Response to Reviewer #2:

We would like to thank the referee for the valuable comments on our 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.

General comments:

This manuscript presents a proof of concept for a method that can be used to retrieve cloud optical thickness and cloud fraction from multi-angle polarization observations. In particular from measurements at two viewing angles: one within the cloudbow at a scattering angle of approximately 140° and a second in the sun-glint region or at a scattering angle of approximately 90°. Further, the method consists of a look-up table generated using a 1D radiative transfer code. In addition, the authors provide information on the theoretical basis of their approach based on a limited (but sufficient) sensitivity analysis under idealized setups using the same 1D radiative transfer code.
Overall, the manuscript well suited for AMT and I believe the community can benefit from it. Also, the methods used seem to be robust and the language is fluent and precise. However, there some aspects of the manuscript that I am concerned about (see my comments below), and I believe are required to be addressed and clarified.

Specific comments:

1. The authors claim that they are presenting a retrieval algorithm that can be used to retrieve cloud optical thickness and cloud fraction from multi-angle polarization observations. Despite the authors' claim, the contents of the manuscript present the theory and proof of concept that the theory would work. Let me further explain this: an algorithm is defined as "a process or set of rules to be followed in calculations or other problem-solving operations". Here is an example to put things in perspective: you can have multiple lookup tables for a wide range of surface and aerosol characteristics, plus different cloud types. For this method to be called an algorithm, it must contain an automated mechanism to select between those lookup-tables. Or, for example, it should also contain automated steps for discriminating the cloud phase. I believe this issue can be addressed by either rephrasing the text and correcting the statement, or by developing the further steps required and expanding the simulations for the method to be called an algorithm. Also, the entire manuscript, including the title and abstract should reflect this matter.

OK. We fully understand this point. Indeed, our intention is to present a new idea to retrieve cloud fraction from satellite observations and to provide a proof-of-concept. We have renamed “algorithm” to “method” throughout the paper.

2. Under real conditions, the measurements will contain some degrees of error associated with them. It is not clear how the instrumental noises are accounted for in the tests provided in this manuscript.

At this point, we assume that the measurement errors are smaller than errors due to uncertain assumptions (e.g. about wind speed and aerosol optical properties). In a complete “algorithm” this certainly needs to be included, but for the proof of concept we believe that this is not necessary.
As a demonstration we apply the method on real airborne observations (Section 5), and we obtain consistent results from two methods to derive the cloud fraction, which should be sufficient for demonstration purposes.

3. Given the fact that this manuscript is based on very few test scenes and idealized simulations, I find a bit difficult to understand why addressing the effects of the 3D radiative transfer should be a separate manuscript.

