginning of the spectrum (between 0.3 and 0.8 µm, Warren, 1982), the most important errors are **consequently** located in this wavelength range. **The method is indeed based on the ice refractive index (e.g. Eq. 10) and thus partly failed to reproduce changes in the refractive index due to the presence of LAPs.** "

and in the discussion P16-17 L282-287 :

"The presence of LAPs in the snow cover leads to an increase in errors on the absorbed energy, **especially at the beginning of the spectrum where LAPs strongly impact the absorption efficiency**. **The method fails to accurately represent the absorbed energy between two tps in the visible range in presence of LAPs since it is based on the ice refractive index only**. To reduce the uncertainties at the beginning of the spectrum and thus reduce the broadband error, it would be possible to increase the number of tps at the beginning of the spectrum. However, this would increase the calculation time."

e) The zenodo archive really doesn't contain much helpful documentation. A quick review of the code indicates there are significant dependencies including a development environment that includes both tartes and sbdart with specific configurations – it also seems to be OS specific judging by calls out to the sbdart command line tool. I think these and related issues need to be explained in the model documentation in the form of some basic user instructions.

AC: Documentation of the archive has been improved by adding in each folder a README file that provides information on the content of each file including headers and units. Information on how to use the code with examples of running commands are given in the README file of the main folder. The whole environment has been developed under linux and this is now also specified in the README file of the main folder. Since sbdart is a .exe which can be called with python or other and tartes is a python module, only the calls out to the sbdart and tartes command lines tool are OS specific. The updated archive can be found at

:https://zenodo.org/record/5289201#.YSjk35w6_mE