

We thank the reviewers for their careful evaluation of our manuscript and for their constructive comments. We have carefully considered all comments and provide our responses below in red.

Reviewer #1:

This paper presents a framework for classification of properties of marine stratocumulus clouds, by simply placing the clouds in space defined by three corners of optical thickness classes. The method is demonstrated by application to one year of satellite data, and large-eddy simulation, and thereby gives insight into cloud processes and reveals how cloud susceptibility to aerosol perturbations depends on cloud morphology. Several quite remarkable conclusions can be drawn regarding magnitudes and even sign of radiative effects of aerosol-cloud interaction.

The paper is well written, the methodology overall clearly and reliably described and the results very relevant. It presents a useful perspective for estimating susceptibility, for classifying and determining representativity of means, and for refining classifications based on often used discrete classifications from ambient quantities.

I would recommend for publication in ACP after only minor revisions, according to the following comments.

General comments

1. Scope and focus

The title can be read as having a focus on marine cloud brightening as a climate intervention method, which is actually mentioned only at the very end of the paper as one application of relevance to the results. One way to go would be to discuss the results in relation to MCB literature more but I would rather recommend emphasizing some of the general findings more. Perhaps even remove or replace the “suggests weak cloud brightening potential” in the title to make it more general, to reflect the broad application of the method and results, not limiting it to MCB. Also, arguably, MCB would be a candidate for the strong local aerosol perturbations that are explicitly said not to be considered (line 95-96), and if the authors want to turn the focus more to MCB that should be discussed too.

Thank you for this comment. The original title indeed overemphasized marine cloud brightening relative to its role in the manuscript. We have therefore revised the title to better reflect the generality of the results:

“A New Representation of Marine Stratocumulus Cloud Morphology Reveals Morphology-Dependent Variability in Cloud Susceptibilities”.

There are many noteworthy results and conclusions, such as how the scene mean is not representative of the morphology (line 157-158), that S_{LWP} is negative everywhere (line 212), that S_{LWP} dominates Stwomey (line 253), that S_{net} near zero is the most common response (line 253). I think these results should be emphasized, and also could be discussed more in relation to previous literature. For instance for the sign of S_{LWP} , what might be the explanation for many earlier estimates of positive S_{LWP} in precipitating cases, and V-shaped sensitivity? There are some hints e.g. in line 225 and 288-289 to sampling biases, but it would be interesting to dig deeper, if possible.

The conclusion section has been revised accordingly to better summarize the main findings”

“We have introduced a new method for defining stratocumulus cloud morphologies using a ternary diagram. The ternary is composed of three τ_c classes and provides a continuous morphology space, in contrast to commonly used discrete cloud morphology regime classifications (Wood and Hartmann, 2006; Muhlbauer et al., 2014; Erfani and Hosseinpour, 2025; Wu et al., 2025; Yuan et al., 2020; Geiss et al., 2024). Using one year of satellite observations, we quantify the occurrence of scenes across the morphology space, revealing a preference for a confined range of morphologies. Complemented by LES, we show that cloud morphology evolution follows a preferred path across the ternary morphology space, explaining why most observations fall within a confined range of morphologies. The ternary framework also reveals insights into cloud processes associated with morphology changes, including cloud thickening, the diurnal cycle, and cloud breakup driven by precipitation. This suggests that the ternary encodes information about cloud processes that can be inferred from instantaneous satellite snapshots when projected into this space. The analysis also shows that scenes are often composed of mixtures of thick and thin clouds, making scene-mean values of spatially varying cloud properties, such as LWP and τ_c , not representative of the underlying cloud field. Using these means can therefore introduce biases in quantities that rely on these mean values (Goren et al., 2023).

The ternary framework allows us to estimate the susceptibilities of LWP, CF, and Ac to Nd, conditioned on cloud morphology. SLWP is found to be negative across all morphologies, including in precipitating ones, in contrast to studies that have reported positive SLWP and attributed it to precipitation suppression (Dipu et al., 2022; Glassmeier et al., 2021; Gryspeerd et al., 2019; Mülmenstädt et al., 2024; Possner et al., 2020). Our results support Goren et al. (2025), who showed that the positive SLWP inferred from inverted-V joint histograms of LWP and Nd arises as an artifact of aggregated sampling across different cloud morphologies. The strength of the negative SLWP is found to depend on morphology, even for non-precipitating clouds, consistent with Zhou and Feingold (2023). Earlier studies, however, often reported a bulk approximation for SLWP (Gryspeerd et al., 2019; Glassmeier et al., 2021; Possner et al., 2020), thereby not capturing the morphology-dependent variability. Detecting a morphology-dependent SLWP was possible by treating morphology as an observed variable, which also reduces confounding aerosol–meteorology co-variability that has been suggested to produce spurious negative values of SLWP (Goren et al., 2025; Mülmenstädt et al., 2024).

