

Dear Reviewer,

thank you for taking the time to review our manuscript. Your feedback is greatly appreciated and was helpful in improving the quality of this research. We value your constructive criticism and thoughtful comments, which have helped to identify areas that require further clarification and refinement.

The topic has significant interest for both weather and climate applications. The paper is well written and organized. One suggestion is some more detailed discussions on the ground truth data (DARDAR) could be added for limitations and further improvements. A few minor revisions below, mostly for more clarification, will also help to improve the manuscript for publication.

We carefully considered your suggestions and incorporated them into the revised manuscript to address the issues raised, as specified below (referee comments in blue; our answers in black).

We have added more details about the DARDAR data, mainly in section 2.1. These additions are outlined in the responses to the referee's comments below (see in particular the responses to comments on lines 46-47 and 76-77 above).

Line 5 Abstract: Add (PRObabilistic cloud top Phase retrieval for Seviri) to ProPS

We added the suggestion.

Line 30-34: Add full name of GOES: Instead of GOES-R/S, GOES-R series or GOES-16/17/18: Add sensors: ABI and AHI with references, like SEVIRI. GOES -> GOES-R

We added the names of the imagers and corrected the GOES-R name.

Line 40:" the Lidar-Radar cloud product DARDAR..." Add a brief summary for readers who are not familiar with this data, space-borne data derived from CloudSat-CALIPSO, even though the details are followed in the next section but it appears first here.

We added a brief description of DARDAR as follows:

"We use the Lidar-Radar cloud product DARDAR (liDAR/raDAR, Delanoë and Hogan, 2010) as the basis for this method. DARDAR is based on the combination of active radar and lidar measurements from the A-Train satellites CloudSat and CALIPSO and provides a consolidated classification of the measured clouds into different cloud phases."

Line 46-47: For "DARDAR as ground truth" - If the data is temperature only-based, still limitations especially for supercooled and mixed? If any, it would be better to include some discussions on the of the ground truth in the data or conclusion sections.

The DARDAR phase classification is not only based on temperature, but also uses the lidar backscatter, radar reflectivity and cloud layer thickness as criteria. DARDAR combines the sensitivity of lidar to optically thin cirrus with the ability of radar to penetrate optically thicker clouds in the following way (explanation following Mayer et al. (2023)): Atmospheric targets are labelled as warm liquid clouds where the wet bulb temperature is $> 0^{\circ}\text{C}$, calculated from temperature, pressure and humidity from the ECMWF-AUX dataset (Benedetti, 2005). In addition, cloud layers containing supercooled water are identified by their strong lidar backscatter and subsequent attenuation in temperature ranges between 0°C and -40°C . A further distinction into pure supercooled water without ice crystals is made using the absence of radar return, since the diameter of cloud droplets is mostly below the CloudSat sensitivity (Hogan et al., 2003). If the layer is thicker than 300 m in the

temperature range 0 °C to -40 °C, it is assumed to be fully glaciated. Further details can be found in Ceccaldi et al. (2013).

We extended the explanation in the paper to make these points clear as follows:

“As ground truth for cloud occurrence and cloud thermodynamic phase, this study uses the product DARDAR-MASK, part of the synergistic active remote sensing product DARDAR (Delanoë and Hogan, 2010; Ceccaldi et al., 2013). DARDAR-MASK is derived from the sun-synchronous, low-earth orbit satellites CloudSat (Stephens et al., 2002) and CALIPSO (Winker et al., 2003). To distinguish between cloud phases, DARDAR-MASK uses the wet bulb temperature derived from the ECMWF-AUX dataset (Benedetti, 2005) and the extent of cloud layers as well as the different sensitivities of lidar and radar to cloud particles of varying sizes: cloud layers containing water have a strong lidar backscatter and subsequent attenuation; the CloudSat radar is mostly only sensitive to the larger ice crystals (Hogan et al., 2003). DARDAR-MASK provides vertically resolved cloud thermodynamic phase along the track of the CALIPSO and CloudSat satellites with a spatial resolution of 1.1 km along track and 60 m in the vertical direction.”