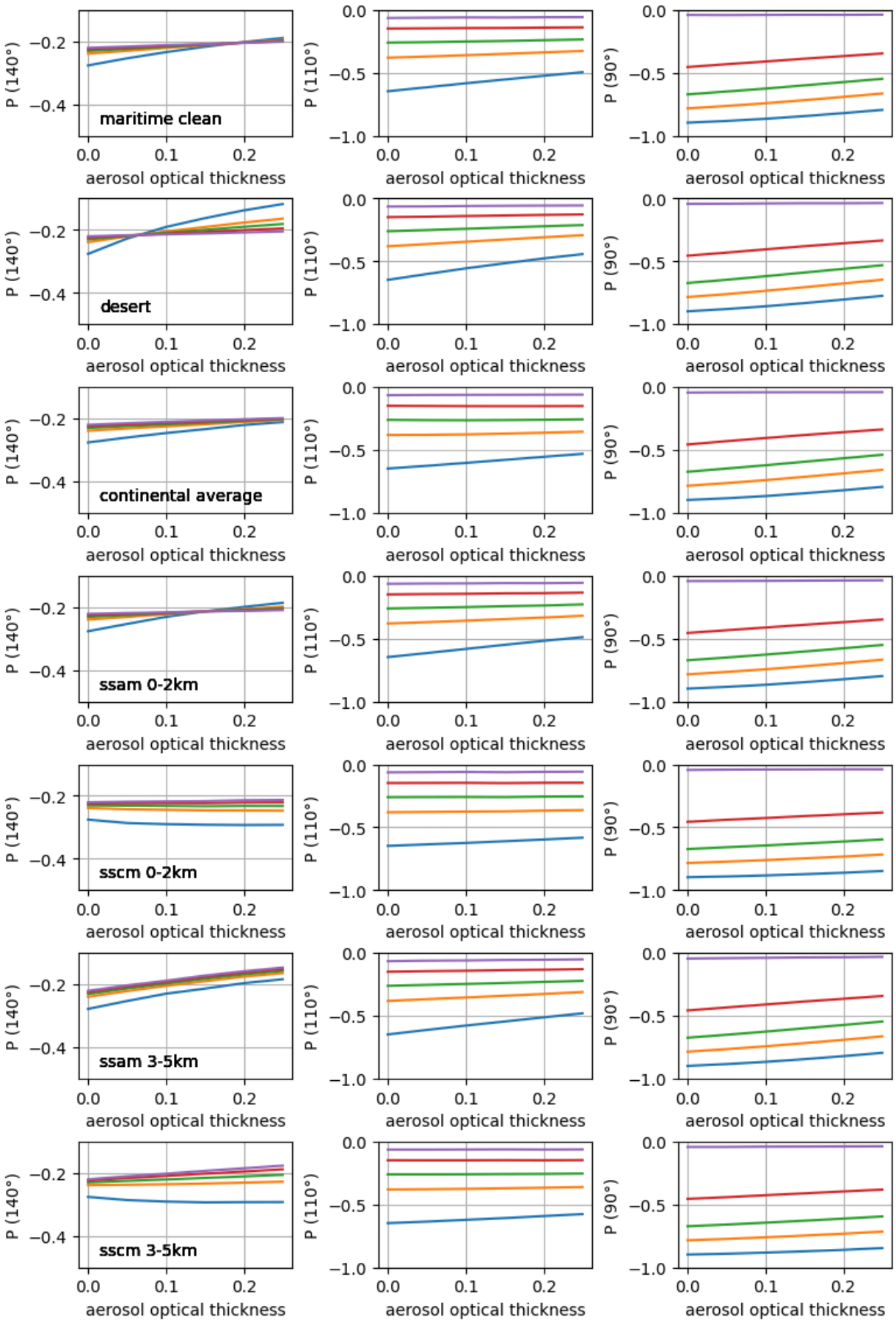
We included a new section with 3D radiative transfer simulations to demonstrate the basic 3D effects (shadowing and in-scattering) impacting the retrieved cloud fraction in opposite directions.

Also we studied randomly generated simple shallow cloud fields, for which the cloud fraction is overestimated due to cloud shadows.

A more detailed study including realistic LES clouds should be presented in a separate manuscript.

4. The analysis performed to evaluate the sensitivity of the responses to aerosols needs to be expanded to address as the total AOD is probably not the only affecting factor. In particular, the above-cloud-AOD, aerosol composition and size can also be important.

We performed additional sensitivity analysis for different aerosol types, different aerosol layer heights. and different size distributions (shown in the figures below). We find significant impacts on P(140), and only very small impacts on P(110) and P(90), where the degree of polarization is dominated by the sun glint. Therefore, for the cloud fraction retrieval, one needs to take into account only the total aerosol optical thickness. Other parameters, such as aerosol size distribution, composition and vertical profile have a smaller influence and can safely be neglected. For the optical thickness retrieval however, detailed aerosol characterization is more important.


P (140°)
P (110°)
P (90°)
aerosol optical thickness
maritime clean
desert
continental average
ssam 0-2km
sscm 0-2km
ssam 3-5km
sscm 3-5km

5. It is not clear whether the approach is intended to be developed for ice or liquid clouds or both. Also, whether for application over land or water. This has to be clarified along the manuscript including the title and abstract.

For this paper, we have now limited the method for liquid clouds over the ocean (the title has been changed accordingly). We added the following in the introduction for clarification:

“The global cloud cover cannot be obtained using our method because it is developed only for liquid clouds over ocean.
Since ice clouds do not produce a cloudbow, the methodology cannot directly be applied to determine the cloud fraction and the optical thickness of ice clouds. However, it would be possible to replace the degree of linear polarization in the cloudbow region by an intensity observation at the same angle to retrieve the ice cloud optical thickness. For retrievals over land, polarization due to surface reflection is too small to be used for a cloud fraction retrieval. Therefore an additional method needs to be developed which could use the strong polarization caused by Rayleigh scattering between the clouds to obtain information about the cloud fraction. This method should use shorter wavelengths which are mostly insensitive to surface properties and for which the Rayleigh scattering contribution is much higher.

