Answers to reviewer #1

We thank the referee for constructive comments on the revised version of the manuscript. Please find below the answers. We report in blue the comments by the reviewer, and our answers can be found below each comment in black.

The authors present a novel method for retrieving cloud fraction from multi-angle polarized measurements that observe both cloud-bow and oceanic sun-glint. The novel contribution of this work is especially in the utilization of the polarized sun-glint signal to retrieve a resolution-independent measure of cloud fraction. The manuscript is well-written and acts as a demonstration of the key physical dependencies of the retrieval, using a combination of 1D RT and simple 3D RT simulations. This work can form the basis for the potential development and more widespread validation of an operational algorithm.
For this version, I have three comments for which I recommend minor revisions to the manuscript.

First, the method relies on the presence of unambiguous liquid within the field of view. This becomes increasingly unlikely when combining multi-angle observations at coarse-resolution as is done here. Naturally, the final effect of undetected ice will depend on the details of the cloud-top phase algorithm that is utilized. I don't think that a detailed emulation of the role of the cloud-top phase algorithm in filtering errors is necessary for this work. However, no phase determination algorithm will be perfect. So, this study should also perform a similar sensitivity study using 1D RT on the effect of the presence of overlying optically thin ice layers (e.g., cirrus) on the retrieval.

We added another scenario (h) to Fig. 4, where we included a sub-visible cirrus layer above the broken liquid water clouds. We find the following (included in text):
"In order to test how much the retrieval will be influenced by sub-visible cirrus clouds above the liquid clouds we added an optically thin cirrus layer with a cloud top height of 11 km and a geometrical thickness of 1 km (scenario (h)). The effective radius of the crystals is set to 30 µm and the parameterisation by Baum et al. 2014 is applied to obtain the ice cloud optical properties. Generally we see as expected a decrease in degree of polarization with increasing cirrus optical thickness at all scattering angles. This means that with increasing cirrus optical thickness the retrieved liquid water cloud optical thickness will slightly decrease and the retrieved cloud fraction will slightly increase. The sub-visible cirrus layer does not block the glint, therefore the retrieved cloud fraction corresponds approximately to that of the liquid clouds."

Second, the utility of this product for testing scientific hypotheses relies on its algorithmic stability. While threshold-based, pixel-by-pixel cloud masks provide an unstable estimate of the cloud fraction when the cloud size distribution changes, they can be designed to be invariant to solar-viewing geometry. On the other hand, the method developed here depends on the cloud fraction in the sun-glint view, which will change in viewing zenith angle with solar zenith angle.

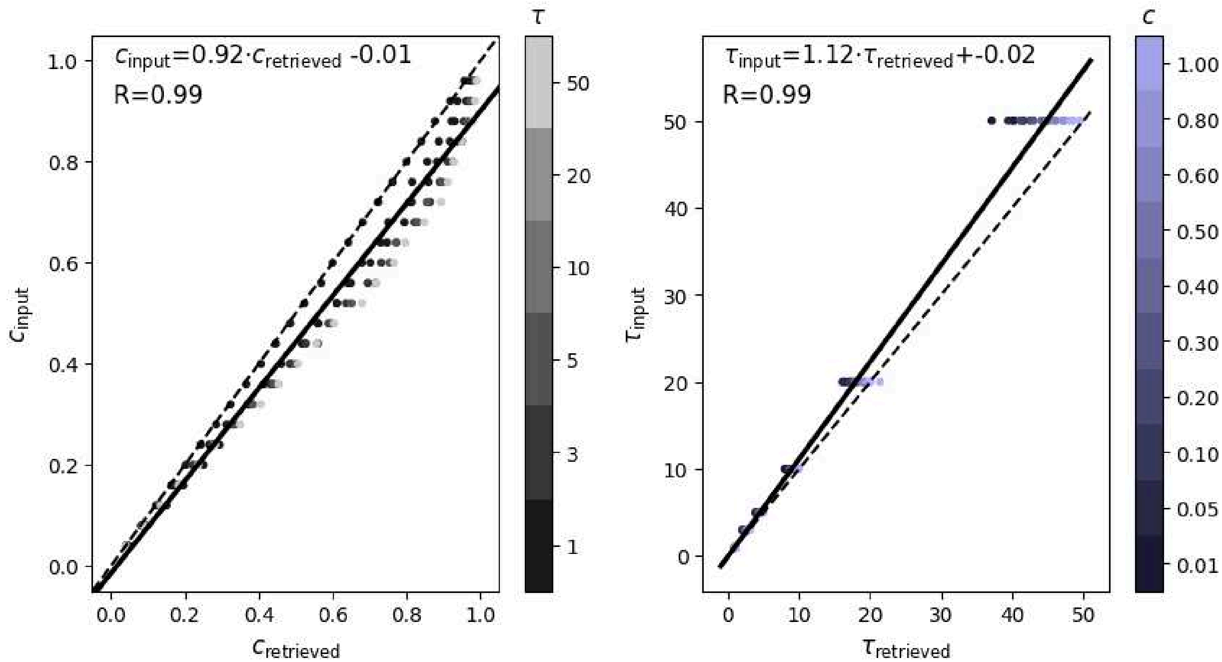
The cloud fraction at an oblique view is not the same as the vertically projected cloud fraction that is used as a model diagnostic, for example. For a polar-orbiting satellite this difference will introduce a regionally and seasonally varying bias in the apparent vertically projected cloud fraction. The magnitude of this bias is one of the foremost controls on the utility of this proposed method. This concept should be discussed within the text, with a recommendation that this effect should be evaluated in further studies.

