Reply to Reviewer #2

(Referee comment on "Impact of clouds on vegetation albedo quantified by coupling an atmosphere and a vegetation radiative transfer model" by K. Wolf et al. (egusphere-2024-3614),https://doi.org/10.5194/egusphere-2024-3614-RC2, 2025)

We thank the Reviewer for the time she/he spent on the manuscript. We appreciate the provided comments and we believe that the manuscript has been significantly improved by incorporating the Reviewer's suggestions.
To improve readability and logical structure, the order of sections and subsections has been revised. We hope that this will allow the reader to better navigate through the different points discussed in the manuscript. The manuscript has also been extended to include a discussion of modeling limitations and the influence of the selected default values.

For better legibility, the Reviewer’s comments are highlighted in **bold** and changes in the manuscript are in *italic*.

This is a modelling study applying coupled RTM in the atmosphere and vegetation canopy to quantify vegetation albedo under cloudy conditions. The study is timely as understanding of biophysical forest effects on radiation balance and further on climate are essential for forest management strategies. However, the structure and content of the manuscript has to be significantly improved before it can be published. In addition, there are a lot of small misprints in the text, and I encourage the authors to read the manuscript thoroughly during the next iteration.

Major comments

1. **The authors put a lot of efforts in the description of the models, which is done very good, while all other parts got less attention. Results section is currently a mixture of methods and results. I would strongly recommend describing all the modelling setups and their purposes in the Methods section, making a separate subsection, where this information can be added.**
   We respectfully disagree with the Reviewer's comment regarding the mixing of methods and results. If the Reviewer is referring to Eq.9 (old version of the manuscript), the definition of the relative contribution of multiple scattering, and Eq.10 (old version of the manuscript), the definition of the solar albedo-forcing that appear in the result section, then we think that it is appropriate to define these along the way in the results section. The definitions themselves are short and best explained in the context of the surrounding text. Presenting the definitions out of context in a separate “Method” section would make them appear as a surprise.

   The authors could also explain better why they consider this range of variables or specific variables they chose for simulations. Otherwise, all the results come as a surprise.

It is not exactly clear to us what the Reviewer means by “this range of variables or specific variables” since it is not specified to which part of the manuscript the Reviewer is referring.
In our understanding, the choice of parameters for the atmospheric model is explained in Section “Atmospheric radiative transfer model libRadtran”, where the model set-up is described, parameter ranges are given, and supported by the cited literature.
For the vegetation part, the simulations mostly follow the default parameter settings of SCOPE2.0, which are considered to be a reasonable first guess for generic vegetation / a generic canopy. The spherical leaf angle distribution (default of SCOPE2.0) was chosen as the general case, and the planophile and erectophile leaf angle distributions were chosen as extremes. The leaf area index with a value of 3 (default in SCOPE2.0) was initially varied from 2 to 5 to obtain a range / variety around the default. The LAI was extended to include LAI=1.
The chosen values of cloud optical thickness τ from 0 to 4 and 6 in Figures 3, 4, 6, and 7 were chosen because this is the range where the direct fraction of downward irradiance is most sensitive to changes in τ. This is also explained in the text.
For Figure 6 the *x*-axis was extended to include $\tau = 60$ since a different process, here multiple scattering, was investigated.
We rephrased the following lines in the manuscript to be more specific:
“The solar zenith angle θ_0 was varied between 25° and 70° to cover the typical range of the mid-latitudes.”
“The cloud optical thickness τ , was varied between values of 0 and 80 to simulate natural conditions of stratus clouds ranging from cloud-free to densely overcast, and to include values of τ at which the cloud top reflectivity saturates (King, 1987; Nakajima et al., 1991; Tselioudis et al., 1992). ”
“Analyzing the coupled simulations, it was found that the sensitivity of the simulated spectral and broadband $F(\lambda)$ and $\alpha(\lambda)$ was greatest below $\tau = 6$, thus, defining the range of τ, which is most interesting for understanding cloud–vegetation–radiation interactions. The simulations are performed for an intermediate $\theta_0 = 45°$ and $\tau = 2$, where diffuse radiation dominates but direct radiation is still contributing to the radiation field.”