SCF is found to be positive in precipitating scenes, presumably because increased Nd delays precipitation and, consequently, cloud breakup (Goren et al., 2019; Wang and Feingold, 2009; Yamaguchi et al., 2017). On the other hand, in non-precipitating scenes with low LWP, SCF is found to be negative, presumably because the strong negative SLWP in these scenes reduces CF through entrainment-related evaporation processes. It should be noted that scenes with negative SCF occur less frequently than those with positive SCF, indicating that positive SCF dominates the global signal.

The net in-cloud albedo susceptibility is the most relevant for the radiation budget because it includes the combined contributions of cloud albedo and LWP susceptibilities. Snet is found to vary between -0.3 and 0.3 depending on cloud morphology, largely modulated by the strong control of SLWP. This implies that, in some morphological regimes, Twomey-induced brightening is offset by LWP adjustments, consistent with findings from previous studies (Prabhakaran et al., 2023; Toll et al., 2019; Diamond et al., 2020). Here, we further show that this offset can fully cancel, and even exceed, the Twomey-induced brightening, leading to a net negative effect. When averaged over all

morphologies, Snet is overall small (0.015 ± 0.007), as it is dominated by the most frequently occurring morphologies, which have lower values. This implies that a global 10% increase in Nd would result in an increase in cloud albedo of approximately $0.15 \pm 0.07\%$, not accounting for changes in CF. The analysis suggests that marine cloud brightening would need to target morphologies with positive Snet and rely on persistently positive SCF to be effective. The results also have implications for estimates of aerosol–cloud radiative forcing, which should account for morphology-weighted contributions.”

2. Data and methods

a) The method is demonstrated with one year of satellite data (line 52), and this is what the results are based on. Why is not more data used? Do you think it matters? Is there any sensitivity in the results to the year chosen? Does the screening and selection (lines 54-59) affect the results?

It is possible that the global means (e.g., of Snet) are affected, as they reflect the morphological occurrence in a single year. The same data were used in Goren et al. (2025) to study LWP susceptibility, which reproduced previously reported LWP–Nd occurrences of scens across the LWP–Nd space obtained in other studies using several years of data (e.g., Gryspeerdt et al., 2019). This suggests that the single year used here represents also the interannual mean. The complementary LES analysis is also consistent with the high-occurrence regions in the observations, providing an additional line of evidence that the ternary space occupied by the cloud observations is representative. A follow-up study will examine regional variability in cloud morphologies and statistics, including seasonality and interannual variability, for example, the influence of El Nino on the cloud morphology. We added the following text to the revised section 3.4.3: “It should be noted that the global mean Snet reflects the morphological occurrence of the year analyzed here. A future study will explore whether there are interannual differences in morphological occurrence, for example during El Nino years, as well as across seasons and regions.”

We also note that producing the dataset requires processing MODIS Level 2 daily data to derive the variables used in the analysis (such as cloud optical partitioning on 2×2 degree grids). This processing is computationally demanding, and therefore the analysis was limited to one year of data. The data screening and selection criteria are designed to minimize retrieval biases. Similar screening approaches are widely used in the literature, allowing the comparability of our results.

b) Is it not possible to reach a certain state (or morphology) in different ways? The LES simulations present one plausible path, but discussing this equifinality could be interesting. Could it matter to the susceptibility-properties ascribed to the categories?

This is an interesting question that we have also been considering. Addressing it would require analyzing an ensemble of cloud trajectories to determine whether different pathways can lead to similar morphologies and whether this equifinality affects the associated susceptibility–property relationships. Such an analysis is beyond the scope of the present study and would require a more extensive investigation, but it represents an important direction for future work. We added the following text to Section 3.2.2: “It remains an open question for future study whether a given morphological state can be reached through different paths”.

c) S_{net} is defined as the in-cloud susceptibility (eg line 25), which seems to mean that cloud fraction adjustment is not taken into account, only LWP adjustment. This is also indicated by equation 1, that doesn't have a term $d\ln A_c/d\ln CF * d\ln CF/d\ln N_d$. But equation 8 in Bellouin et al (2019), that the nomenclature follows, does on the other hand include a term for cloud fraction adjustment to N_d . It is not clear how the satellite derived S can distinguish the in-cloud and total contributions to albedo-changes and exclude S_{CF} , and hence why the residual between theoretical S_{Ac} and satellite observed S_{net} is attributable to S_{LWP} (as stated in line 107, and then used to estimate S_{LWP}). Might this approach to estimating S_{LWP} as a residual affect the results?

The difference between our formulation and that of Bellouin et al. (2019) is that we consider in-cloud albedo, whereas Bellouin et al. consider scene-mean albedo, which includes cloud fraction effects. Therefore, the cloud fraction adjustment term does not appear in our formulation. The original text could be confusing, as it introduced S_{net} as in-cloud albedo susceptibility while also referencing Bellouin et al. (2019). This has been clarified in the revised manuscript to explicitly distinguish between in-cloud and scene-mean formulations. The following text was added after introducing Equation 2: "Here, S_{net} is defined as the susceptibility of in-cloud albedo to N_d , and therefore does not include adjustments in CF. This differs from formulations based on scene-mean albedo (Bellouin et al., 2019), where cloud fraction changes contribute an additional term."