Included the following in the outlook section:
"The retrieved cloud fraction corresponds to that of the pixel observing the sun-glint. Since the viewing direction of the corresponding pixels is not constant, the retrieved cloud fraction will be biased compared to the vertically projected cloud fraction which is commonly used as model diagnostic. This bias will vary regionally and seasonally. A detailed investigation on the distribution of this bias should be performed and based on this a bias correction method needs to be developed. "

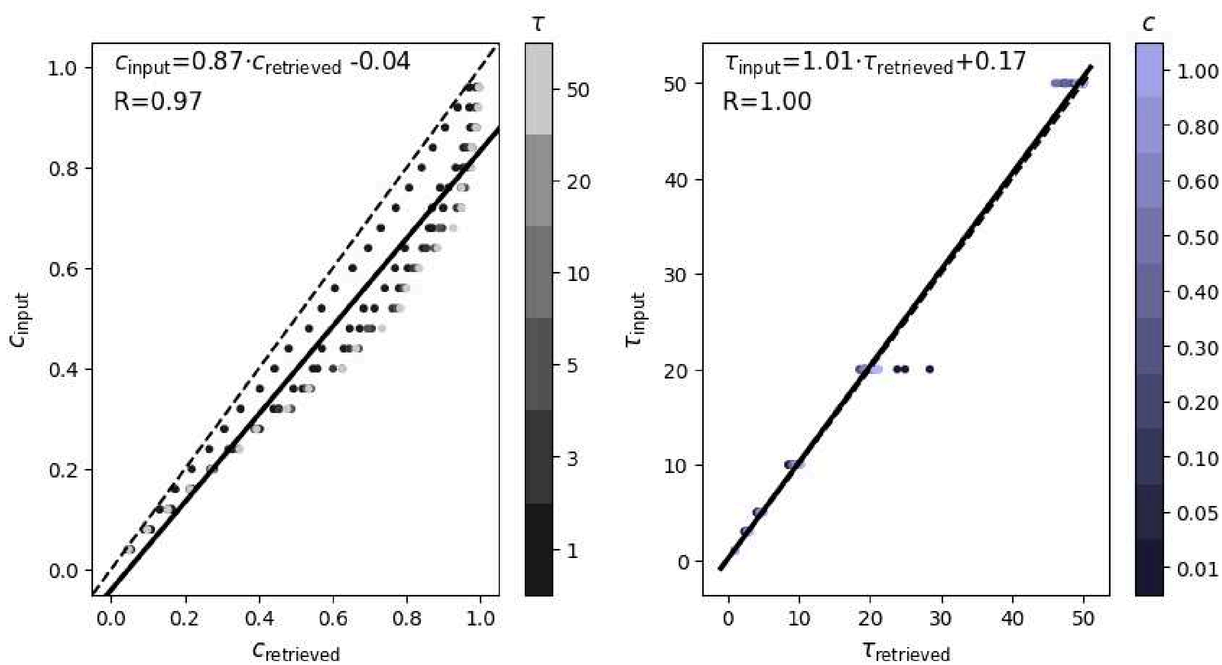
It appears the 3D RT simulations are at a single SZA of 50 degrees, which is associated with an overestimation of cloud fraction. The magnitude of the SZA-dependence of the retrieval will depend strongly on the realism of the cloud geometry. The 3D RT simulations utilize relatively large horizontal-to-vertical aspect ratios (5:1), when compared with typical cumulus, which might be more on the order of 2:1 or 1:1. Therefore, I don't see it as strictly necessary to quantify this with the simplified cloud fields presented here (though I would welcome it if the authors choose to also include 3D RT results for SZA=15 to contrast). However, it is very important to describe the concept so that readers can understand all of the expected behavior of the technique.

