Reply to Anonymous Referee #1

We thank Anonymous Referee #1 very much for his/her encouraging review of our manuscript. We do however also realize based on her/him comments, that some aspects of our draft require further clarification, in particular the relation of this paper to the companion paper of Werner and Deneke (2020) (hereafter referred to as WD20) and other prior studies, as is evident from several of the comments raised by him/her.

We have adopted the following convention for our review: citations of the comments are given in italics, followed by our reply. Below each reply, a screen shot of the marked-up text modifications is given, generated with latexdiff. Deletions are shown in red/strike-through style, while insertions are underlined and shown in blue.

Please note that we have also considered several related comments by both reviewers on Sec.4.1 in combination, yielding a more substantial revision which can no longer can be directly associated with a single comment. An identical text listing the revisions including their rationale is included in the replies to both referees at the end.

Reply to Specific Comments

C1.1. Line: 19: MODIS team has an updated paper Platnick et al. 2017. Please update or add the reference.

Indeed, we unfortunately missed to reference this paper on the latest collection of the MODIS cloud products, as also noted by Referee #2 (see C2.2). We have added this as additional reference in the revised manuscript.

~~(Platnick et al., 2003).~~ (Platnick et al., 2003, 2017).

C1.2: The footnote about the numbers of Google scholar hits is very interesting! I guess the factor that Aqua-MODIS is part of A-train helps.

We also found that a fun detail. From my perspective, MODIS in itself was an incredibly successful mission, maybe due to the fact that it made data access a lot easier than any previous satellite mission by having easily accessible products via the LAADS DAAC, but also due to the excellent work done by the various Science Teams towards providing high-quality/regularly improved products to end users. We have updated the query results in the footnote of the revised manuscript (NB: we plan to update these numbers once more for a final version of the manuscript).

[1] A search of Google Scholar ™, https://scholar.google.com for the term cloud combined with MODIS yields ~~167.000~~ 196.000 hits, compared to ~~58.300~~ 59.600 hits for the term AVHRR, ~~10.800~~ 11.700 for SEVIRI, and ~~9.930~~ 11.700 for VIIRS (Date of access: 3 ~~August 2020~~March 2021)

C1.3: Page 4 around line 20: How well are the HRV band and other narrow bands spatially collocated, especially off the nadir region? For example, does a 3 x 3 km narrowband (e.g., 1.6 µm) pixel always contain 9 x 9 HRV pixels? If not, how are they collocated?

Thank you for pointing out this important aspect, which has in fact been addressed in a previous paper by Deneke and Roebeling (2011). From the results given in that paper, the collocation of the HRV and the narrow-band channels agrees quite well, with systematic and random shifts of about 0.36km/0.1km(East-West vs. North South) +/- 0.1km, respectively (e.g. less than 10% of the optical resolution of a low-resolution pixel size). We consider this collocation sufficiently accurate for our purposes, in particular well above the target requirement of 0.6 km specified by EUMETSAT. While that paper attempted a correction for the remaining shift, this correction has not been done in the present study (it should however be rather simple to implement this correction in our processing). We have added the following text to the manuscript to clarify this point.

transform (see Deneke and Roebeling, 2010, for details). The difference of the MTFs of the HRV and the $0.6\,\mu\mathrm{m}$ channel is also plotted in the figure. It is used in our method to extract the high spatial frequency component contained in the HRV channel observations which is not resolved by the lower-resolution channels, as is described in detail in Sec. 3.5 of the paper. ~~It should~~ The combination of this high frequency component with the narrowband channels relies on a sufficiently accurate channel co-registration. For the solar channels, the co-registration accuracy is specified to be better than $0.6\,\mathrm{km}$ by EUMETSAT (Schmetz et al., 2002). The results of Deneke and Roebeling (2010) suggest that the true accuracy is in fact significantly better, with a systematic and random magnitude of about $0.1\,\mathrm{km}$ and $0.3\,\mathrm{km}$, respectively, and effects of misalignment are neglected here. It should also be noted that the optical resolution of the SEVIRI channels is lower than their sampling resolution by a factor of about 1.6, which can be seen by the significant attenuation of the frequency response well below the Nyquist limit.

C1.4: It is mentioned in Section 3.1 that, the cloud mask from NWC SAF is used. What is the spatial resolution for this cloud mask? Then it is also mentioned that a HRV-based cloud mask is also used. How are the two cloud masks reconciled or combined?