In addition, this manuscript lacks discussion part. How do all these results compare to the previous findings? At least some of these effects were previously reported in other studies, for example, the change in albedo between low-diffuse- and high-diffuse-fraction conditions at low and high zenith angles.
Following the Reviewer's comment we have placed our results in the context of existing literature. The following sentences and paragraphs have been expanded and added to the manuscript.
“Cloud–vegetation-radiation interactions, here primarily multiple scattering between cloud base and the canopy, are known to enhance the observed spectral albedo (Weihs et al., 2001; Wendisch et al., 2004; Gueymard, 2017). The enhancement is caused by an additional contribution of radiation to $F^{\downarrow}_{dif}(\lambda)$ that was reflected at the TOC back to the atmosphere and again back to the canopy by the cloud base

(Freedman et al., 2001; Min and Wang, 2008; Kanniah et al., 2012; Gueymard, 2017). ..."
"Generally, all cases with high surface albedo, i.e., over snow and ice covered areas, are prone to enhanced diffuse radiation and albedo below clouds (Hay, 1976; Kierkus and Colborne, 1989; Gueymard and Ruiz-Arias, 2016; Gueymard, 2017). However, the absolute enhancement of diffuse radiation above vegetation is smaller due to the generally lower albedo compared to ice."
"Although vegetated surfaces have a lower spectral albedo compared to Arctic regions, it can be expected that clouds have a similar effect on the TOC albedo. For example, Gueymard (2017) showed that clouds can enhance the broadband albedo, also called albedo enhancement, by backscattering radiation at cloud base towards to surface, which leads to an increase in the diffuse downward irradiance. Neglecting potential albedo enhancements in models may cause biases in the simulated radiative budget. Furthermore, it is known that very thin cloud layers with $\tau \leq 6$ *tend to increase the diffuse downward irradiance that can penetrate deeper into the canopy and enhance the photosynthesis rate, which is also called the diffuse fertilization effect. A further increase in* τ *then leads to an overall reduction in downward irradiance and lower photosynthesis rates (Freedman et al., 2001; Min and Wang, 2008; Kanniah et al., 2012). "*
"For values of θ_0 *of 25° and 50°,* α_{BB} *is lowest for the black-sky albedo, while the highest values of* α_{BB} *are found for the white-sky albedo. The black-sky and white-sky albedo increase with increasing* τ *. The blue-sky albedo, as an intermediate condition between the black-sky and white-sky albedo, is closest to the black-sky albedo for cloud-free conditions and approaches the white-sky albedo under overcast conditions (*$\tau > 6$*). This agrees with the observations by Freedman et al. (2001) and Kanniah et al. (2012), who found an increase in the canopy albedo under cloudy conditions compared to clear-sky conditions."*

2. **The title and abstract refer to clouds in general but in fact, as far as I could see, simulated clouds represent liquid altostratus, which I think should be mentioned explicitly already in the introduction, and a couple of words can be said about justification of this choice.**
We agree with the Reviewer that we need to be more precise in this regard. The title has been rephrased as follows:
“Impact of stratiform liquid water clouds on vegetation albedo quantified by coupling an atmosphere and a vegetation radiative transfer model”.

Stratiform liquid water clouds have been selected since this is a common cloud type over land. In addition, one-dimensional radiative transfer simulations best resemble stratiform clouds.
"Since one-dimensional RT models assume homogeneous clouds that best resemble stratiform clouds, this study focuses on low- and mid-level warm stratus and altostratus, which cover between 4 and 12 % of the entire globe at any time (Eastman et al., 2011). These clouds are represented by liquid water clouds with a

fixed cloud base at an altitude of 3 km and a cloud top altitude of 3.5 km representative of mid-latitude, continental clouds. The cloud droplet effective radius is fixed to 10 μm that is typically found in such clouds over continents (Stephens, 1994; Frisch et al., 2002; Aebi et al., 2020). "

3. **Related to the estimates of the radiative forcing:**
   first, it is not mentioned at all anywhere before the corresponding Results subsection starts;
   The following sentence was modified and added in the introduction:
   "For example, Gueymard (2017) showed that clouds can enhance the broadband albedo, also called albedo enhancement, by backscattering radiation at cloud base towards to surface, which leads to an increase in the diffuse downward irradiance. Neglecting potential albedo enhancements in models may cause biases in the simulated radiative budget"
   (Please also see the answer to major comment #1.)

   second, I do not really understand why it is done for clear sky downwelling irradiance if the whole point of the study is that albedo is calculated for cloudy conditions, and changes are associated with the present clouds. To me, it would make more sense either to compare the difference in radiation balance between cloudy coupled and uncoupled simulations or cloudy-coupled vs clear-sky albedo for cloudy conditions.
   Following the Reviewer's comments the contributions from cloud--vegetation-radiation interactions and the influence of the diffuse and direct radiation on the surface albedo are now presented separately. To avoid potential misunderstandings, the definitions of the individual radiative forcing components are explicitly given in equations 10 to 12 in the new manuscript and it is clearly stated when uncoupled and coupled models are used.
   We hope this makes it clearer that we are not comparing cloudy and clear-sky simulations, as the Reviewer assumed. Due to the length of the revised section, we would like to refer the Reviewer to the new version of the manuscript.