We need an observation in the cloudbow and a separate observation in the sun-glint. For SZA=15° the cloudbow and the sunglint overlap and the contributions of cloud and surface to the polarization signal are not well separated. In order to see the dependence on solar zenith angle, we have run the same setup with SZA=30° and SZA=70°.

For SZA=30°, we use a scattering angle of 110° for which we get a signal from the ocean glint, and we obtain very similar results as for SZA=50° for the particular shallow cumulus clouds:

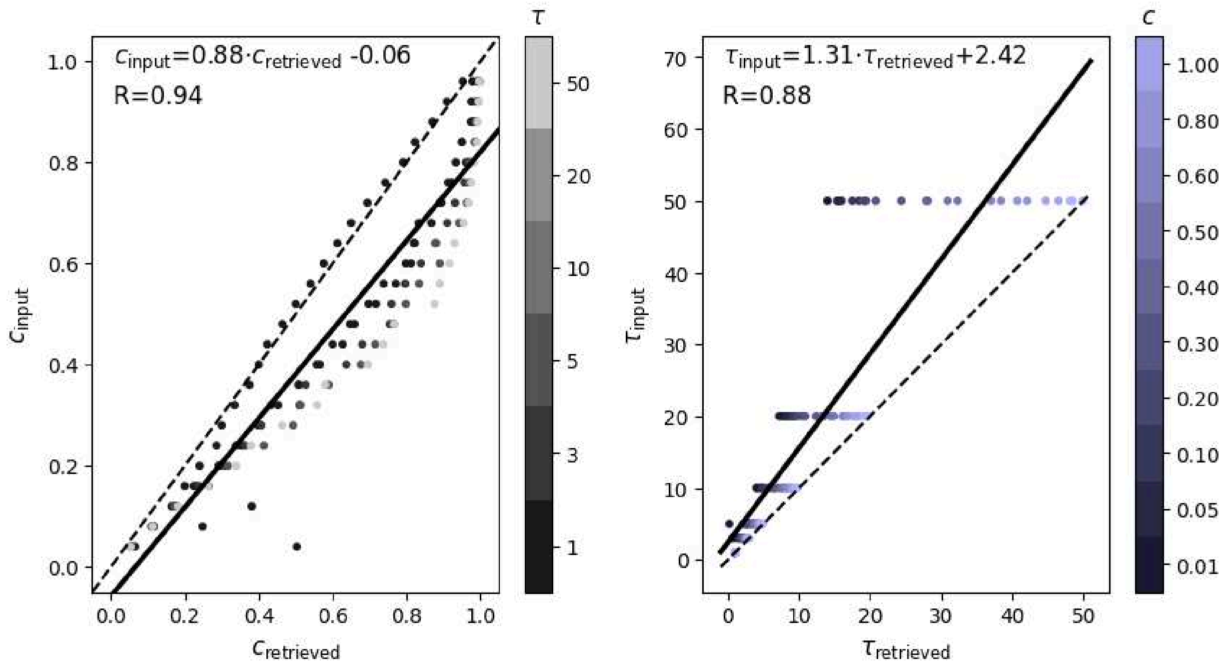


And also for SZA=70° the method works as expected when we use a scattering angle of 60° for the cloud glint signal:



We find the behavior that is expected from the observation geometry: The overestimation of the cloud fraction increases with increasing solar zenith angle whereas the underestimation of cloud optical thickness decreases.