In this framework, changes in in-cloud albedo, S_{net} , arise from two contributions: the Twomey effect (S_{Ac}) and LWP adjustments (S_{LWP}). The residual between the satellite-derived S_{net} and the theoretical S_{Ac} is therefore interpreted as an LWP adjustment term. Cloud fraction changes can influence the in-cloud LWP, for example by adding more cloudy pixels that change the area weighted mean in-cloud LWP. Separating LWP and CF adjustments is inherently challenging, as it is not clear how LWP changes can be associated to the changes in CF. For instance, in a heterogeneous LWP field where CF is increasing, it is ambiguous whether the increase in CF should be associated with the lower or higher LWP added fractions of the cloud field. This ambiguity can affect both the magnitude and even the sign of the inferred LWP adjustment. This complicates a clean decomposition into LWP and CF contributions. In Goren and Rosenfeld (2014), a simplifying assumption was introduced to address this issue for transitions between closed and open cells. The following text was added at the end of Section 2.2.2: "Explicitly disentangling S_{LWP} from S_{CF} is challenging, as it is not uniquely defined how spatially heterogeneous changes in LWP should be attributed to variations in CF (Hoffmann et al., 2025)."

LWP adjustment studies typically do not explicitly separate the effects of cloud fraction changes. For example, in "inverted V" studies (e.g., Gryspeerdt et al., 2019; Mülmenstädt et al., 2024; Possner et al., 2020; Goren et al., 2025), scenes with different cloud fractions are aggregated, and changes in LWP are primarily interpreted in terms of in-cloud properties. The following text was added to Section 2.2.2: " S_{LWP} as defined here may implicitly include the influence of CF adjustments on the sampled in-cloud LWP, consistent with previous LWP adjustment studies (Gryspeerdt et al., 2019; Possner et al., 2020; Mülmenstädt et al., 2024)."

Specific and technical comments

Line 17: Why not introduce re annotation for cloud droplet size, it appears fist on line 57

The "cloud-top effective radius" differs from "cloud droplet size". Droplet size varies throughout the cloud column from base to top, whereas satellite observations are primarily sensitive to the

cloud top. The retrieved cloud-top effective radius characterizes the radiatively weighted droplet size at the cloud top and is formally defined as the ratio of the third to the second moment of the droplet size distribution. These two quantities are therefore not equivalent.

Line 21, 24: How certain is S_{Ac}, compared to S_{LWP} described as "uncertain" (cf. Bellouin et al 2019)?

S_{Ac} is based on well-understood theory (Twomey, 1974; Platnick and Twomey, 1994) and can be derived analytically under standard assumptions. In contrast, S_{LWP} is not well constrained theoretically and emerges from cloud dynamical and microphysical feedbacks, such as evaporation–entrainment and sedimentation–entrainment processes. It depends on meteorological and environmental conditions, precipitation, and the timescale of the response. Accordingly, studies report a wide range of LWP responses to aerosol perturbations.

The following was added to the revised introduction section: “This leads to an increase in Ac through a well established physical mechanism (Platnick and Twomey, 1994; Twomey, 1974)”, and “Its sign and magnitude remain uncertain due to the complexity of the underlying processes (Glassmeier et al., 2021; Bellouin et al., 2020; Forster et al., 2021; Toll et al., 2019; Goren et al., 2025)“.

Line 42 says S_{LWP} greater in small MCCs, with the explanation that the adjustment is active in cloud cores rather than peripheries. But wouldn't we expect smaller horizontal-extent clouds to have more periphery relative to cell core? The Zhou and Feingold (2023) reference given rather states that small MCC cores have higher Nd, and more evenly distributed LWP. Maybe the explanation could be expanded a bit, to clarify the mechanism.

In Zhou and Feingold (2023), the stronger S_{LWP} reduction in small MCCs is not primarily attributed to a larger fractional contribution from cloud cores relative to peripheries. Instead, they suggest that entrainment-driven evaporation plays a stronger role in smaller MCCs due to enhanced turbulence and stronger boundary-layer coupling.

The text has been revised accordingly: “Zhou and Feingold (2023), for example, showed that S_{LWP} in closed cells with smaller horizontal extent can be up to ten times larger than in cells with larger horizontal extent. They attributed these differences to dynamically stronger entrainment-driven evaporation in the smaller cells”.

Line 68: Please specify the Ac used, if and how it is based on radiative fluxes for clear sky and all sky, or on cloud properties, or other

The following text was added to the revised Section 2.1:

“Ac was calculated following the approach of Schneider and Dickinson (1976):

$$A_c = \frac{A_{\text{all-sky}} - A_{\text{clear-sky}}(1 - CF)}{CF}$$

where A_{all-sky} and A_{clear-sky} were obtained from the Clouds and the Earth's Radiant Energy System (CERES) aboard Aqua (Loeb et al., 2005), and gridded to 2° × 2° to match the gridded MODIS data. CF was obtained from MODIS Aqua (Platnick et al., 2016).”