Line 76-77 Add more details. Did the authors use the cloud top phase info in DARDAR from CloudSat-CALIPSO as is? Assumed there was no further consideration on the lower layer phase from the active-sensors for passive radiometers like SEVIRI, correct? What exactly mixed phase is defined?

To answer these questions and make the collocation procedure clearer, we extended the explanation of the collocation of DARDAR and SEVIRI in Sect. 2.1 as follows:

“From the DARDAR data we extract two key pieces of information for each SEVIRI pixel: 1) whether a pixel is clear or cloudy, and 2) a cloud top phase. This cloud top phase at SEVIRI resolution is defined by horizontal and vertical averaging of DARDAR gates using a simplified penetration depth (Mayer et al., 2023). We distinguish between warm liquid (LQ), supercooled liquid (SC), mixed phase (MP) and ice. MP cloud tops in SEVIRI resolution are defined as containing either only gates classified as mixed-phase by DARDAR or a mixture of liquid, ice and/or mixed-phase DARDAR gates in the cloud top gates considered for the collocation (see Mayer et al. (2023) for details). To ensure that the averaging over DARDAR gates for a SEVIRI pixel is not done over two different clouds, the gates are all required to have a similar cloud top height. For multilayered clouds, e.g., a high cirrus cloud on top of lower clouds, only the uppermost cloud layer is considered.”

Line 54 and nighttime eval.in sect 8: Have you ever considered 3.9 um or a channel difference including this, particularly for nighttime retrievals?

We have considered the 3.9 μm channel, but decided against using it, since CO₂ and water vapor absorption effects can have a possibly large influence on the channel, which we can not account for. (see for instance https://www-cdn.eumetsat.int/files/2020-04/pdf_conf_p50_s10_05_charvat_p.pdf)

Line 65: “DARDAR (liDAR/raDAR, Delanoë and Hogan, 2010)” repeated in Intro and here.

Thank you for noticing; we deleted it.

Line 66: Probably need references for these satellites, CloudSat and CALIPSO, although they are well know.

We added the corresponding citations.

Line 72: MET-9 -> maybe better to write the full name, Meteosat-9?

We rewrote to: "SEVIRI aboard the geostationary satellite Meteosat-9 (part of the Meteosat Second Generation series)".

Line 79: "...observed (see Mayer et al. (2023) for details)." - more info about the phase data used as a ground truth in this study will be desirable here, briefly from Mayer et al. (2023) if needed.

We added more details about the "ground truth" DARDAR data as well as the collocation procedure with SEVIRI in Sect. 2.1 (see the responses to comments on lines 46-47 and 76-77 above).

Line 98: "combinations, at probability distributions are used" – more clarification?

We rewrote the passage to make it clearer as follows:

"For the regions of the parameter space without samples for high sza and umu combinations, the solar channels are effectively not used. In a Bayesian update, this is done by imposing flat probability distributions for the solar channels in these regions of the parameter space, i.e. the cloud state probabilities are not changed by the solar channels.

The Bayesian update is further explained in Sect. 6.

Figure 2: Hope the figure quality with larger fonts can be added in the final version.

We increased the figure resolution and quality for the final version.

Line 135: M2 means the other channel measurement?

Yes, that is correct. To make that clearer in the text, we added "SEVIRI" in the sentence:

"Updating the probability with a second SEVIRI measurement M2 leads to..."

Line 157: "most likely": Any minimum threshold which may give 'uncertain'?

No, we always use the most likely cloud state, i.e. the cloud state with the highest probability for each SEVIRI pixel. However, to quantify the uncertainty of a retrieved result, we define a "certainty parameter" from the computed probabilities (explained in Sect. 3.3).