4. **Results section starts with a long text, which in fact represents a separate subsection. Please make it a subsection and give it a title. Instead, a reader would appreciate a brief summary of the story in the different Results subsections right after the title Results and Discussion. Oppositely, subsection 3.3.1 is too short, and it is not clear to me why it is separated from the next subsection which discusses panels of the same figure. Related to that, Subsection 3.3 is called simply 'Broadband' and must be renamed.**
   We do agree with the statement of the Reviewer and completely revised the structure of the paper in order to facilitate the readability. Due to the comprehensive re-ordering we would like to direct the Reviewer to the new version of the manuscript.

Minor comments:

L18-19: ‘an important boundary between the lithosphere and atmosphere, across which energy fluxes (latent and sensible heat, turbulence, gases, aerosol particles, and radiation) are exchanged’ – please rewrite, turbulence and aerosol particles are not present in the lithosphere

The first sentence has been rephrased as follows:

"The Earth’s surface represents an important boundary between the lithosphere and atmosphere, through which energy fluxes (latent and sensible heat, turbulence, gases, aerosol particles, and radiation) are exchanged. Land-surface–atmosphere interactions are a key concern in dynamic modeling (Ardaneh et al., 2025). In the context of radiative processes, the spectral surface albedo α(λ), with λ the wavelength, determines the extent to which solar radiation is absorbed and reflected by the Earth’s surface. The surface albedo determines the surplus of energy that is transferred into sensible and latent heat (Moene and Van Dam, 2014)."

L60-61 ‘As a result of this discussion, there are two question to be addressed in this paper’ – please link the previous discussion and the research questions better and state explicitly the novelty of the current approach. To me, it clearly comes later in lines 136-138.

We followed the suggestion of the Reviewer and rephrased the section as follows:

“As a result of this discussion and since the radiation interactions of clouds and vegetation have not been explicitly simulated yet, the following four questions are addressed in this paper:

i How strongly do clouds impact the spectral and broadband albedo of vegetation?

ii How large are the improvements in broadband albedo by coupling atmospheric and vegetation RT models?

iii Can we separate and quantify individual coupling effects?

iv What are the consequences for cloud radiative effects?

To answer the above questions and to systematically investigate CVRIs, we iteratively coupled the atmospheric RT model libRadtran and the vegetation RT model SCOPE2.0 to investigate the radiative interaction of clouds and vegetation. The model coupling provides a more realistic input to the atmospheric radiative transfer model libRadtran by incorporating the vegetation albedo from SCOPE2.0, while the simulated spectral downward irradiance from libRadtran fed into SCOPE2.0 accounts for scattering and absorption by clouds.”

L 197: tau = 80 is optically thick overcast. So far it looks the authors simulate mid-level clear sky and overcast mid-level liquid clouds (altostratus) with different cloud thickness.

In section "2.2.1 Atmospheric radiative transfer model libRadtran" we better describe the selection of the cloud optical thickness values by:

"...The cloud optical thickness τ , was varied between values of 0 and 80 to simulate conditions ranging from cloud-free to densely overcast. ..."

If this does not adequately address the Reviewer's comment and the Reviewer would like us to pursue this comment further, we ask the Reviewer to be more specific in his or her request.

L 202: tau = 2 mentioned but then in Fig. 2 tau is 4

The Reviewer is right. The value of τ=4 was incorrect in the figure caption and is now corrected to τ=2.

Fig. 2: In legends, check 'uncoupled' and dots are not needed. Related to inserts, the choice of coupled simulations albedo as a reference value is counterintuitive. I'd prefer to see the change in albedo quantified with regards to uncoupled simulations.

The labels have been changed. Together with the modifications in the text, we hope that this better clarifies what is shown in the plots and avoids misunderstandings. The coupled simulations were chosen as the reference because they represent irradiance and albedo closer to the values that would be observed in nature. Therefore, we keep the coupled simulations as the reference.

Please note that Fig.2 has been updated to be more precise in the wording and to address the Reviewer's concern raised in the comment.

L213: 'different stages of coupling'. Is clear-sky case really the stage of coupling for cloudy conditions? I think the authors speak of different setups here.

