Response to comments

Note: All line numbers refer to the revised manuscript (with track changes hidden).

Reviewer 1 (RC1)

Review of Wojciechowska et al., 2025.

This paper tests the performance of a simplified calculation of all-sky albedo vs CERES satellite data. The simplified calculation consists of a function or look-up table (LUT) using the MODIS observed 1x1 degree daily cloud fraction (CF), droplet number (N_d) and Liquid Water Path (LWP) values as inputs. It is constructed using a kernel approach that (presumably – there needs to be more detail on this in the paper) uses several other MODIS variables as inputs along with the CF, N_d and LWP. Using a single (time and global) mean LUT leads to large errors that exhibit a spatial pattern and a dependence on Estimated Inversion Strength (EIS) and Solar Zenith Angle (SZA). Attempts were made to improve the LUT. Correcting for the SZA bias using the single global mean LUT had only a small impact. However, moving to using a separate time-averaged LUTs for each 1x1 gridbox led to significant improvements leaving only small errors. This suggests that regional information (in addition to the CF, N_d and LWP values) is needed for an accurate estimate of albedo.

The paper describes a potentially very useful simplified way to calculate albedo quickly and easily based on only 3 cloud variables. I recommend its publication after the changes below are made – mostly clarifications of the methods and some extra description.

General and line-by-line comments

It is interesting that there is no need for separate seasonal/time-varying LUTs – one time-mean LUT for the whole data period for each location seems sufficient to get low errors. It might be worth commenting on this a little more.

Reply: We have introduced two additional modifications of the method related to the temporal aggregation used in the kernel construction: modifications IX and X. In the original method, the kernel is constructed using CF, N_d, and LWP values from the full annual time series. In modification IX, the kernel is instead constructed from monthly-averaged CF, N_d, and LWP, while in modification X it is constructed from daily-averaged values of CF, N_d, and LWP. When evaluating the difference between estimated and observed albedo, the reconstructed albedo is compared against observations corresponding to the same month (modification IX) or the same day (modification X), respectively.

Both temporal aggregations lead to an improvement in the method (Table 1 in the manuscript and Table R1 below). The ratio of correct albedo reconstructions increased from 40.9% for no temporal aggregation (original method without modifications) to 57.7% when the kernel is constructed from the monthly-averaged CF, N_d, and LWP and 60.6% when the kernel is constructed from the daily-averaged CF, N_d, and LWP.

The revised text in the manuscript now reads as follows:

Lines 232–237: "In all of the above modifications, the kernel was constructed using CF, N_d, and LWP values from the full annual time series. The last two modifications were related to the temporal aggregation used in the kernel construction. In modification IX, the kernel is instead constructed from monthly-averaged CF, N_d, and LWP, while in modification X it is constructed from daily-averaged values of CF, N_d, and LWP. When evaluating the difference between estimated and observed albedo, the reconstructed albedo is compared against observations corresponding to the same month (modification IX) or the same day (modification X), respectively."

Lines 267–273: "When applying modifications IX and X, an improvement in the method is observed, with the ratio of correct albedo reconstructions increasing from 40.9% for no temporal aggregation (original method without modifications) to 57.7% when the kernel is constructed from the monthly-averaged CF, N_d, and LWP and to 60.6% when it is constructed from the daily-averaged CF, N_d, and LWP (Tab. 1). However, it should be noted that the daily-averaged version (modification X) may also be subject to bin undersampling, as the number of datapoints available on individual days is considerably smaller than over longer averaging periods. Therefore, the daily results should be interpreted with similar caution as the finest spatial resolution case."

This response and Table R1 are also included in response to a similar comment from the other reviewer.

Table R1. Ratio of underestimated ($\Delta\alpha < -0.02$) and overestimated ($\Delta\alpha > 0.02$) cases of albedo for methodological modifications no. IX and X. Values in brackets indicate the difference with respect to the original method.

Methodological modification	**Ratio of cases (%) with:**			
	$\Delta\alpha < -0.02$	**$\Delta\alpha > 0.02$**	**$\lvert\Delta\alpha\rvert > 0.02$**	**$\lvert\Delta\alpha\rvert \leq 0.02$**
Original method	27.7	31.4	59.1	40.9
IX: monthly-averaged	20.0 (–7.7)	22.3 (–9.1)	42.3 (–16.8)	57.7 (+16.8)
X: daily-averaged	19.2 (–8.5)	20.2 (–11.2)	39.4 (–19.7)	60.6 (+19.7)

Is there an advantage to using the LUTs vs using the kernel method directly? Especially if there is a need to have a separate LUT for each grid-box requiring a fairly large array to be stored? If we knew what is required by the kernel method then this might be clearer to the reader – presumably it requires lots of extra variables (see comments later)?