Line 66: It wouldn't hurt to include Fig A1 int the main manuscript

We appreciate the suggestion. As Fig. A1 is included in the appendix, it is readily accessible within the same PDF, immediately following the main text. We therefore prefer to retain it in the appendix in order to keep the main manuscript focused on the key figures.

Line 78: Fractions of cloudy pixels, should rather be percentage

Thank you for noticing. “fractions” was changed to “percentage”.

Line 125: S_CF notation has not been defined before

Thank you for noticing. Changed accordingly:

“S_CF, defined as the CF susceptibility to Nd, was calculated by regressing the observed $\ln(\text{CF})$ on $\ln(\text{Nd})$ for each ternary bin”

Line 136-137 repeats line 43-45, and again in line 158-159

The text in lines 136–137 has been removed. The similar text in lines 43–45 is part of the background and literature review, while the text in lines 158–159 serves to connect the results of our study with those of the referenced.

Fig 1: Where is this/these scene/s (lat, lon)?

Scene (a) is off the coast of North America. Scene (b) is off the coast of South America. The revised caption was modified to include this.

Line 166: “represent -> represents”

Corrected. Thank you.

Line 179: It is not clear from Fig 2 c/d that nighttime thickening follows the same trajectory as the thickening during the previous night, the two trajectories marked with arrows are rather separated. Please clarify this statement.

The recovery trajectory overlap with the nighttime trajectory, although this was not sufficiently clear in the original figure. We have added additional arrows to Figs. 2c and 2d to indicate the direction of the daytime evolution loop, which makes the trajectories easier to follow.

The following text was added to the caption: “The closed-loop trajectory represents daytime cloud thinning, with the recovery later in the day overlapping the preceding nighttime trajectory”.

We also revised the text for clarity: “Interestingly, the afternoon cloud thickening follows the same morphological trajectory as the cloud thickening during the previous night, suggesting a preferred evolutionary path.”

Line 188: The phrasing is a bit unclear here. I think you mean that the information from a satellite snapshot placed in the ternary diagram can give information about the state of the cloud scene, as different parts of the diagram represent different processes. Directly from the satellite snapshot, without the help of the ternary this arguably *can't* be inferred. Perhaps rephrase to clarify. The same formulation appears in line 282.

We revised the text accordingly:

In Section 3.2.2: “The above demonstrates that the distribution of scenes within the ternary space encodes information about underlying cloud processes, such as cloud thickening, thinning, and collision–coalescence. Satellite observations projected into the ternary space can therefore provide

information about the state of the cloud field, as different regions of the diagram correspond to distinct cloud processes”.

And in the Conclusions Section: “This suggests that the ternary encodes information about cloud processes that can be inferred from instantaneous satellite snapshots when projected into this space”.

Line 209: Would anything else be possible, than clouds forming in a thin state, and dissipating via a thin state?

Clouds initially form as thin and dissipate to thin layers, and are therefore thin at both stages. Thin clouds may also persist for extended periods or temporarily thin during their evolution. To avoid being overly definitive, we have revised the text from “These scenes are associated with” to “These scenes can be associated with”.

Figure 2: Caption could say what contours (in b) represent. That information is currently only in later figures. Also, Figure A2 and Fig A3 refer to figure 2a (for what the contours represent, presumably), whereas Fig 3 and Fig 4 refer to Figure 1a. Please correct and/or clarify in the figure captions.

Thank you for noticing. Figure 2 caption was modified accordingly: “(b) Median CF for each morphology bin, with contours indicating scene occurrence derived from (a).”

In the remaining Figures, the captions were modified to: “Contours represent scene occurrence, as in Figure 2b.”

Fig A3: What is REF here? This could be made consistent with text (line 240) referring to Ac.

REF should be cloud Ac. The Figure was corrected accordingly.

Fig 4b: Diagram says Stwomey but text says S_Ac, this would be good to make consistent

Corrected. Thank you for spotting these inconsistency.

Line 270: “fig 2c and 2c” -> “fig 2c and 2d”

Corrected.

Line 271: “are found” -> “is found”

It should be “are” because S_CF is used here in a plural sense, referring to multiple values across scenes.

Line 296: Is it possible to give an error estimate on that number?

Following this comment, we calculated the standard error of the mean susceptibility which was found to be 0.007, yielding a mean of 0.015 ± 0.007 . The text in the conclusion section was revised accordingly:

“When averaged over all morphologies, S_net is overall small (0.015 ± 0.007), as it is dominated by the most frequently occurring morphologies, which have lower values. This implies that a global 10% increase in Nd would result in an increase in cloud albedo of approximately $0.15 \pm 0.07\%$, not accounting for changes in CF”.

In Section 3.4.3 we also added: “The uncertainty of the weighted mean slope was estimated from the variability across bin-specific slopes, accounting for the effective sample size.”