6. The authors claim that the approach is suitable for space-born multi-angle polarimetric remote sensing and they are waiting for the PACE data to become available. But it could also be test on the PARASOL-POLDER measurements (https://www.aeris-data.fr/catalogue/?checkBoxCriteria=%7B%22projects%22%3A%5B%22SPATIAL.PARASOL%22%2C%22SPATIAL.POLDER%22%5D%7D#masthead) as this data is available?

Yes, it would be possible to also test it on POLDER measurements, but this is also a separate study.

7. Adding some thoughts on how the authors are planning to validate the retrieved cloud optical thickness could be nice.

We have now included the 3D radiative transfer simulations to generate synthetic observations with known input. Using this, we also validated the optical thickness retrieval and found that it is generally underestimated for cases where 3D cloud scattering plays a role.

8. I believe, a viewing angle with a scattering angle that is exactly 90 and 140 degrees may not always be available. What is the protocol for such cases? Also, I see that the authors are using the word “approximately” in this context. It would be nice to add some words on the impacts of this non-exact scattering angles on the accuracy of the retrievals.

For specMACS we could not get 90° and 140° simultaneously, therefore we have used 110° and 140° and we show that this works equally well. It is only important to have one scattering in the cloudbow and another one in the sun-glint region, they do not need to be exactly at 90° and 140°. This has also been clarified in the text (Section 6):

“We also generated lookup tables using scattering angles of 140° and 110° and again obtained a well-separated lookup-table grid. This demonstrates that it is not important to choose exact scattering angles to set up the retrieval, one only has to make sure that one angle includes the cloudbow and the second angle a part of the sun-glint.”

9. Some words on how the retrieval accuracy can be affected by using only the central band wavelengths and not applying the instrument response function can be beneficial.

We added the following to the description of the setup of the lookup tables for specMACS:
“For the selected scenes, we generated lookup-tables using the cloud size distribution parameters from the cloudbow retrieval in addition. Of course, it would make sense to combine the method with further retrieval algorithms, e.g., with the simultaneous aerosol and ocean glint retrieval by \citet{knobelspiesse2011}. When accurate a priori information about wind speed and aeorosol optical thickness is included, one should also take into account the filter function of the instrument rather than running monochromatic simulations to generate the lookup-table. These improvements are not necessarily needed to demonstrate the method for a few specific cases, which is the purpose of this study.”

Technical corrections:

1. In my opinion, the abstract does not well represent the contents of the manuscript (i.e., data used, theoretical analysis presented, testing performed and applications).

We have revised the abstract accordingly.

2. The story line in the Introduction section seems a bit off (sounds to me that some random information is being given to reader to fill the space) and can benefit from some revision. Here are some examples:

a. The text given between lines 23-25 seems redundant or at least requires rephrasing. Also, I don’t get how as the authors state the need for more observations is linked to algorithm development (that is the further exploitation of the existing data). Also, it does not connect well the previous and the next paragraphs.
b. Something seems to be missing between the third and fourth paragraphs. And then it jumps from clouds to aerosols. And then

jumps to clouds.
c. Then the authors jump to giving information about the upcoming satellite missions.

3. It will be nice to have the hypothesis of the manuscript defined in the introduction and also specify why such a product is required / what this product adds to the existing information.

We have also revised the introduction. We have now put the focus on the cloud fraction, on problems related to its definition and on the problems related to the observation of the cloud fraction from space. In particular it depends on spatial resolution for most cloud fraction retrieval algorithms and also on settings of various thresholds. Due to the limited spatial resolution, cloud fraction is often overestimated. Our method provides a continuous and resolution-independent estimate of the cloud fraction, and we demonstrate using specMACS observations that this correlates well to the cloud fraction derived from observations at very high spatial resolution of 10m.

4. The structure of section 2 is not very straight-forward and can benefit from some adjustments. Here are some suggestions:
a. I would start the Methodology section with some brief information on what is it that is intended to be addressed and how (i.e., testing and explaining the theory behind the method, followed by the fact that synthetic measurements are produced …). Followed by two sub-sections that explain the methods for the theory and testing parts, respectively. Include all the methodology here, unless it is not possible.
b. The sensitivity analysis performed seems like a result to me that explains the theory behind the approach. For this reason, I would create a new section 3 and dedicate it to the sensitivity analysis and call it something like “theoretical basis”.
c. The current section 3 can then be the new section 4.