Re-reading the manuscript based on this comment, it became evident to us that too little information is been given to fully understand this aspect, and we have revised the text to more clearly describe the approach. The NWCSAF cloud mask has a $3\text{x}3\text{km}^2$ resolution. The HRV-based mask is used subsequently to improve its resolution as a post-processing step, using a rule-based approach to combine the two outputs. The following 2 text sections have been change to better describe this approach:

1. At the start of Section 3:

neighbor (N.N.) interpolation is used for the cloud products and bilinear interpolation for the ancillary datasets. In addition, a high-resolution cloud masking algorithm is applied to the HRV channel reflectances, which has been introduced previously by Bley and Deneke (2013), and is used to improve the standard-resolution NWCSAF cloud mask in particular with respect to the occurence of small convective clouds as is described in Sec. 3.5. In the final step of the processing chain, these cloud

2. At the beginning of Sect. 3.5:

as coastal/shore. As the information content of the HRV channel for cloud masking is limited, a set of rules is used to combine the standard- and high-resolution cloud masks, considering blocks of 3×3 pixels, the HRV cloud mask and the NWCSAF cloud type. Semitransparent high clouds are frequently missed by the HRV cloud mask, and are thus labeled as cloudy based on the NWCSAF cloud type. The NWCSAF cloud mask does however frequently misclassify small clouds as cloud-free due to its coarser pixel resolution. Thus, pixels detected as cloudy by the HRV mask and as cloud-free by the NWCSAF mask are labeled as cloudy. The only exception to this rule are pixel blocks labeled as snow-covered land or sea-ice by the NWCSAF cloud type algorithm, which are expected to be highly reflective and are thus left unchanged.

C1.5: On page 11, it is a little disappointing to see that the new method does not improve the CER retrievals. Nevertheless, some results of CER retrieval (e.g., a scatter plot or histogram) should be shown here. It is hard to picture the difference between SEVIRI and MODIS based on the description between line ∼20 to ∼30.

We agree that this is finding is somewhat disappointing, but it is also not unexpected (note however the different expectation expressed by referee #2, C2.14). The spectral response of the HRV channel only covers wavelengths within the conservative scattering regime. Hence, from a physical point of view, it cannot add a remote-sensing-based constraint on the effective radius. Thus, any improvement would have to come from a cloud-physics based constraint linking COT/CER, such as the adiabatic cloud assumption (see also C1.6). We would also like to stress that the aspect of CER quality is discussed more exensively in WD20, and it is shown there that a naive approach can even reduce the accuracy of CER retrievals. For concrete changes also prompted by this comment, see the description of the revisions to Sec.4.1 given below, which addresses the difference in CER in more detail.

C1.6: Page 9 about LUT downscaling: There seems another way to do the downscaling, which is to assume the cloud effective radius remains invariant within the 3x3 km pixel. This seems to be easier than the slope-based Eq. (5). Can you comment on whether such method is feasible/practical or not and why?

This assumption would force reflectances from a 3x3 pixel box to lie exactly on a CER contour in a classical Nakajima-King-style plot. Note that our current implementation does treat each HRV-resolution pixel independently / lower-resolution channels are interpolated to the HRV grid, which does not allow an exact implementation of this contraint, as the standard resolution channel radiances might thus vary across a 3x3 HRV pixel block. Nevertheless, the suggested approach has been investigated as one candidate approach in the companion paper by WD20. While we expected this (or the approach based on sub-adiabatic theory, see also reply to C1.5) to perform well/maybe even better than the method chosen here, the evaluation in WD20 showed otherwise. This finding is summarized by the following quote from WD20: "It is also an indication that assuming constant subpixel r_{eff} values within each LRES pixel is not sufficient." To explain better that this and other approaches have been tested in WD20, and that the approach used is the one which has been found to perform best, we have revised the text as follows:

> ~~While it is simplest~~ The simplest approach to implement the cloud retrievals ~~based on~~ is the assumption that $\delta r_{16} = 0$, i.e., that the high-frequency residual of the ~~absorbing~~ SWIR channel reflectance can be neglected~~, this assumption has been found~~. This assumption has however been observed to cause a ~~degraded~~ reduced accuracy of the ~~retrieved effective radius even~~ effective radius in comparison to the standard resolution retrievals (see Werner and Deneke (2020) and the discussion in Sec. 4.1). Two other candidate approaches were considered in this study but found to be sub-optimal: the assumption of an adiabatic cloud, and that the effective radius remains constant within a 3×3 pixel neighbourhood.
>
> [Figure 4 about here.]
>
> Instead, the ~~retrieval has been modified to determine~~ approach determined to be most accurate by Werner and Deneke (2020) is used here: it determines the high-frequency residual $\delta r_{16} = 0$ based on the tangent of the τ-contour at the location of the standard-resolution reflectances in the Nakajima-King diagram (referred to as lookup-table approach with slope adjustment in Werner and Deneke (2020)). Mathematically, this can be expressed as the slope of the τ-contour at the point $\mathcal{F}(\tilde{\tau}, \tilde{r}_e)$, or