Reviewer #2:

This paper seeks to better understand cloud adjustments to aerosol perturbations, with a focus on the response of the liquid water path. Noting that the likely adjustment in different cloud types or morphologies will vary, they propose a novel method for constraining for this factor, using the distribution of cloud optical depth. They find that in many cases, the intrinsic cloud responses (Twomey and LWP adjustment) offset each other, leaving the overall cloud field response to be driven by cloud fraction changes, which they find can be negative under some circumstances.

This is a novel and clever decomposition that aims to solve a long-standing problem. It is clearly in scope for Atmospheric Chemistry and Physics. I have a few points, primarily about the framing of some of the results, but following these I think it would be suitable for publication.

Main points

The method for calculating S_{LWP} is supported by theoretical considerations, but I am a little unclear as to how well this decomposition works in practice. Almost all of the terms are determined by the average bin optical depth, other than S_{net} (which is determined from observations). To what extent is S_{net} also being determined at a constant optical depth? Given the authors define their cloud type based on the properties that are expected to vary under an aerosol perturbation, is this restricting the magnitude of the response? I appreciate the authors have already made considerable effort to demonstrate this, but perhaps it is possible to demonstrate (potentially using some synthetic data), that this method is able to extract the required susceptibilities?

Thank you for this important comment. As noted in Section 2.2.2, the method focuses on within-morphology variability. Changes in S_{net} may be larger when cloud morphology transitions across regimes, for example when aerosols delay the transition from closed to open cells (Goren et al., 2019). Such transitions are not considered here, as they involve temporal aerosol effects on the evolving cloud morphology.

It is important to emphasize that although the ternary binning constrains the τ_c composition within each morphology bin, variability within each bin is retained. Figures 3b and 3c show the scene LWP and core LWP, which can differ substantially across parts of the ternary space, reflecting this variability also within single morphology bins. Each bin therefore retains natural variability in N_d , LWP, A_c , and CF associate with the given morphology, over which S_{net} is estimated. Consequently, S_{net} is not evaluated at constant optical depth. Sensitivity tests in which the bin size was increased, allowing greater variability in cloud properties within each bin, did not affect the results (Section 2.2.2). The purpose of the binning is thus to reduce mixing between fundamentally different cloud morphologies, which is a key aspect of the approach.

We have revised the first paragraph of Section 2.2.2 to emphasize this point:

“The ternary framework allows us to estimate cloud susceptibilities to N_d , conditioned on τ_c morphology. It should also be emphasized that the ternary binning does not fix τ or other cloud properties within each morphology bin, as each bin retains natural variability in N_d , LWP, τ_c , A_c , and CF. This is evident, for example, in the difference between the LWP of cloud cores and that of the entire scene (Figure 3c and 3d). Sensitivity tests in which the bin size was increased to allow greater variability in cloud properties within each bin did not affect the results. Transitions between morphology bins could have a stronger albedo response, such as in the case of transitions between

closed and open cells (Goren and Rosenfeld, 2014; Watson-Parris et al., 2021), however these are temporally dependent (Goren et al., 2019) and not considered here”.

To what extent is the albedo-Nd relationship due to meteorological covariations? This has been some uncertainty about it in the past. Would we expect it to be free of the same issues that drive the negative Nd-LWP relationship (Arola et al., 2022)? Would the use of a microwave LWP product to determine the Nd-LWP relationship address some of the issues raised in this work (as it doesn't depend directly on the LWP)?

This is a good point. As shown by Goren et al. (2025), the negative sensitivity reported in inverted-V studies can arise from covariability between aerosols and meteorology. They further demonstrated that different parts of the inverted-V curve, from which the negative slope of S_{LWP} is derived, are associated with distinct cloud morphologies. This suggests that the slope may reflect also co-variability between cloud morphology, LWP, and Nd, rather than a purely causal relationship. In the present study, by conditioning S_{LWP} on cloud morphology, we reduce this source of covariability. This allows us to more directly assess how variations in Nd are associated with changes in LWP within a given morphology. Therefore, while meteorological covariability may influence bulk relationships, our framework mitigates this effect by conditioning on cloud morphology.

The following text was added to the Conclusion Section: “Detecting a morphology-dependent S_{LWP} was possible by treating morphology as an observed variable, which also reduces confounding aerosol–meteorology co-variability that has been suggested to produce spurious negative values of S_{LWP} (Goren et al., 2025; Mülmenstädt et al., 2024).”

We also note that Gryspeerdt et al. (2019) compared microwave-derived LWP with MODIS LWP to assess the role of correlated retrieval errors between LWP and Nd, and found that the relationships were largely unchanged. This suggests that such retrieval artifacts are unlikely to fully explain the observed relationships.

The negative cloud fraction response to aerosol is interesting, being different from almost all previous studies. I would note that the Meskhidze et al (2009) result is likely due to a regression to the mean effect. Analyses that controls for the initial cloud state shows a (very weak) increase in cloud amount during the day (Gryspeerdt et al., 2014a; Pugsley et al, 2025). While a don't think the results presented here are affected by the same bias, it does make them almost unique (and so perhaps worth some additional scrutiny).

