Reply to Reviewer #1
(Referee comment on "Biases in estimated vegetation indices from observations under cloudy conditions" by K. Wolf et al. (egusphere-2025-2082),https://doi.org/10.5194/egusphere-2025-2082-RC1, 2025)

We would like to thank the Reviewer for taking the time to review the manuscript and for providing comments that helped us improve it. Below, we respond to the Reviewer's comments. For clarity, the Reviewer's comments are in **bold** and the changes to the manuscript are *in italics*. Please note that some additional changes have also been made to improve the writing and style.

Dear Dr. Wolf and co-authors,

Thank you for developing this framework to address the cloud influence on ground reflectance measurements. Indeed, in the remote sensing community, our field measurements are highly dependent on the illumination conditions, frequently altered by clouds. I have several minor remarks for your consideration.

In eq. 1, 4, 6 what do you mean by the 'sr' argument? Pi is already assumed to be in steradian (sr) units, cancelling steradian in the upwelling radiance I.
While in some publications π is considered to have the unit "sr", we disagree in the point that this is always the case. In our case, π and it's unit result from integrating over all solid angles of the hemisphere and assuming an isotropic / Lambertian surface. Thus there is no "sr" related to π. Therefore, we kept the notation of "sr" in equations 1, 4, and 6.

A bit on the same line, multiplication by pi suggests that the surface reflects homogeneously in all directions, Lambertian reflectance. How big would you expect the influence of the directionality of the actual surface to be on the reflectance value?
The Reviewer is right that we have to be more precise with the definition of reflectivity. The paragraph to define the reflectivity has been update as follows:
"All remotely sensed VIs rely on the spectral reflectivity ρ(λ). In its most general form, ρ(λ) is defined as the ratio of the surface-reflected radiance from within an infinite solid angle to the incoming radiance from within an infinite solid angle (Nicodemus, 1977; Martonchik et al., 2000; Schaepman-Strub et al., 2006). The amount of radiation reflected into a given solid angle is defined by the surface-specific bidirectional reflectance distribution function (BRDF, Schaepman-Strub et al., 2006). Furthermore, the surface reflected radiation depends on topography (Matsushita et al., 2007) and on changes in illumination conditions determined by solar zenith angle, aerosol particles, and clouds (Singh and Frazier, 2018). Definitions of ρ(λ) based on first principals are given by Nicodemus (1977) and Schaepman-Strub et al. (2006). For brevity and simplicity, we restrict the definition of ρ(λ), assuming idealized conditions of pure diffuse illumination and Lambertian reflection at the surface, which results in: [...]"

Under natural conditions, incoming radiation is neither purely diffuse nor purely direct. In such cases, the deviation from a Lambertian surface is expressed by the hemispherical-directional reflectance function (HDRF). SCOPE2.0 internally considers for the HDRF, since we prescribe the direct and diffuse irradiance obtained from libRadtran, and specify the solar zenith and azimuth angles, as well as the observation zenith and azimuth angles. This allows to obtain radiances that would be observed under field conditions, demonstrating the advantage of coupling SCOPE2.0 with libRadtran.

To make this more clear, we added the following sentence to section 2.2.2 Vegetation radiative transfer model SCOPE2.0:
"The angular dependence of $I^{\uparrow}(\lambda)$ is considered for by the actual illumination and observation geometries, the direct and diffuse $F^{\downarrow}(\lambda)$, and the internal calculation of the reflectivity in SCOPE2.0. "

Figure A1 in the Appendix of the submitted manuscript shows the normalized hemispherical–directional reflectance factor R_{HDRF} at 550 nm wavelength. The plot displays R_{HDRF} for different illumination conditions, which are specified by the cloud optical thickness τ and two solar zenith angles θ_i , and resulting direct to diffuse ratios f_{dir}.
The polar plots and particularly the cross-sections show that the actual surface reflectivity deviates strongly from the isotropic assumption. In the general case, the amount of radiation that is reflected in a specific direction depends on the angles of the incoming irradiance, as it is given in equations A1 and A2 in the Appendix. The dependence on viewing geometry is pronounced along the principal plane, which is defined along the 0°-180° azimuth line, with the Sun positioned at 0°. For the example given in Fig. A1 a-d with solar zenith angle θ_i of 25° and τ=0, a change in the viewing direction from nadir (θ_r=0°) towards the hot spot at 25°, observed reflectivity would almost double. With increasing values of τ the pronounced effect of the hot spot vanishes but the effects towards large viewing angles become more pronounced (see Fig. A1 d). Even greater difference in between nadir observation and more slant observation geometries appear with increasing values of θ_i (see Fig. A1 e-h). Also other azimuth directions off the principle plane show a strong dependence on the viewing geometry (see Fig A1 right most column)

On the SCOPE model (section 2.2.2 and Table 2).