Thank you for your suggestion, we have revised the structure accordingly. The “Methodology” Section 2 includes the description of the model setup for 1D and 3D simulations. Section 2 includes the results of the 1D simulations and the setup of the retrieval lookup table. Section 4 includes the results of the 3D simulations and the investigation of the impact of 3D scattering on the retrieval accuracy (retrieval test based on synthetic observations). Section 5 includes the retrieval test on real airborne observations.

5. It will be of a great importance to provide the bi-directional reflectance and polarization functions corresponding to the surfaces used.

This information was given in the results section: “we include an ocean surface which is modelled using the reflectance matrix based on the Fresnel equations convolved with a

Gaussian kernel to account for the ocean waves (Mishchenko and Travis, 1997; Tsang et al., 1985; Cox and Munk, 1954a, b).” We moved this now to the methodology section. For land surfaces we only included Lambertian surfaces.

6. Both “clear sky” and “cloud free” terms are used in the manuscript. Please harmonize unless the meaning is not different (in that case define it more clearly).

Ok, now we consistently use “clear sky”.

7. When talking about cloud layer height, is that cloud top height that you are referring to or base height?

We always refer to “cloud top height”, this is now included in the text.

8. Paragraphs 3 and 4 of section 4 contain plenty of unnecessary repetition of information that does not help concluding anything. Rephrase, shorten or remove.

OK. The summary has been shortened.

9. Figure 5:
a. It will be useful to have likes of Figure 5 for different land types somewhere in the manuscript (appendix would do as well).

As mentioned, we now focus on retrieval over the ocean. Over land, it becomes far more complicated because cloud height will become important as well as the vertical profile of the aerosols.

b. Write in the caption that the figure is for the case of ocean.
OK.

c. AOD: is it AOD above cloud or total column AOD?
It is the total column AOD.

d. It would make it easier to read the figure if you add just beside the figure (where a, b, c, … are) some small text that can be related to the parameter that is being evaluated. Example: a [tau]
The label of the x-axis clearly shows the parameter that is evaluated.

10. Line 195: (tau_c), (c)
Not sure what you mean here. Comma after tau_c?

11. Line 196,197: are separated

OK.

12. Line 200: realize what?
Rephrased: “Therefore, is makes sense to combine the retrieval with an effective radius retrieval based on the cloudbow signature.”

13. Line 202: I believe what is important here is the cloud top height, not the base. Rephrase the sentence based on cloud top height.
Corrected.

14. Line 206-207: The sentence “P(110) …” does not seem to be based on the plot.
Thank you, we mean here the absolute value of P(110°). This has been corrected.

15. Info given in page 12 can go to the Methodology section explained above in comment 4.
We prefer to leave the information on the observational data in Section 5 to keep the test on real observations separate from the theoretical part including synthetic observations. The definition of the signed degree of linear polarization has been moved to the “Methodology”.

16. Lines 201-202: explain the abbreviation the first time that the abbreviation is used. Also, do EUREC4A and HALO stand for something?
OK. Explained specMACS, EUREC4A and HALO where they are first used.

17. Line 236: the word “corresponding” seems strange there.
Replaced “corresponding” by “equivalent”.

18. Lines 243-245: it is not very clear, please rephrase or expand.
The reader is referred to the references Kölling et al. 2019 and Pörtge et al. 2023 for more details.

19. Figure 6:
a. Panel names are difficult to see (font size is too small).
The panel names are now on a white background to see them more clearly.

b. The terms left and right are not very clear, maybe they could more clearly be labeled.
We included the scattering angles as additional labels at the top of the images.

c. Make the boarders of the shaded area more visible. It is hard to see it.
Done.

20. Line 255: total column AOD=0.08 or above-cloud-AOD?
Clarified.

21. Lines 268-269: omit “for this scene”, and the second “which”.
This part has been rewritten, because we exchanged some of the scenes.

22. Line 287: Please further explain.
Rephrased.

23. Line 282: comma is missing: palne, making
Added comma.

24. Line 298: comma is missing: ,for instance,
Included.

25. Line 331: MYSTIC?
Included expansion of MYSTIC where it is first used.