Thank you for this comment. The difference from previous studies likely reflects the S_{LWP} being conditioned on cloud morphology. This allows to isolate relationships within morphology types and reveals behavior that may be obscured in analyses that aggregate scenes across morphologies. We also note that scenes with negative S_{CF} are relatively rare, whereas those with positive S_{CF} are much more common, indicating that positive cloud fraction susceptibility dominates the global signal. This suggests that, although negative responses occur in specific regimes, they do not dominate the overall behavior.

We have added the following text to the abstract: “We also find that cloud fraction susceptibility can be negative in low-LWP morphologies, presumably due to strong negative LWP adjustments”, and the following to the conclusion section: “It should be noted that scenes with negative S_{CF} occur

less frequently than those with positive S_{CF} , indicating that positive S_{CF} dominates the global signal”.

Minor comments

L14 - Is this not a bit more broadly relevant? If I understand it correctly, it would suggest that almost all of the net aerosol forcing would have to come from the cloud fraction response too?

The sentence in abstract was changed to: “We also find that cloud fraction susceptibility can be negative in low-LWP morphologies, presumably due to strong negative LWP adjustments”. This is more specific.

The conclusions includes the following sentence after summarizing the overall low S_{net} : “Therefore, marine cloud brightening would need to target morphologies with positive S_{net} and rely on persistently positive S_{CF} to be effective.”.

L28 - There is some earlier work in this area from Landsat studies, e.g. Davis et al, JAS, 1997 (10.1175/1520-0469(1997)054<0241:TLBSIS>2.0.CO;2).

The reference was added.

L37 - To what extent is this different? Presumably cloud morphology controlled by meteorological factors? To me, a strong aspect here is that morphology is an observed parameter, unlike the large scale meteorology (which will have biases and uncertainties). I would note that there have been some studies that investigated susceptibilities as a function of observed cloud properties (which is related to the method here; e.g. Gryspeerdt et al., GRL, 2012; Langton et al., GRL, 2021)

Cloud morphology is indeed influenced by precipitation, meteorological conditions, and cloud history. Previous studies have mostly classified cloud scenes using discrete thresholds, for example in LTS or precipitation state, which are typically associated with different CF regimes. These regimes are often referred to as CF morphologies (e.g., closed and open cells). Nevertheless, substantial variability in LWP and cloud optical depth can still exist within these discrete regimes. We have modified the entire paragraph accordingly:

“Most studies examine the dependence of cloud susceptibilities on cloud morphology by separating data into cloud scenes associated with different meteorological conditions or precipitation states. These factors co-vary with cloud morphology, which is typically defined by CF regime (Gryspeerdt and Stier, 2012; Gryspeerdt et al., 2019; Chen et al., 2025; Hoffmann et al., 2024, 2025; Toll et al., 2019; Glassmeier et al., 2021; Rosenfeld et al., 2019; Zhang et al., 2022). Nevertheless, even within the same type of CF regime, LWP and τ_c may still exhibit spatial variability, for example due to variations in veil cloud extent in open cells or in cell size distribution within closed cells (Goren et al., 2023; Wood et al., 2018; Zhou and Feingold, 2023). These variations can affect the inferred susceptibilities (Goren et al., 2023; Zhou and Feingold, 2023). Zhou and Feingold (2023), for example, showed that S_{LWP} in closed cells with smaller horizontal extent can be up to ten times larger than in cells with larger horizontal extent. They attributed these differences to dynamically stronger entrainment-driven evaporation in the smaller cells. Also S_{Ac} has been shown to depend on morphology, as demonstrated by Goren et al. (2023), who found that S_{Ac} can be positively biased by up to 50% if the spatial distribution of τ_c within a given 1×1 degree scene is ignored.”

L55 - SPI filters have been shown to help improve retrieval biases (Grosvenor et al, Rev. Geophys., 2018). Are these not used due to the morphology decomposition? How does this affect the distribution of biases in the results?

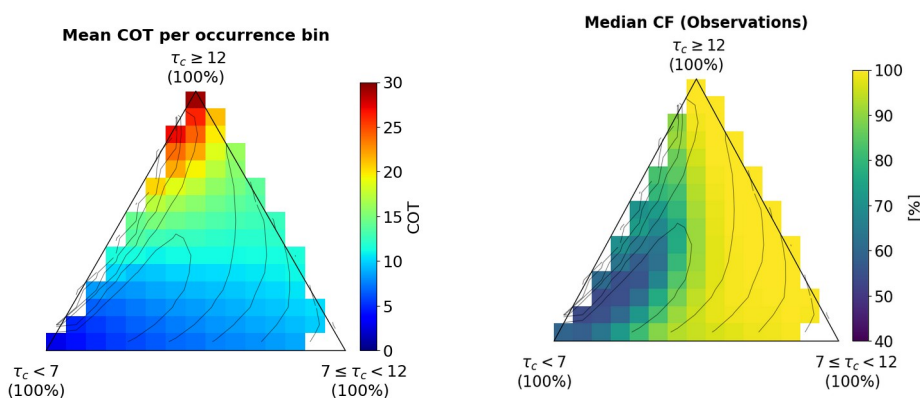
More heterogeneous regimes (e.g., open cells) typically exhibit higher SPI. Applying an SPI filter would therefore preferentially exclude certain clouds and bias the sample toward more homogeneous clouds, leading to incomplete representation. Since our analysis aims to explicitly capture variability associated with cloud morphology, we did not apply SPI filtering in order to retain the full range of cloud morphologies.