- **First of all, it is unclear why SCOPE was chosen instead of SAIL or INFORM. The latter is more suitable for pine forest (L163) simulations, as it explicitly has the concept of trunks and branches in it. SCOPE has energy balance, thermal domain, photosynthesis and chlorophyll fluorescence that other models do not have. Using it as a tool for a single reflectance simulation is overkill. Nonetheless, your choice.**
  Thank you for providing your model suggestions. However, we are aware that several models for vegetation radiative transfer exist.
  To our knowledge, an equivalent model to SCOPE2.0 would be, for example, PROSAIL, which combines PROSPECT (for leaf optical properties) and SAIL (for radiative transfer in the canopy). We chose SCOPE2.0 over other models because it provides an accessible way

to couple it with libRadtran, without the need to make fundamental changes in the code base of both models. Another factor is the ability of SCOPE2.0 to provide simulations in the thermal wavelength range, a potential topic that we are interested in future investigations. Using SCOPE2.0, now for the visible and near-infrared, and later for the thermal infrared, allows us to use the same or similar model framework for both wavelength ranges with only minor modifications.
We also acknowledge that INFORM may be better suited for an erectophile leaf angle distribution, but since we also simulated spherical and planophile leaf angle distribution, SCOPE2.0 appears to be a reasonable choice to us.

- **Why was only half of the important SCOPE input parameters chosen? The BSM model, for example, has brightness, two shape parameters and moisture content, but only B is shown in Table 2. In any case, those parameters are set to their default values so it is also not clear why highlighting them at all.**
  In the companion paper by Wolf et al. (2025a) [https://bg.copernicus.org/articles/22/2909/2025/bg-22-2909-2025.html], we presented a sensitivity study of selected SCOPE parameters relevant to canopy optical properties within the visible and near-infrared wavelength range. In the sensitivity study, the selected variables have been varied around their default values and the effects on the surface reflectivity and canopy albedo have been determined. Based on the relevance of these factors, ordered by their magnitude, they were selected to be included in Table 2 in the current manuscript. While some of the parameter default values have been modified to represent forest, others were kept constant, like the BSM parameter. The default value of the BSM model is listed because it was found to be an influential parameter in surface reflectivity. To better clarify the selection of parameters and the values, we added the following sentences to section "2.2.2 Vegetation radiative transfer model SCOPE2.0".
  "Table 2 provides an overview of the selected parameters for the vegetation RT simulations. The parameters were selected based on their relevance to surface reflectivity within the visible and near-infrared wavelength ranges. Their individual relevance was estimated in a sensitivity study by Wolf et al. (2025a)."

- **Finally, could you please be more explicit about which SCOPE output was integrated with the libRadtran output and how? I am a bit confused because L152 says “*As an initial guess of the surface albedo in libRadtran, the "mixed-forest" albedo was taken from the IGBP data base.*” According to my understanding, it was sufficient to take some spectral forest reflectance for the exercise instead of running an RTM.**
  The Reviewer is right that we were not very clear about the iterative nature of the model coupling.
  The introductory subsection "2.2 Radiative transfer simulations" was modified, now including a rephrased sentence, which reads as follows:
  "Furthermore, radiation interactions may occur between the surface and the cloud, which can be accounted for by ***iterative*** *coupling of the RT models of the atmosphere and vegetation (Wolf et al., 2025a). In the present paper we use the same model coupling setup*

introduced and described by Wolf et al. (2025a)".

To clarify the confusion about the initial guess of surface albdo:
When the atmosphere radiative transfer (RT) model libRadtran is run for the first time, it is initialized with a first guess for surface albedo, which is taken from the IGBP database. After that, SCOPE2.0 is run with the provided downward irradiance from libRadtran. In the second iteration, the initial guess is replaced by the surface albedo that is based on the upward irradiance provided by SCOPE2.0 and the downward irradiance provided by libRadtran. Two iterations were found to be sufficient for the simulated cases.
To emphasize that the IGBP is only used in the initial run and is later replaced by the albedo determined from the coupled atmosphere-vegetation model, the following sentence in section "2.2.1 Atmospheric radiative transfer model libRadtran", was modified:
"The iteration process was first started by running libRadtran, with an initial guess for the surface albedo. The "mixed-forest" albedo was taken from the IGBP database (Loveland and Belward, 1997). After one iteration cycle, the surface albedo determined during the iterative model coupling process was used (Wolf et al., 2025a)."
We hope that this answers the Reviewer's question. However, we do refrain from providing a more detailed description of the model coupling and implementation in the submitted manuscript because the coupling is described in depth in the companion paper by Wolf et al 2025.