C1.7: In addition to correlation, some more statistics should be added and discussed here, e.g., whether there is any systematic bias in CER? How about the extreme values?

See our description of the revisions to Sec.4.1 given below, which addresses this point.

C1.8: One aspect missing in the discussion of COT and CER retrievals is about failed retrievals. As shown in Cho et al. 2015, MODIS retrievals frequently fail in broken cloud regions and/or at special angles (low sun, sunglint etc). Does the SEVIRI retrieval product also suffer from failed retrieval problems? If so, whether and how does the HRV

alleviate the problems? Some discussions here would make the paper more interesting and useful.
See our description of the revisions to Sec.4.1 given below, which now also addresses this point.

Revision of Sec.4.1: Based on comments C1.5 , C1.7, C1.8 by referee #1, as well as comments C2.3, C2.7, C2.10, C2.11 by referee #2, we have decided to substantially revise the presentation of Sec.4.1, with the following objectives:

- Add a description of the observing and sun geometries, including the true MODIS spatial resolution
- Discuss discrepancies in retrieval assumptions/conditions by MODIS/CPP, in particular including the width of the cloud drop size distribution and its relevance close to the cloud bow
- Mention the frequency of retrieval failures in both MODIS and CPP retrievals
- More detailed discussion of the accuracy of CER, which is known to be limited for such types of cloud fields, and point out the limitations of a comparison based on a single scene.
- Added an RGB image as 4th panel of the scene to Fig.5
- Revised Fig.6 to use separate panels/also show MODIS partially cloud retrievals
- Remove the erroneous interpretation of Fig.6 that SEVIRI retrieves too few optically thin clouds

The revised sub-section 4.1 is appended to this reply.

4.1 Shallow Convective Clouds

[Figure 5 about here.]

[Figure 6 about here.]

The main motivation for the development of the HRV-based cloud retrieval scheme has been the expectation that the increase in spatial resolution will lead to more accurate cloud retrievals, and will bring the instrumental capabilities of SEVIRI closer to those of MODIS. Improvements are expected to be significant in particular for shallow convective clouds due to their comparatively small size and their large spatio-temporal variability.

To verify this aspect, a shallow convective cloud field is considered here, and retrieval results are contrasted to those obtained from collocated MODIS observations. A scene viewed by the MODIS instrument flown aboard the Terra Earth observing satellite on 2 June 2013 at 10:50Z over North-Eastern France has been selected for this purpose. The choice of observations from Terra allows the consistent use of MODIS retrievals based on the 1.6 μm channel for comparison with SEVIRI, as this channel of the MODIS instrument is affected by defective detectors on Aqua. While the satellite zenith angle of SEVIRI is about 55.6°, the MODIS zenith angle is close to the nadir direction (2.7°), which implies that the true pixel size is also close to the nominal spatial resolution of MODIS ($1006 \times 1007\,\mathrm{m}^2$). The scattering angles have values of about 155° and 150° for MODIS and SEVIRI, respectively.

The MOD06 cloud properties from the collection 6.1 release are used here ~~, and retrieval results for fully overcast and partially cloudy pixels have been combined. It should be realized that in contrast to the results~~ for comparison (Platnick et al., 2017) . It has to be pointed out that this comparison differs from that presented in Werner and Deneke (2020), ~~products from two inependent~~ where MODIS reflectances have been re-projected to the SEVIRI standard- and HRV-resolution grids first, and then used as input to the CPP retrieval. In contrast, cloud products obtained from two independent retrievals and two different instruments are compared ~~, thus~~ here. Hence, besides differences caused by the spatial resolution, the comparison is also affected by temporal changes due to the mismatch in observation times about one minute, by the different observation geometries, and differences in the assumptions underlying both retrievals. Such assumptions include the width of the cloud droplet size distribution, which have values of 0.15 and 0.1 in the CPP and MODIS retrievals, respectively (Benas et al., 2019). A scene with scattering angles outside the cloud bow and cloud glory has been selected to minimize this sensitivity. The reflectances observed by SEVIRI will also include a significant contribution from cloud sides due to the large satellite viewing angle, while the nadir view of MODIS implies that reflected radiation mainly originates from the cloud tops. Retrieval results will also depend on the assumed values of surface reflectance. Thus, deviations are expected to be substantially larger than the ~~results presented in that study.~~ differences reported in Werner and Deneke (2020).