Fig. 1e - These scenes are relatively important as they have a reader decide what cloud types each part of the diagram refers to. How were they chosen?

The scenes were selected from the data. To clarify this, we have added the following to the caption of Fig. 1e: “The scenes were selected such that their ternary composition matches their position within the ternary diagram”.

L162 - To what extent is this a CF-optical depth relationship, rather than the more complex morphology-dependant relationship?

To assess this, the left panel of the figure below shows the mean cloud optical depth in each ternary bin. No clear relationship is found between CF (right panel, as shown in the manuscript) and cloud optical depth. This suggests that the observed CF is not governed by cloud optical depth, but is instead more likely linked to cloud morphology.



L183 - I am not quite clear what the LES diagrams are demonstrating. There is a small loop which looks like it is related to the diurnal cycle (daytime breakup), but I am not clear what the transition to/from the bottom left of the diagram represents? Is this the spinup of the simulation? A night time breakup is more unusual.

The LES diagram shows Lagrangian simulations of closed cells transitioning to open cells over 24 hours. The arrows indicate the direction of the temporal evolution across the ternary space. To clarify this, we have added a pin icon indicating $t=0$ (at night time, as shown in the colorbar), added more arrows around the loop, and modified the caption accordingly:

”... (c) LES simulation of overcast closed cells transitioning to open cells over a 24-hour period, with time indicated by the color bar. (d) Same as (c), but showing CF. Arrows indicate the direction of the temporal evolution across the ternary space, with the pin icon indicating the beginning of the

simulation. The closed-loop represents daytime cloud thinning, with the recovery later in the day overlapping the previous nighttime trajectory.”

L192 - I agree that precipitation must play an important role in cloud breakup, but this might not be the whole story, as there is relatively little precipitation during the day (Burleyson et al, JAS, 2013), which might explain the lack of an aerosol impact on cloud development during the daytime breakup period (Pugsley et al, PNAS, 2025).

The text aims to indicate that lower CF is associated with precipitating scenes. We have modified the text accordingly: “Figure 3 shows the microphysical properties across the ternary morphology space. In morphology bins characterized by low CF (Figure 2b), Nd is relatively low and re exceeds $15 \mu\text{m}$ (Figure 3a and 3b). This suggests that precipitation-driven breakup of overcast clouds could lead to the observed lower CF (Rosenfeld et al., 2006; Stevens et al., 2005; Wang and Feingold, 2009; Goren et al., 2019).”

Fig. 2 - Assuming the authors are using python, the use of a mesh plotting command (e.g. pcolormesh) might help make these plots more triangular

Thank you for this comment. The plots have been reproduced and now look much improved.

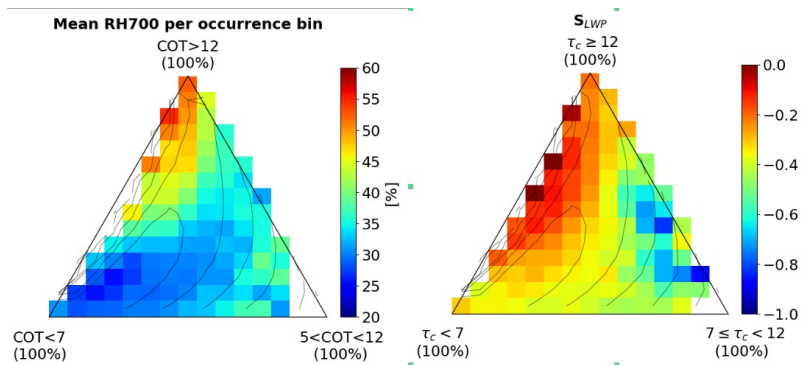
L214 - Some studies have cast doubt on the causality of the Nd-LWP relationship (e.g Gryspeerd et al., ACP, 2019; Arola et al, 2022). Does this method avoid the retrieval biases that have been hypothesised to drive this?

Retrieval errors in cloud effective radius, as discussed in Gryspeerd et al. (2019) and Arola et al. (2022), can bias the LWP–Nd relationship toward negative slopes. In particular, Gryspeerd et al. (2019) show that variations in effective radius can induce an apparent sensitivity of about -0.4 in $\text{dlnLWP}/\text{dlnNd}$ under the assumption of constant cloud optical depth. This reflects the mathematical dependence of retrieved quantities rather than a physical cloud adjustment. In our analysis, we attempt to reduce the impact of this bias by diagnosing S_{LWP} as the residual of S_{net} after subtracting S_{Ac} (Section 2.2.2 and Fig. A2).