Eq 7: "season" - How was it quantified in the computation?

We defined "season" in Eq. 7 more clearly as "... and season is one of the four seasons of the year (December - January - February, March - April - May, June - July - August or September - October - November).".

Line 201: "parameters A introduced above in Sect. 7 " -> need to be corrected?

Thank you for noticing this mistake, we corrected it.

Line 203-205: Not very clear. Could you explain more details? It is explaining Fig. 3, right?

Yes, it refers to Fig. 3, which shows the mutual information values of the prior (first panel) for different sets of conditions. We expanded the caption of Fig. 3 to make it clearer (see two questions below). We also rewrote the explanation in the text as follows:

“Furthermore, our mutual information calculations show that conditioning on latitude, longitude and season yields the prior with the optimal information content compared to other possible sets of conditions (see Fig. 3). This means that location (latitude and longitude) and season are the main dependencies.”

Line 207: BT: - What about putting this acronym to the place where it appears first, and using BT for consistency?

Good point, we changed it accordingly.

Figure 3: Higher resolution one with bigger fonts, please. The figure caption doesn't seem very straightforward, please more clarify it for better understanding?

We increased both the resolution and the font. We extended the caption to make it clearer as follows:

“First panel: Mutual information I between the latitude and the cloud state q (first row), cloudy/clear, abbreviated as c/c , (second row) and cloud phases (third row) for different sets of conditions C . This represents the information content of the different priors we considered, where latitude is a fixed condition, i.e. $P(q | \text{lat}, C)$. Other panels: Mutual information I between SEVIRI channel (combinations) and cloud state q , cloudy/clear and cloud phases for different sets of conditions C . Empty spaces for C mean no condition, i.e. the starting point of I before conditions are introduced. The different mutual information values for q , cloudy/clear and phase indicate whether a channel (combination) contributes more to cloud or phase detection. The blue boxes indicate the sets of conditions selected for ProPS.”

Line 214: “the brightness temperature” -> BT10.8

We changed brightness temperature to BT10.8.

Line 217: BT -> BT10.8

We changed it accordingly.

Line 276: Bayesian retrieval methods -> specify which cloud property retrievals

We specified in the text that texture parameters have been used in Bayesian retrieval methods for cloud detection.

Line 376: Fig. 6 -> Figure 6

Thank you for noticing this; we changed it.

Line 379: “...retrieval detects (most) clouds which...” Can we think the retrieval method is for cloud detection in the first place, not just cloud phase discrimination?

Yes, that is correct. The method combines a cloud detection and phase discrimination since it distinguishes between clear sky and the different cloud types (TI, IC, MP, SC, LQ).

Line 379: Add the full name for ITCZ, even though most of us know what it is.

We added the full name for ITCZ.

Line 523-524: Again, addition to using 3.9 um info, have you ever considered additional environment parameters from ERA-5 such as low level humidity and SST/low level atmos temperature combinations?

We considered using additional parameters from ERA-5. However, for this first version of ProPS we decided not to do so for practical reasons: 1) The data requirements to compute statistically valid probabilities scale with the number of parameters used. We therefore limited the number of parameters for each probability. 2) Parameters from ERA-5 have to be retrieved and regridded for each SEVIRI time step, which increases the computational cost.

However, the inclusion of more parameters from ERA-5 could be reconsidered in future developments of the method.

Appendix B: I would think this discussion can be part of the main section 8.

We added a brief discussion of the results of the ProPS night version in the SEVIRI disc to section 8.4:

“For the night version of ProPS, the POD of clouds is similar to the day version while the POD of clear sky is slightly lower almost everywhere in the SEVIRI disc (see Fig. C1). This suggests that ProPS tends to overestimate cloudiness during the night. The spatial distribution of the POD of the different phases is very similar to the daytime version (see Fig. C2).”

References: Cover 1999: Some info still missed.

Thank you for noticing. We added the missing information in the reference.

References

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