Reply: The kernel we use is a 3D joint histogram constructed from global observational data, where mean albedo is calculated for discrete bins of CF, LWP, and N_d. Once constructed, this kernel functions as a reference distribution that maps combinations of these three cloud properties to expected albedo values, without requiring additional variables beyond CF, LWP, and N_d. This differs from radiative kernels such as that in Duran et al. (2025), which diagnose the TOA shortwave radiative response rather than albedo. Our approach is purely diagnostic and conceptually closer to the cloud-feedback kernels of Zelinka et al. (2012), as it is derived from observational relationships without requiring model perturbations or radiative transfer calculations.

The advantage of using regionally defined kernels is that the CF–LWP–N_d–albedo relationship varies geographically, so a single global kernel would not adequately represent this spatial variability.

We have clarified the kernel methodology in the manuscript:

Lines 111–118: "The main method of the study is a 3D joint histogram (kernel) constructed from global observational data, where mean albedo is calculated for discrete bins of CF, LWP, and N_d. Once constructed, this kernel functions as a reference distribution that maps combinations of these three cloud properties to expected albedo values, without requiring additional variables beyond CF, LWP, and N_d. This differs from radiative kernels such as that in Duran et al. (2025), which diagnose the TOA shortwave radiative response rather than albedo. Our approach is purely diagnostic and conceptually closer to the cloud-feedback kernels of Zelinka et al. (2012), as it is derived from observational relationships without requiring model perturbations or radiative transfer calculations. The kernel was constructed as follows."

Line 94 – How much does the filtering by ice cloud fraction restrict the altitude of the clouds studied? It would be useful to show this somewhere. E.g., are you just looking at low-altitude clouds after the filtering?

Reply: Filtering by ice cloud fraction indeed restricts the analysis primarily to low-altitude clouds (Figure R1). We have added the following sentence to the manuscript:

Lines 108–109: ", which restricted the analysis primarily to low-altitude clouds (with cloud top pressure usually above ~680 hPa; not shown)."

As the analysis is focused on liquid clouds, this filtering is consistent with the intended cloud regime and does not affect the scope of the study.

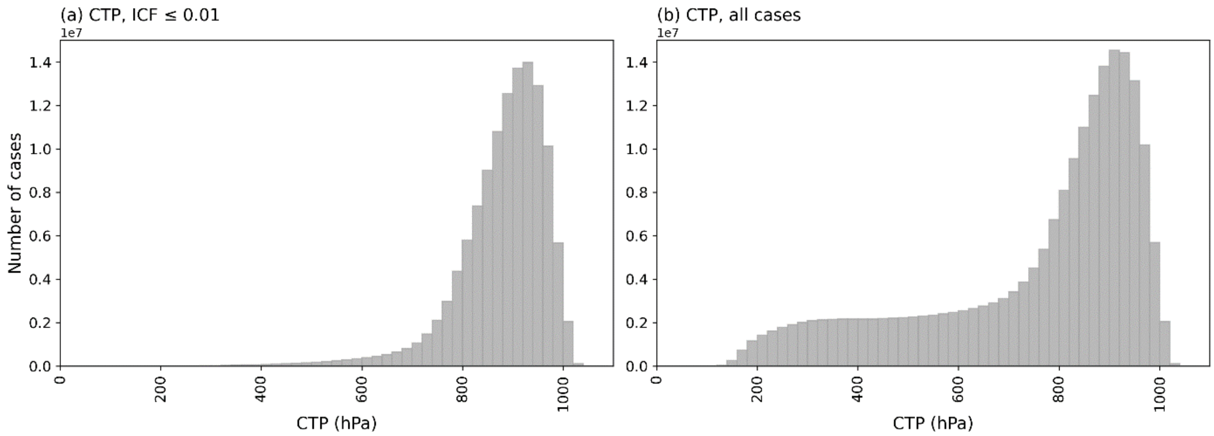

Fig. R1. Distribution of cloud top pressure (CTP) in the 2003–2021 MODIS (Terra and Aqua) dataset, with (a) and without (b) filtering by ice cloud fraction.