We also run a simulation for the broken cloud fields with an aspect ratio of 1:1, i.e. a cloud geometrical thickness of 0.5 km:



The overestimation of cloud fraction is increased compared to the aspect ratio of 5:1 and also the underestimation of cloud optical thickness is larger (as expected because more radiation can escape through the cloud sides).

Since the main topic of the paper is to present the idea of the cloud fraction retrieval and the paper is already quite long, we decided to not include these results. We have added the following general conclusion at the end of Section 4.2:

"All results presented in this section are for a solar zenith angle of 50°. We have run the same simulations for solar zenith angles of 30° and 70° and found a similar performance of the retrieval. Generally, with increasing solar zenith angle the overestimation of cloud fraction increases. The underestimation of cloud optical thickness on the other hand decreases with increasing solar zenith angle."

Third, I believe the value of the specMACS analysis is to validate the cloud fraction derived from the coarse-resolution polarization method. However, at the moment, there is just an intercomparison of two cloud masks. Based on figure 16, the pixel-by-pixel cloud mask is missing a lot of cloud, which makes its use as a reference for assessing cloud fraction not as helpful. As stated in the text, the pixel-by-pixel cloud mask is designed to identify candidates for microphysical retrievals, leading to a tendency to be cloud-conservative, rather than being designed to optimally estimate cloud fraction. Fig. 18 may therefore be underestimating the presence of a more significant underestimate by the new cloud fraction estimate.

Given the relatively small number of data-points selected for the comparison, there is not really a need to compromise accuracy by utilizing an automatic Otsu thresholding method. I recommend that the thresholds be tuned by hand to each scene to ensure that all cloud is included. This way ambiguities such as mentioned in Line 441-442 can be avoided."

The goal of this intercomparison is to demonstrate the cloud fraction retrieval using the polarization of the glint. As we mention there are several reasons why they do not agree perfectly, which is probably always the case when comparing cloud fraction retrievals.

We think that using an automated approach is more reliable and comparable than using different thresholds for each scene to match our visual impression.
Note that the number of data points is not so small, in addition to the 6 “selected scenes” Figures 15 and 17 include the results of 70 further scenes which were automatically processed.

Also, we use this cloud detection algorithm to identify the pixels for which the cloud microphysics retrieval is performed. The output of this retrieval (reff, veff) is then used as a constraint for the cloud fraction/optical thickness retrieval (c1/tau1), so we would not like to introduce another inconsistency here.

For these reasons we have decided to keep the automatic cloud detection algorithm.

Answers to reviewer #2

We thank the referee for constructive comments on the revised version of the manuscript, in particular for carefully reading and commenting on the new section including 3D radiative transfer simulations. Please find below the answers. We report in blue the comments by the reviewer, and our answers can be found below each comment in black.

1. Line 14 (Abstract): Please specify what kind of algorithms (e.g., … existing "aerosol and cloud" retrieval algorithms).
Done.

2. Lines 52-64 (Introduction): This paragraph could benefit from some words on a recent paper published on the use of polarimetric measurements for retrieving sub-pixel cloud fraction: Yuan, et al. 2024. Cloud detection from multi-angular polarimetric satellite measurements using a neural network ensemble approach, Atmos. Meas. Tech., 17, 2595–2610, https://doi.org/10.5194/amt-17-2595-2024.

Thank you for this very interesting reference which we have added to the introduction as suggested.

3. Line 58 (Introduction): The acronyms "GOME" and "SCIAMACHY" have been defined, but never used again. They can be removed.
OK.

4. Line 143 (Section 2.1): from? Do you mean "around"? Please clarify.
Now included geometrical thickness of cloud layer and cloud top height.

5. Line 144 (Section 2.2): Please specify how the cloud optical thickness values are distributed between 1 and 50.
Added the specific values of the optical thickness values

6. Line 265 (Section 4): "on" -> "to the".
OK.

7. Section 4.1 (optional): I believe combining figures 6 and 7 into one figure with two panels may help the reader to see the differences between both cases.
Good point. We will make sure during the typesetting procedure that the two figures are on the same page, so that they can easily be compared.