To be more clear, the color code and the legend in Fig.2 have been updated. In this way, simulations from panel a and b cannot be confused. The adjoined text is also revised to better express, why we consider cloud-free simulations and cloudy simulations with and without coupling. The text now reads as follows:

"The necessity to initialize vegetation RT simulations with realistic $F^{\downarrow}(\lambda)$ and the need for RT model coupling is demonstrated in Fig. 2a and b, which show an example of $F^{\downarrow}_{dif}(\lambda)$ and $\alpha(\lambda)$ at different stages of model coupling and iteration. The simulations are performed for an intermediate θ_0 = 45° and τ = 2, where diffuse radiation dominates but direct radiation is still contributing to the radiation field. Under cloud-free conditions (black line), downward diffuse irradiance $F^{\downarrow}_{dif}(\lambda)$ above the canopy is generally small, except below 700 nm wavelengths, where the contribution from Rayleigh scattering increases. Including clouds in the atmospheric RT model increases $F^{\downarrow}_{dif}(\lambda)$ (red line) compared to the cloud-free case due to scattering at cloud particles. The spectrum is characterized by water vapor

absorption in the wavelength bands of 933–946 nm, 1118–1144 nm, 1350–1480 nm, and 1810–1959 nm. Coupling of libRadtran and SCOPE2.0 iteratively results in $F^{\downarrow}_{dif}(\lambda)$ (orange line) which is slightly higher compared to the uncoupled simulations since multiple-scattering enhances $F^{\downarrow}_{dif}(\lambda)$. Relative differences, given in the subpanel of Fig. 2a, up to −5% are identified between the uncoupled and coupled cloudy simulations for wavelengths between 700 and 1200 nm, where the total $F^{\downarrow}$ and α(λ) are generally largest. Since clouds modify $F^{\downarrow}(\lambda)$ spectrally and $f_{dir}(\lambda)$, they also impact α(λ). Figure 2b shows α(λ) during different model set-ups and iterations. A generic α(λ) is provided by the IGBP data base (brown line), which was also used as a first-guess to initialize the libRadtran simulations. The radiation is reflected isotropically and does not take into account any dependence on the incident angle nor the presence of clouds. Running SCOPE2.0 freely without any constraints from the atmosphere, i.e., assuming a cloud-free atmosphere, a better resolved α(λ) is obtained (gray line). By providing spectra of direct and diffuse $F^{\downarrow}(\lambda)$ that represent cloudy conditions with τ = 2, a higher α(λ) is obtained (blue line), which is caused by the greater fraction of diffuse radiation. Relative differences of about −2 to 15 % are determined. Simulations at this stage of the iteration still neglect CVRIs. Coupling both models under cloud conditions results in α(λ) (green line), which is slightly further enhanced compared to the blue line due to multi-scattering between TOC and cloud base. For the given example, the relative differences range between 3 and −5 %, with respect to the fully coupled simulations (see subpanel Fig. 2b). The following analysis will systematically examine the discrepancies in spectral and broadband F (λ) and α between uncoupled and coupled simulations, depending on θ_0 and the optical properties of clouds and vegetation."

Fig. 3 panel b: why are there increases of this ratio above 1 close to absorbing intervals at large theta? Are these some artifacts resulting from too low radiation in the denominator?

The Reviewer is correct that these are due to artifacts in the denominator. The numerically unstable values have been masked and an updated version of the figure is now included in the manuscript.

Add in the captions that Fig. 3 uses spherical LAD and Fig. 4 erectofile

The Reviewer is right. We added titles to Fig. 3 and 4. In addition, we explicitly mention the LAD in the figure captions:

"Simulations for a solar zenith angle θ_0 = 25° (left column) and θ_0 = 70° (right column), a leaf area index LAI = 3, and a spherical leaf angle distribution. "

"Simulations for a solar zenith angle θ_0 = 25° (left column) and θ_0 = 70° (right column), a leaf area index LAI = 3, and an erectophile leaf angle distribution"

Fig. 6: I’d prefer to see legends in these figures than overlapping numbers
Due to the number of different colors and the fact that there are two parameters, solar zenith angle and cloud optical thickness, we still think that writing the values next to the lines is easier to interpret. However, we do agree with the Reviewer and rearranged the labels to avoid the overlap.

L 359: Fig. 7(d-f) - no such figures
The Reviewer is correct. The figure has been modified during the preparation of the manuscript; some panels were removed, but the reference was forgotten in the text, which is now removed.