Figure 2b. Please, add a legend.
Figure 2a and b share the same legend. To clarify this, the following sentence has been added to the figure caption.
"Panels (a) and (b) share the same legend."

L187 – "*Wolf et al. (2024) have shown the influence of clouds on direct and diffuse F↓(λ), the associated effects on F↑(λ),*" please, write exactly what the influence was. I guess more clouds – more diffuse radiation.
Yes, this is correct, Wolf et al. (2024) showed, that clouds increase the diffuse radiation. An increase in cloud optical thickness τ leads to a decrease in direct irradiance $F^{\downarrow}_{dir}(\lambda)$. However, the response of the diffuse irradiance $F^{\downarrow}_{dif}(\lambda)$ depends on τ. For values of τ below 4 to 6, the diffuse irradiance first increases, and then decreases as τ increases further. The total amount of $F^{\downarrow}(\lambda)$, direct plus diffuse $F^{\downarrow}(\lambda)$, decreases as τ increases, with an increasing fraction of diffuse radiation.
Furthermore, an increase in the diffuse fraction reduces the influence of changes in the solar zenith angle on the upward irradiance. Lastly, the presences of clouds shifts the weighting of the incoming radiation towards shorter wavelengths, as clouds primarily absorb radiation at longer wavelengths.
The paragraph in section 3.1 has been rephrased as follows:
"Wolf et al. (2025a) have shown the influence of clouds on direct and diffuse $F^{\downarrow}(\lambda)$, the effects on $F^{\uparrow}(\lambda)$, and the resulting albedo effects over vegetated areas using coupled atmosphere–vegetation radiative transfer models. An increase in τ leads to a decrease in $F^{\downarrow}dir(\lambda)$, while the response of $F^{\downarrow}dif\ (\lambda)$ depends on τ . For values of τ less than 4 to 6, $F^{\downarrow}dif\ (\lambda)$ first increases and then decreases as τ increases further. The total $F^{\downarrow}(\lambda)$ and $f_{dir}(\lambda)$ both continuously decrease as τ increases. In addition, $F^{\uparrow}(\lambda)$ became less sensitive to changes in θ. Lastly, the presence of clouds modulates the

incoming radiation spectrally by shifting the incoming radiation towards shorter wavelengths, as clouds primarily scatter radiation at shorter wavelength and absorb radiation at longer wavelengths. Wolf et al. (2025a) also showed that radiative interactions between the canopy and the cloud base increase $F^{\downarrow}dif\ (\lambda)$ *and albedo compared to cloud-free conditions. The present paper focuses on the related effects on* $I^{\uparrow}(\lambda)$ *and* $\rho(\lambda)$*."*

Figure 3. What do grey areas show? Sentinel-2 bands?
"The gray marked areas highlight the Sentinel-2 bands B2, B4, B8, B8a, and B11." The very same sentence was added to the figure captions of Fig. 2 and Fig. 3.

Figures 3 and 4 captions. Please, note, you are working with synthetic (modelled) data. Remove the term “measured” reflectance; do not mislead the readers.
To be more clear, we added the word "synthetic" to all instances, where we refereed to "measurements" to make clear that we refer to the simulated measurements. The sentence in caption of Fig 3 was changed to: *"... and constant cloud optical thickness during calibration and the actual synthetic measurements ..."*

Figure 5. Please, check the location of symbols inside the heatmaps Whereas for NDVI (circle) lambda1 and lambda2 are matching the expected NIR and RED, NDWI1240 is definitely far from lambda1=1240 nm. Furthermore, the symbol in Figures 5c and 5d around lambda1=900nm, lambda2=1600nm is unclear (or absent from the legend).
Thank you for pointing this out. The second Reviewer had a similar comment. The figure has been revised, now with the correct position of the markers and the completed legend. The color-style has been adjusted to improve the legibility of the markers.