Response to comments

5 ## Reviewer 2 (RC3)

Wojciechowska and Gryspeerdt present a simplified framework for estimating marine liquid cloud albedo using cloud fraction (CF), liquid water path (LWP), and cloud droplet number concentration (N_d). Their approach combines climatological, collocated MODIS cloud properties with CERES albedo
10 to construct a reduced cloud albedo kernel. The authors show that this formulation yields robust albedo estimates, with more than 80 percent of samples differing from CERES by less than 0.05. The results also exhibit a clear spatial structure in regions where albedo is systematically underestimated or overestimated.

15 The manuscript is clearly written, and I find no major issues with the methodology or the interpretation of results. My comments concern a few missing details and clarifications. I also suggest a straightforward way to incorporate cloud morphology into the algorithm, which may further enhance the albedo estimates. I recommend acceptance of the manuscript after the following minor comments are addressed:
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Line 57: One of the key factors that controls the relationship between albedo and CF and/or LWP and/or N_d/CER is the cloud morphology or sub-grid cloud heterogeneity (Goren et al., 2023; McCoy et al., 2023; Choudhury and Goren, 2024).

It is still unclear to me what the main motivation is for assessing how accurately cloud albedo can be
25 estimated from cloud microphysical and macrophysical properties. Is the aim to evaluate these relationships because they are used to quantify changes in cloud albedo driven by changes in cloud properties, as in Zhang et al. (2021) or Wall et al. (2022)? If so, then this study seems to assess whether kernel-based decompositions of cloud albedo are justified. Could the authors clarify this point in the introduction?

30 Reply: We have clarified the motivation of the study in the introduction and added the suggested references. We now state specifically that the purpose of this work is to assess whether kernel-based decompositions of cloud albedo are justified, and how well mean cloud properties (CF, LWP and N_d) can be used to reconstruct the albedo of cloud scenes across the globe. This has been framed in the context of the cloud morphology and sub-grid cloud heterogeneity.

35 The revised text in the introduction (54–75) now reads:

"However, these kernels/relationships assume some linearity between cloud properties and albedo. While this can be partially addressed by using a larger number of bins in the radiative kernel (e.g. Gryspeerdt et al., 2019), this approach does not account for the sub-gridbox distribution of cloud properties. The impact of cloud heterogeneity on radiative transfer has been extensively studied, with
40 cloud inhomogeneity shown to introduce biases in grid-averaged albedo calculations (Cahalan et al., 1994; Oreopoulos and Davies, 1998) and significant effects on the Earth's radiation budget through mesoscale cloud variations (Rossow et al., 2002). Climate models have developed parameterizations to account for subgrid-scale cloud variability (Barker and Räisänen, 2005), though uncertainties remain in how well mean properties capture scene albedo. For example, with a non-linear relationship between
45 LWP and cloud albedo, the mean LWP of a field of clouds does not uniquely determine the mean cloud albedo (Zhang and Feingold, 2023), as cloud morphology and sub-grid cloud heterogeneity play key roles in controlling the relationship between albedo and CF, LWP, and/or N_d is (Choudhury and Goren, 2024; Goren et al., 2023; McCoy et al., 2023).

Relationships between cloud properties and albedo are commonly used to quantify changes in cloud
50 albedo associated with variations in cloud macrophysical and microphysical properties, for example in the context of aerosol forcing and cloud feedback studies (Wall et al., 2022; Zhang et al., 2021). It remains unclear to what extent scene albedo is accurately captured by a three-parameter decomposition

(CF, LWP and N_d). While climate model results suggest this is sufficient, they do not represent the details of the sub-gridbox cloud distribution needed to accurately test this assumption.

This study aims to assess whether kernel-based decompositions of cloud albedo are justified and how well mean cloud properties (CF, LWP and N_d) can be used to reconstruct the albedo of liquid cloud scenes across the globe. Using a joint-histogram/kernel approach, this work reconstructs albedo from average cloud properties at 100 km scales, characterising regional variations in the error in the reconstructed albedo compared to observations. Different methods for accounting for these biases were assessed, providing recommendations for future observation-based calculations of aerosol forcing and cloud feedbacks."