These biases are also expected to vary across scenes with different degrees of cloud heterogeneity, with more heterogeneous cloud fields expected to exhibit a stronger negative bias in the inferred S_{LWP} . However, our analysis shows that S_{LWP} becomes less negative in more heterogeneous morphologies (characterized by lower cloud fraction and a mix of thick and thin clouds), which is opposite to what would be expected from retrieval-induced biases. While this does not rule out the presence of such biases, it suggests that they are unlikely to be the primary driver of the diagnosed S_{LWP} in our analysis.

L219 - Does this relationship depend on cloud top RH? This would add confidence that the negative relationship is due to entrainment, rather than a retrieval bias/effect.

To assess this, the left figure below shows RH at 700 hPa across the ternary space. Regions with more negative S_{LWP} (right plot, as shown in the manuscript) tend to be associated with lower RH, which is consistent with enhanced entrainment drying. However, the relationship between RH700 and S_{LWP} is not monotonic and varies across morphologies, suggesting that additional factors also play a role. Given this apparent complexity, we have not included this discussion in the manuscript, but note here that it warrants further investigation in future work, which is already underway.



L237/Fig. 4b - S_{Ac} is called S_{Twomey} in the figure

Corrected.

Fig. 4b - What are the units for S_{Twomey}?

Thank you for noticing this. The units have been removed.

L239 - I think S_{Ac} is defined in Eq. 2 such that it would be at a maximum for the smallest Ac

Yes, that is correct, and thank you for pointing this out, which made us realize that Figure 4b (S_{Ac}) was showing the absolute susceptibility (i.e. the expression for S_{Ac} multiplied by Ac) rather than the fractional susceptibility as defined in the equation (numbered as equation 3 in the revised manuscript). The figure has been replaced, as well as the description in Section 3.4.2:

“Figure 4b shows that the strongest S_{Ac} occurs in the lowest τ_c class and extends toward the top corner, towards the highest τ_c class, with the largest gradient along the left side of the ternary diagram. This is consistent with the theoretical approximation of S_{Ac} (Platnick and Twomey, 1994; Twomey, 1991), which predicts the largest susceptibility for scenes with the lowest Ac (see Figure A3 for the distribution of Ac across the ternary space)”.

L242/Fig. 4c - The S_{net} pattern looks very similar to S_{LWP}. this appears to be due to the S_{Twomey}/S_{Ac} values having very little variability.

Indeed. We have modified the text for clarity: “The similarity between the morphological dependence of S_{net} and S_{LWP} (Figure 4a) arises because S_{Ac} (Figure 4b) exhibits relatively little variability compared to S_{LWP}. This indicates that S_{net} is primarily controlled by S_{LWP}.”

L295 - Given the small overall relationship in the most common cases, why is this not consistent with other methods (or is it)?

Some previous studies have reported a substantial offset of Twomey-induced brightening by LWP adjustments (Prabhakaran et al., 2023; Toll et al., 2019; Diamond et al., 2020), although generally weaker than found here. This difference likely arises from our methodology, which enables a morphology-conditioned analysis and thereby better captures the susceptibility without mixing morphologies and biasing the inferred susceptibilities (for example, by the Simpson paradox). We have revised the paragraph to better place our findings in the context of the literature:

“The strength of the negative SLWP is found to depend on morphology, even for non-precipitating clouds, consistent with Zhou and Feingold (2023). Earlier studies, however, often reported a bulk approximation for SLWP (Gryspeerd et al., 2019; Glassmeier et al., 2021; Possner et al., 2020), thereby not capturing the morphology-dependent variability. Detecting a morphology-dependent

SLWP was possible by treating morphology as an observed variable, which also reduces confounding aerosol–meteorology co-variability that has been suggested to produce spurious negative values of SLWP (Goren et al., 2025; Mülmenstädt et al., 2024)”.

We then discuss the net effect, which is strongly modulated by S_LWP: “The net in-cloud albedo susceptibility is the most relevant for the radiation budget because it includes the combined contributions of cloud albedo and LWP susceptibilities. S_{net} is found to vary between -0.3 and 0.3 depending on cloud morphology, largely modulated by the strong control of SLWP. This implies that, in some morphological regimes, Twomey-induced brightening is offset by LWP adjustments, consistent with findings from previous studies (Prabhakaran et al., 2023; Toll et al., 2019; Diamond et al., 2020). Here, we further show that this offset can fully cancel, and even exceed, the Twomey-induced brightening, leading to a net negative effect. When averaged over all morphologies, S_{net} is overall small (0.015 ± 0.007), as it is dominated by the most frequently occurring morphologies, which have lower values. This implies that a global 10% increase in Nd would result in an increase in cloud albedo of approximately $0.15 \pm 0.07\%$, not accounting for changes in CF”.

Fig A2 - This should be in same colorscheme as Fig 4a to make comparison simpler.

Corrected.