Fig. 5 shows the fields of τ obtained for the example scene provided by MODIS, and both the standard and improved HRV-based SEVIRI retrievals together with the day-natural color RGB rendering of the MODIS reflectances (Lensky and Rosenfeld, 2008) . SEVIRI data has been re-projected to the MODIS grid using nearest-neighbour interpolation, and a translation has been applied to account for parallax shift and cloud motion in combination with ~~a~~ the mismatch in observation time~~of about one minute~~. This translation has been determined by maximizing the cross-correlation of both τ-fields, and results in a shift of the

SEVIRI data by about 2.6 km and 0.4 km in North and East directions, respectively. While 83.8 % of the pixels are classified as probably or likely cloudy by the MODIS cloud mask, τ-retrievals are reported for 72.4 % of the pixels (43.6 and 28.8 % in the Cloud_Optical_Thickness_16 and Cloud_Optical_Thickness_16_PCL datasets, respectively), with a remaining 11.3 % of pixels without a valid retrievals. In case of the SEVIRI-based CPP retrievals, the quality flags showed that for 44.8 % and 33.3 % of the pixels for standard- and high-resolution retrievals, convergence could only be achieved for the 0.6 μm reflectance, and the observed 1.6 μm reflectance exceeded the range of values of the LUT, indicating in particular that the use of the HRV channel improves the fraction of pixels with high-quality retrievals.

It is clearly ~~evident~~ visible that the increased spatial resolution obtained by using the HRV channel in the retrieval helps to better resolve the small-scale structure of this cloud field. This visual impression is confirmed quantitatively by a significantly higher correlation coefficient of about 0.78 found for the HRV-based τ~~field~~ -field and the corresponding MODIS C6.1 product, compared to a value of 0.47 obtained for the standard-resolution retrieval results.

Both fully overcast and partially cloudy retrieval results have been included in the calculation. Fig. 6 shows the corresponding histograms of the derived τ using logarithmic bin spacing for this scene. The standard-resolution SEVIRI retrieval exhibits the narrowest distribution of values, with too few optically thin and thick clouds compared to the MODIS product. While the HRV-based SEVIRI retrieval still yields fewer optically thick clouds than MODIS, it reports a similar amount of optically thin clouds, and is able to better reproduce the dynamic range of the MODIS product than the standard-resolution retrieval scheme. For the standard retrieval, the maximum value of retrieved τ is only 16.5, while values of 40.3 and 61.8 are observed for the SEVIRI HRV-based and MODIS products, respectively. A likely explanation for the remaining underestimation of cloud optical depth is the oblique viewing angle of Meteosat over Europe, which increases the pixel size in North-South direction by a factor of about ~~2, in combination with the lower~~ 2. Combined with the optical resolution of SEVIRI, ~~and limits the maximum τ for the HRV-based retrieval below that of MODIS. The HRV-based retrieval also reports a significantly larger number of optically thin clouds compared to MODIS~~which is lower than the sample resolution by a factor of 1.6, this results in a 5-fold larger pixel area despite a nominally equal nadir sampling resolution. While it is beyond the scope of ~~this~~ the present article to fully resolve and explain the remaining discrepancies, they are likely due to the combined effects of differences in retrieval algorithms, sensor calibration, pixel resolution and/or viewing geometry. ~~In particular, the MODIS processing scheme has a rather strict quality control, which might be responsible for the fact that no values are being reported for these rather optically thin clouds, despite our choice to also include MODIS results for partially cloudy pixels.~~

It should be noted that for solar energy applications, the correct representation of τ-values at and below a value of 5 is highly relevant, as such values will result in non-zero direct irradiance. While rejecting such retrieval results in the cloud retrieval scheme due to their large uncertainties will most likely improve the τ-retrieval accuracy itself, it will cause a subsequent overestimate of SSI if these pixels are assumed to be cloud-free. Both global and direct irradiance components will be affected, but errors will be most pronounced for the direct irradiance and the direct-diffuse ratio, parameters which are critical for the calculation of the tilted irradiance, e.g., on the plane of a photovoltaic module or the focal plane of a concentrating solar power plant.