Line 73: Which cloud fraction is used? Is it the cloud fraction derived only from pixels with successful cloud property retrievals, as is common in many aerosol–cloud interaction studies, or the total cloud fraction including partially cloudy pixels and those with failed retrievals?

Reply: The cloud fraction used in this study corresponds to the MODIS "Cloud Retrieval Fraction Liquid" and is derived only from pixels with successful cloud optical property retrievals. This information has now been added to the text (lines 83–84).

Line 79: Were CERES Aqua and Terra products considered separately and paired with their respective MODIS-cloud retrievals, or were the datasets averaged across the two platforms?

Reply: The text has been revised to clarify that CERES and MODIS retrievals were paired by satellite platform and not averaged across platforms (see lines 95–96). The revised text now reads: "CERES and MODIS retrievals were paired by satellite platform (Aqua–Aqua and Terra–Terra) and analysed jointly."

Section 3.1: I recommend including an additional global map showing the geographical distribution of albedo bias (potentially as an extension of Figure 4). This figure should be supported by a short description summarizing the mean bias and its spatial pattern, noting regions where the discrepancies are especially pronounced.

Reply: The map has been added to Figure 4, together with a short description summarizing the mean bias and its spatial pattern:

Lines 162–165: "Figure 4c presents the geographical distribution of absolute albedo bias (cases with either underestimated or overestimated albedo by more than 0.02). Generally, albedo biases are mostly evenly distributed spatially, regardless of the number of datapoints at a given location (Figure 1)."

Section 3.1: Does the bias decrease when the data are resampled to the monthly scale, which is the temporal resolution typically used in studies that construct such kernels?

Reply: Thank you for this suggestion. 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 – 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:			
	$\Delta\alpha < -0.02$	$\Delta\alpha > 0.02$	$|\Delta\alpha| > 0.02$	$|\Delta\alpha| \leq 0.02$
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)

Figure 6b: How does the solar zenith angle extend beyond 65 degrees when this threshold was used in the G18 sampling strategy for estimating N_d?

Reply: We would like to thank the reviewer for this comment. We have now excluded from the analysis all cases with solar zenith angles exceeding 65º. All figures and Table 1 have been updated accordingly, using only data with $SZA_{max} < 65º$. This additional filtering, however, has not impacted the study results. The cases with SZA_{max} exceeding 65º likely resulted from gridboxes in which observations from multiple orbits (and hence a range of solar zenith angles) were averaged.

Line 213: "… more restricted to location …" Perhaps "cloud morphology" is intended here?

Reply: The text has been revised as suggested.

Line 224: What explains the seasonal variability? Did you construct the kernel at each grid point as well as for all days of the year separately? If not, this might help reduce the bias further.

Reply: We have now introduced two modifications related to the temporal aggregation, as described in the lines 88–118 of this response document, and have added the relevant description to the manuscript (see lines 232–237 and 267–273).

I also suggest adding thin cloud fraction (F_thin, a proxy for cloud morphology) to the kernel. F_thin can be computed from the MODIS Level-3 "Cloud_Optical_Thickness_Liquid_Histogram_Counts" dataset by using COT < 3 or < 5. Including F_thin alongside CF, LWP and N_d/CER may improve the albedo estimation (McCoy et al., 2023).

Reply: We thank the reviewer for this suggestion. Following the recommendation, we have now implemented a four-dimensional kernel that incorporates the fraction of optically thin clouds (F_{thin}) computed directly from the MODIS Level-3 "Cloud_Optical_Thickness_Liquid_Histogram_Counts" dataset. We computed F_{thin} using two COT thresholds: COT < 3 and COT < 5, representing clouds with optical thickness below these values. The results of this analysis are presented in Table R3.