Line 96 – it would be useful to reiterate that this is 1x1 degree data. E.g., "The daily gridded 1x1 degree data…".

Reply: The suggested information has been added.

Line 98 – "For each bin, the average albedo (α_{avg}) was then calculated as a multi-year mean value of all pixels across the globe that fall into the same bin of CF, LWP, and N_d."

– It's not clear from the methods section how you calculate the albedo of the pixel using CF, LWP and N_d. Presumably, it is as mentioned on line 62 ("Using a joint histogram/kernel approach from Gryspeerdt et al. (2019),")? But this should be described in the methods section too. Some details on how the method works should be provided too.

Reply: Thank you for this comment. We have clarified the method description and removed the citation from line 72 ("approach from Gryspeerdt et al. (2019)," as this was misleading. We now explicitly describe how the kernel is constructed and how it functions to calculate albedo based solely on CF, LWP, and N_d.

As described in our response to an earlier comment (lines 67–86 of this response document), we have revised the kernel description in the manuscript (lines 111–118) to clarify that the kernel is a 3D joint histogram constructed from global observational data, where mean albedo is calculated for discrete bins of CF, LWP, and N_d, and that this approach is purely diagnostic and does not require additional variables or radiative transfer calculations.

– Otherwise one might think that you could use the bin-center values to calculate albedos for each bin using the kernel method without having to do it for every datapoint and then averaging? But I think this comes from the lack of explanation about the kernel method. Presumably the kernel method requires more information so that this is not possible? It would be good to talk about that a little.

Reply: This point has been addressed in our previous reply regarding the kernel construction (see above).

– It would also be good to say that the average albedo values for each bin are the ones that could form the "look-up table" that might enable rapid albedo calculations based on just CF, N_d and LWP, which would be a lot easier than doing radiative calculations and (presumably) easier than doing the kernel calculation. And then that this approach needs to be tested against CERES (following onto the next sentence). This would be useful to the reader because it is reiterating the aim of the paper, but at the point in the text where you have explained the approach.

Reply: The functionality mentioned by the reviewer is already implemented in our kernel method. Specifically, the average albedo values for each CF–LWP–N_d bin, as constructed in the kernel, effectively serve as a reference for estimating albedo from these three cloud parameters. This approach enables rapid albedo calculations based solely on CF, LWP, and N_d, which is considerably easier than performing full radiative transfer calculations.

As clarified in the revised manuscript text (lines 111–118), as well as described in our response to an earlier comment regarding the kernel method in lines 67–86 of this response document, the approach is conceptually similar to the cloud-feedback kernels of Zelinka et al. (2012). It is derived from observational relationships and does not require radiative calculations. The validation of this approach against CERES observations forms the core aim of this study.

– The word "pixel" here is a bit confusing too – "1x1 degree daily datapoints" would be clearer.

Reply: Corrected, as suggested.

Line 132: "Underestimates of Δα < –0.02 are particularly frequent around 40°latitude in both hemispheres,"

– It looks to me like the frequencies are high at latitudes greater than 40 deg?

Reply: This has now been corrected.

Line 140: "as suggested by the faint diagonal lines visible in Figure 4b."

– I can't really see any faint diagonal lines? I can see some straight lines that look like artefacts, though.

Reply: We have removed this part of the sentence to avoid confusion. The diagonal lines we referred to (aligned with the satellite orbits) were most likely artifacts related to sun glint.

Line 160: "which in Figure 4a appear predominantly brighter than other cloud scenes with similar CF–LWP–N_d characteristics"

– Could be worded better. Fig. 4a more suggests that they "are observed by CERES to be brighter than calculated from the CF–LWP–N_d values using the kernel approach", or similar.

Reply: Rephrased to "cases of thick stratocumulus, which in Figure 4a are observed by CERES to be brighter than calculated from the CF–LWP–N_d values using the kernel approach".

Line 175: "This explains the significant number of strong underestimates also visible in Figure 3."

– It might also suggest why there are underestimates at high latitudes in Fig. 4a.

Reply: This has been now included.

Line 190: "Secondly, in order to ensure that the number of bins (50) was sufficient to reflect the characteristic U-shaped distribution of cloud fraction (with very small or nearly complete cloud cover occurring most frequently, while intermediate values appear relatively rarely), an alternative estimation was also performed using a much larger number of bins – 1000 (modification no. II)."