~~For the effective radius~~Broken and inhomogeneous cloud fields such as the considered scene are known to be particularly problematic for the accuracy of the retrieved effective radius (Marshak et al., 2006; Wolters et al., 2010), and the following results should be interpreted with caution. For a meaningful comparison, only pixels with $\tau > 8$ in all compared datasets and high-quality retrieval results have been considered (full convergence of CPP retrievals, no partially cloudy retrievals from MODIS). These criteria are fulfilled for only 21.5 % of the pixels. Mean values of 8.2, ~~no significant improvement is found resulting from the use of the HRV channel in the retrieval , and correlations between SEVIRI and MODISresults are relatively low for this scene. Restricting the comparison to pixelswith τ exceeding a limit of 6 for both MODIS and SEVIRI to ensure reliable effective radius retrievals,~~ 7.7 and 7.3 μm are found for MODIS and the standard- and high-resolution effective radii retrievals, respectively. The correlations between MODIS- and SEVIRI-based effective radii are much lower than those for optical depth, and only a slight improvement is found from the use of the HRV channel for the retrieval, with Pearson correlation coefficients of 0.43 and ~~0.42 are found~~ 0.39 for the HRV and standard-resolution effective radius results, respectively. The reader is reminded ~~here~~ that a similar magnitude of the correlation is expected, as the retrieval constraint for the 1.6 μm channel ensures that the effective radius is close to that of the standard-resolution retrieval~~in the iterative algorithm. In consequence,~~. This is confirmed by a comparatively high correlation coefficient of ~~0.85 is found between the two SEVIRI retrievals~~ 0.88 between the SEVIRI results at the different spatial resolutions. A modification of the retrieval to only use ~~the~~ a smoothly interpolated value of the 1.6 μm reflectance instead results in a ~~sharp reduction of~~ slightly negative value of -0.04 for the correlation of the high-resolution ~~retrieval results with the~~ effective radius retrieval with MODIS r_e~~to a negative value of -0.05~~. This finding emphasizes that despite the seemingly low values of correlation for r_e ~~found~~ reported above, the choice of the retrieval constraint is important to ensure that the accuracy of the standard-resolution r_e is not degraded by use of the HRV channel.