Our findings show a small but consistent improvement in albedo reconstruction accuracy when including F_{thin} alongside CF, LWP, and N_d (Tab. R3). When using F_{thin} with COT < 3, the fraction of underestimated cases slightly decreased from 27.7% to 27.5%; the fraction of overestimated cases – from 31.4% to 30.7%. Using COT < 5 yields marginally better results: 27.1% of underestimated and 30.4% of overestimated cases.

While this improvement is modest, it demonstrates that cloud morphology information (as captured by the presence of optically thin clouds) does provide additional value for albedo estimation. However, we note that adding F_{thin} as a fourth dimension does increase bin sparsity in the kernel, which already is to some extent a limitation of the implemented method. Given this trade-off, we have retained the three-parameter approach in the main manuscript as our primary method, but we acknowledge that incorporating F_{thin} is a promising avenue for future refinements.

Table R3. Ratio of underestimated ($\Delta\alpha < -0.02$) and overestimated ($\Delta\alpha > 0.02$) cases of albedo for different methodological modifications: original three-parameter kernel, and four-dimensional kernels incorporating F_{thin} computed for COT < 3 and COT < 5.

Methodological modification	Ratio of cases (%) with:			
	$\Delta\alpha < -0.02$	$\Delta\alpha > 0.02$	$|\Delta\alpha| > 0.02$	$|\Delta\alpha| \le 0.02$
Original method	27.7	31.4	59.1	40.9
F_{thin} for COT < 3	27.5 (–0.2)	30.7 (–0.7)	58.2 (–0.9)	41.8 (+0.9)
F_{thin} for COT < 3	27.1 (–0.6)	30.4 (–1.0)	57.5 (–1.6)	42.5 (+1.6)

Could the authors speculate on why albedo is underestimated in stratocumulus regions and overestimated in the tropics?

Reply: We have added a brief discussion addressing this point in the manuscript:

Lines 283–287: "These contrasting biases may reflect differences in cloud morphology and sub-grid heterogeneity: in stratocumulus regions, nonlinear radiative effects and unresolved horizontal variability can lead to an underestimation of scene albedo when using mean cloud properties, whereas in the tropics, highly heterogeneous convective cloud fields may cause mean properties to overrepresent optically thick elements, resulting in albedo overestimates."

Language edits:

Line 55: "more bins in …"?
Reply: Amended.

Line 55: "sub-pixel" or "sub-gridbox"
Reply: Changed to "sub-gridbox".

Line 101: By "pixel," do you mean the 100 km gridbox?
Reply: Rephrased to "1x1 degree gridbox".

Line 123: Do you mean "left-skewed"?
Reply: Amended.

Line 270: Please rephrase. The current wording is unclear.
Reply: The sentence has been rephrased.

References:

Choudhury, G., & Goren, T. (2024). Thin clouds control the cloud radiative effect along the Sc-Cu transition. Journal of Geophysical Research: Atmospheres, 129, e2023JD040406. https://doi.org/10.1029/2023JD040406

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McCoy, I. L., McCoy, D. T., Wood, R., Zuidema, P., & Bender, F. A.-M. (2023). The role of mesoscale cloud morphology in the shortwave cloud feedback. Geophysical Research Letters, 50, e2022GL101042. https://doi.org/10.1029/2022GL101042

195 Wall, C. J., Norris, J. R., Possner, A., McCoy, D. T., McCoy, I. L., and Lutsko, N. J.: Assessing effective radiative forcing from aerosol-cloud interactions over the global ocean, Proc. Natl. Acad. Sci. U. S. A., 119, 1–9, 2022.

Zhang, Y., Jin, Z., and Sikand, M.: The Top-of-Atmosphere, Surface and Atmospheric Cloud Radiative Kernels Based on ISCCP-H Datasets: Method and Evaluation, J. Geophys. Res. Atmos., 126, e2021JD035053, https://doi.org/https://doi.org/10.1029/2021JD035053, 2021

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