8. Figure 7 caption: Please write the full caption.
OK.

9. Figure 8 caption: Retrieval lookup table derived in section 3 "(Figure 2)" … .
OK.

10. Figure 8 and 2: Please use color-codings that show a better contrast between values and variables (i.e., different shades of blue and black look very similar to the eye –at least to mine– and the contrast among different values of the same variable are not easy to spot). One could also try writing the values beside the corresponding lines and consider having two colors to discriminate the horizontal and vertical lines from each other. Also, if possible, try using two completely different symbols for the scattered dots (X and O, for example). One needs to focus a lot to see the different shapes. This applies to all the figures provided in the manuscript.
We included in most of the lookup table plots the values besides the lines and it should now be clear which lines correspond to which variable (since tau is in the range between 0 and 50 and cloud fraction in the range between 0 and 1). As suggested we are now using different symbols (‘O’ for in-scattering and ‘X’ for scattering).

11. Lines 294-309 (Section 4.1): I sense that the paragraph could benefit from including a take-away message that concludes what conclusion can be derived from figure 8?
We included a short conclusion and a transition to the next paragraph describing Fig.9 : “Fig. 8 shows that 3D scattering effects cause significant biases in the retrieval results for both the cloud fraction and the optical thickness. In order to validate these biases more quantitatively we show the retrieved data against the input data as scatter plots in Fig. 9.”

12. Figure 9: color codings are not consistent with the other plots in the manuscript. Please harmonize.
We now use consistent symbols with Fig.8 (‘O’ for in-scattering and ‘X’ for scattering) and plot all points in black to avoid confusion.

Is there a reason for why the scattered dots to be located on a horizontal line?
“In the scatter plots, the data points are located on horizontal lines because the input cloud fraction and optical thickness values are discretized.” This explanation has been added.

Please mention why it is like that. Also, I don’t fully understand what the linear regression lines in this figure tend to show/prove. Could you please elaborate on that?
Included the following explanations:
“The slope of the linear regression line is 1.03 and the correlation coefficient is 0.96. These values show that although there is a large spread in the retrieved cloud fraction, the biases by in-scattering and shadowing almost cancel each other in this particular case.”
“Generally, we find a good correlation between input and retrieved optical thickness, but there is a significant bias towards too small retrieved optical thicknesses (the regression line is shifted to the left compared to the one-one line).”

13. Line 311 (Section 4.1): lines -> dots.
Done.

14. Lines 331-333 (Section 4.1): this part seems to be about the sun glint only. It would be beneficial to give similar explanations for the cloud bow as well.

The explanations for the cloud bow were given before in lines 326ff:
"In the cloudbow, the intensity I is only weakly influenced by 3D scattering effects, i.e. the solid lines for the broken cloud fields lie on top of the dashed lines showing the IPA calculations. |Q|, which saturates quickly for $\tau \geq 3$, is slightly larger for 3D compared to IPA. This difference is enhanced in the degree of polarization shown in the right panels"

15. Line 350 (Section 5): Is there a reference paper for the EUREC4A campaign? Seems like Stevens et al. 2021 is the one. If so, please include it here.
Moved reference to the right place.

16. Figure 12: maybe worth it to say a few words on the difference among the points that fall exactly on the 1:1 line and those that fall apart from that.
Included the following sentence:
"Only the points corresponding to a cloud fraction of 1 (fully cloudy) lie exactly on the one-one line."

17. Line 418 (Section 5.1): … tau_1 and c_1 are, "respectively", … .
Done.

18. Line 434 (Section 5.1): Do you mean that the "difference" in the cloud optical thickness is small?
No, we mean that the optical thickness in scene 4 is larger than in the previously discussed scenes.

19. Line 452 (Section 5.1): has -> have ; (i.e., smaller than 0.2).
Done.

20. General comment (Section 5): merge section 5 with subsection 5.1. As there is no subsection 5.2, I don't see a need for having 5 and then 5.1.
Yes, we agree. The sections are now merged.

21. Section 6 (Conclusions and Outlook): Outlook -> outlook
Done.

22. Line 459 (Section 6): … optical thickness of liquid clouds over ocean …
Included.

23. Line 475 (Section 6): This demonstrates that …"
Done.