– Presumably, this is separate to modification no. I? It would be good to make that clear here.

Reply: The sentence has been revised so that modification no. II is introduced at the beginning of the sentence.

Line 216 – "Figure 7a-b shows the histogram of Δα after applying this correction." – it's not clear which correction you are referring to here. From the text and table I think that this is just the correction using the mean Δα within each SZA_{max} interval (modification IV) and not also modification III?

Reply: We were referring here to modification no. IV, which has now been specified in the text.

Line 232 (and 235) – "These results show that the reconstructed albedo of a scene of clouds based on the mean cloud field properties exhibits systematic biases"

– "based on the mean cloud field properties" is a bit confusing here since you are basing it on the actual CF, LWP and N_d cloud properties – the issue rather seems to be that using a single global mean "look-up table" with mean albedo values for each bin leads to systematic biases?

Reply: The text has been revised.

– Reading on to line 260 makes it clearer what you mean here since you have now explained that there are likely factors other than the cloud properties (CF, N_d and LWP) at play. However, this was not so clear at the start of the section where you should explain the use of the global mean albedo look-up-table (as mentioned in the previous bullet point) and mention that by "mean cloud properties" you mean CF, N_d and LWP only.

Reply: Amended, the beginning of the section has been clarified.

Line 268 – "to build a simplified CF–LWP–N_d–α kernel" – not sure if this is a very descriptive way of describing it. "a simplified method to calculate albedo based only on CF, LWP and N_d values" or similar would be better.

Reply: Rephrased, as suggested.

Line 268 – "spatial differences in albedo-to-cloud-sensitivity.". This is also not clear – do you mean "spatial differences in the sensitivity of albedo to cloud properties"?

Reply: Clarified.

Line 270 – "It was demonstrated that the number of biases in reconstructed albedo can be as high as ~60% of cases, when aiming for the accuracy in estimates (absolute difference between expected for the given CF–LWP–N_d conditions and measured by CERES albedo) at 0.02; which corresponds to about 10% of relative difference (Fig. 3)."

– This would be better as "It was demonstrated that the percentage of datapoints in which the reconstructed albedo biases (relative to the measured CERES albedo) were >+/-0.02 (a relative bias of around +/-10%) can be as high as ~60% (Fig. 3)."

Reply: Rephrased, as suggested.

Line 280 "can be achieved when the average albedo in the given CF–LWP–N_d conditions is calculated at a 1° grid resolution."

– Would be better as "can be achieved when the average albedo for each CF, LWP and N_d bin is calculated at a 1° grid resolution."

Reply: Rephrased, as suggested.

Line 284: "on a pixel level" – again, better as "at a 1 degree resolution"

Reply: Amended, as suggested.

Line 286 – "the mean cloud field properties" – again, it would be good to say that you mean CF, N_d and LWP here.

Reply: Amended.

<u>Typos</u>

Line 55; "bins the" -> "bins in the"

Line 90:" explaining" -> "explain"

Line 95: "Resulting subset of cases considered in this study is pictured at Figure 1." -> "The resulting subset of cases considered in this study is pictured in Figure 1."

Line 189: "may have an larger influence" -> "may have a larger influence"

Line 272: "showed" -> "shown".

Line 279: "in attempt" -> "in an attempt"

Line 282: "with modest" -> "with a modest"

Line 283: "showed" -> "shown"

Line 283: "in CF–LWP–N_d–α" -> "in the CF–LWP–N_d–α"

Reply: All of the above typos have been corrected.

References

Duran, B. M., Wall, C. J., Lutsko, N. J., Michibata, T., Ma, P.-L., Qin, Y., Duffy, M. L., Medeiros, B., and Debolskiy, M.: A new method for diagnosing effective radiative forcing from aerosol–cloud interactions in climate models, Atmos. Chem. Phys., 25, 2123–2146, https://doi.org/10.5194/acp-25-2123-2025, 2025.

Zelinka, M. D., Klein, S. A., and Hartmann, D. L.: Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms. Part II: Attribution to Changes in Cloud Amount, Altitude, and Optical Depth, J. Clim., 25, 3736–3754, https://doi.org/https://doi.org/10.1175/JCLI-D-11-00249.1, 2012.