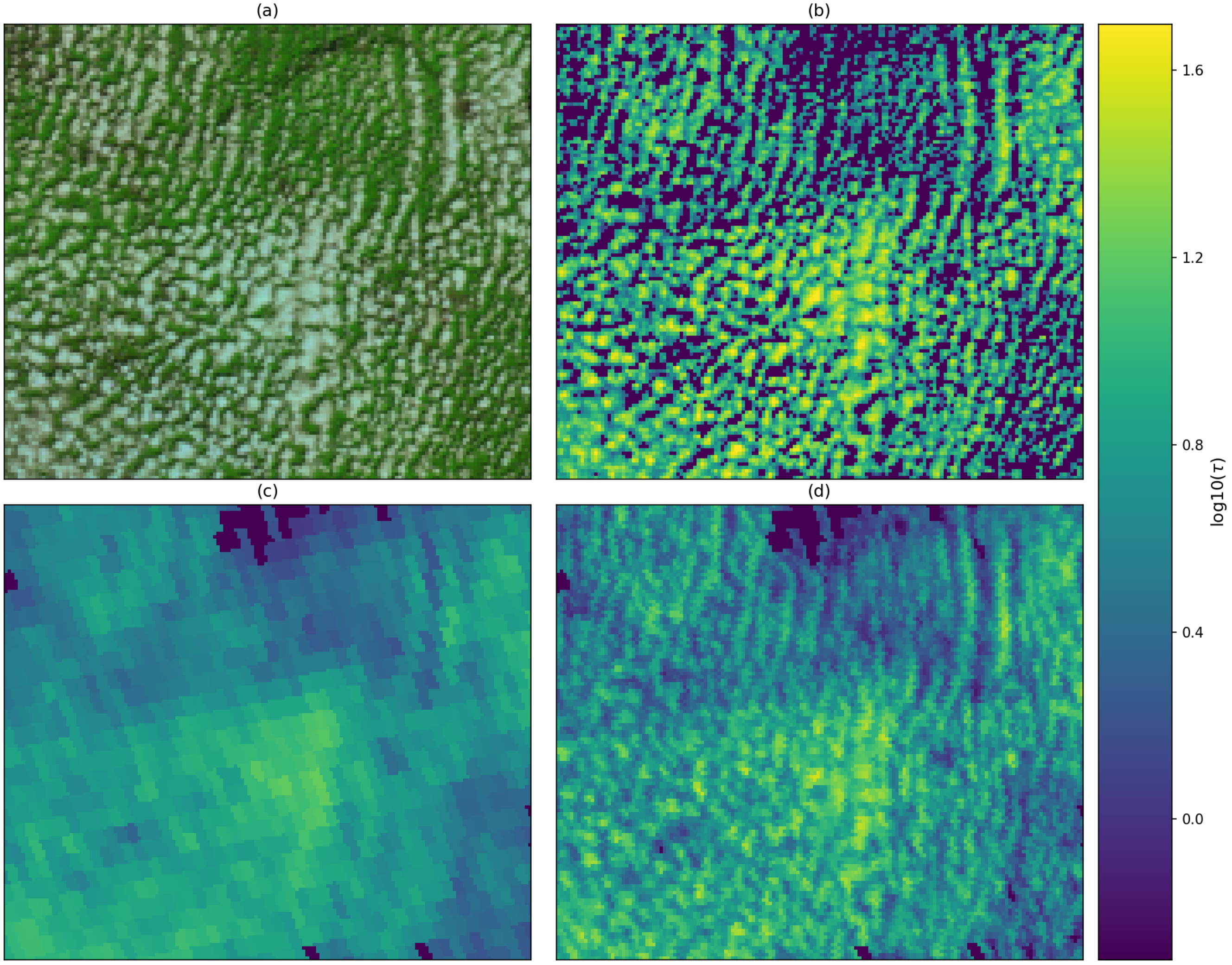

Figure 5. ~~Cloud optical depth (τ) of a shallow~~ Shallow convective cloud field observed over North-Eastern France at $3°25'$ E and $48°7'$ N ~~,~~ on 2 June 2013 at 10:50Z. ~~A logarithmic~~ MODIS reflectances are displayed as day-natural color ~~scale is used. Values~~ RGB composite in (a), and retrieved values of cloud optical depth (τ) are shown for the operational Terra MODIS C6.1 retrieval (~~a~~b), the improved Meteosat SEVIRI retrieval (~~b~~c), and the standard-resolution Meteosat SEVIRI retrieval (~~c~~d) using a logarithmic color scale.

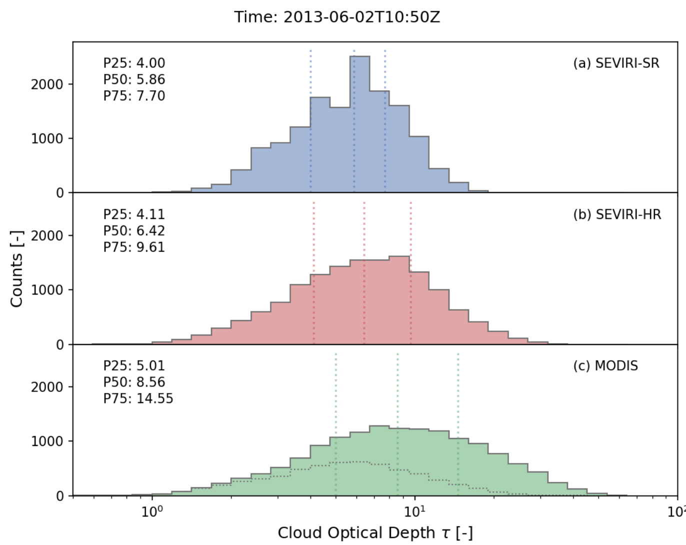

Figure 6. ~~Histogram~~ Histograms of cloud optical depth (τ) using logarithmic bin spacing, for the cloud field displayed in Fig. 5. Values are shown for the ~~Terra MODIS C6.1 retrievals~~ standard-resolution SEVIRI retrieval (~~MODIS~~a, ~~green color~~blue), the improved HRV-resolution Meteosat SEVIRI retrieval (~~SEVIRI-HR~~b, red~~color~~), and for the ~~standard-resolution SEVIRI retrieval~~ Terra MODIS C6.1 retrievals (~~SEVIRI-SR~~c, ~~blue color~~red). The contribution of partially cloudy pixels to the MODIS histogram is indicated by a dotted line. Also, for each histogram, the values of the 25th, 50th and 75th percentile are shown as dotted line listed numerically.