

Response to the referees

Thank you very much for the large number of comments and constructive suggestions!
Please find below the answers to the comments of the reviewers in blue text. The technical corrections that were included are commented with [done] for simplicity.

Anonymous Referee #1

Major comments

1) The TCWV correction algorithm is described in Sect. 4. It uses ground-based MWR data in order to derive a correction for the TMWV retrieval from MODIS. The same MWR data, however, is used to "validate" the algorithm results in Section 5. I do not believe this is appropriate because independent data is needed to provide a meaningful assessment of the algorithm output. Hence, the "validation" exercise using MWR data should be removed and/or replaced.

We generally agree in this point and added another independent source of ground-based measurement (AERONET sun photometer measurements). Still, we think that it is necessary to show that the empirical correction in the forward model is working and that there is no bias left in comparison with the data-set used for the determination of the correction (maybe introduced to other influences).

Furthermore, calling this an "extensive" validation is not justified. Calling it a "comparison" would be more appropriate. In order to solve this issue and to improve the manuscript, the authors may consider to include further datasets into their study. For example, algorithms from many different satellite sensors are mentioned in the introduction. Many of their results are freely accessible or accessible upon request. Why not inter-comparing the results from the new TCWV retrieval from MODIS with those? This information would be of high value for the reader.

See Comment 3)

We agree that the word "extensive" is probably misleading and deleted it. We included it initially because we took more than just one data-set. Additionally the data-sets are from global distributed stations. Comparisons to other (space-borne) data-sets will be done in later studies, when the whole MODIS time-line is processed.

Furthermore, the MODIS algorithm is proposed as a "gap filler" (page 7771, line 26) after MERIS died. What I miss in the manuscript is a showcase that the proposed is indeed feasible. I would like to ask the authors to consider including a comparison of their data with MERIS data from Lindstrot et al., 2012, which should be fairly easy to obtain. The readers should at least know, when this will be done or that it at least should be done.

See Comment 3)

2) The manuscript mentions a cloud filter at several places. The only information I could find about this filter algorithm is "only [...] 100

Included in Section 5:

"We used the cloud-mask from the MOD05-L2-data which was extracted from the MOD35-L2-product. Only pixels with bit-value "100% clear" were used for our study."

3) This paper describes the retrieval of MODIS TCWV and, apparently, at least the entire Aqua data-set has been processed to perform the "validation". Now you have this excellent data set, why not show it? Satellite measurements are a lot about imaging and I found it puzzling that there is not a single map included. Please consider including TCWV maps, e.g. showing - a single orbit from MODIS Terra besides a MERIS orbit, -a monthly average, or - averages of the surroundings of the

three ARM sites used for determining the correction.

Unfortunately we did not process the whole data-set yet. We just processed the area around the ground-based stations that were used for validation. Currently, the processing is being prepared. Nevertheless, we included a comparison of a sample track of MODIS and the corresponding MERIS over-path in an extra paragraph in the validation section:

"Figure * shows the comparison of TCWV derived from MODIS and MERIS Lindstrot et al., 2012 on a regular grid of 0.05° resolution. Each data-point is the mean of all valid corresponding sensor pixels. In the left panel, the MODIS over-path over Europe and northern Africa for the 2 July 2008 (09:32 - 09:49 UTC) is presented. On the right side plot, the corresponding MERIS over-path is shown (09:42 - 09:59 UTC). In the middle panel the difference between both fields is plotted (MERIS minus MODIS). Only pixel with a valid MERIS and MODIS TCWV value were taken into account.

Generally, MERIS has a smaller swath (1150 km) and it just covers the west side of the MODIS track. The structures in the TCWV field agree with each other although the location of cloudy pixels is different.

However, there are significant differences. MERIS TCWV is systematically higher than MODIS (1 to 3 mm apart from a small region above the Sahara. Lindstrot et al., 2012 discovered a small wet bias in comparison to ground-based TCWV measurements. Whether this or an error in the MODIS retrieval explains the differences will be envisaged in future studies. Up to now the comparison to ground-based measurements suggests that the MODIS retrieval is not the reason. Furthermore, along-track stripes appear in the difference plot. These features are due to the architecture of the MERIS instrument. It is built out of 5 individual cameras that have slightly different spectroscopic properties. The central wavelengths of the MERIS channels are viewing angle-dependent. The later indicates that there is still some improvement possible in the MERIS retrieval as well. "

4) Again on the "validation". in lines 17f on page 7769 it is stated: "Additionally, all outliers (deviation > 3) were rejected." I wonder whether applying this filter is actually required. If it is necessary, please explain how it works and why it is really, really necessary. I would prefer including all data in order to increase the significance of the comparison. I believe it is very dangerous to compute correlations using filtered data.

We agree with that point. Initially, that filter was added in order to remove the cases that are still contaminated by clouds (uncertain cloudmask). Consequently, we removed the 3 sigma filter from the whole study. It turned out that it has hardly any influence, probably due to the reliable MODIS-cloud-mask.

removed sentence:

"Additionally, all outliers (deviation >3 sigma) were rejected."

Minor comments

Generally, the verb "see" may always be removed in links: "(see Sect. 3.4)" -> "(Sect.3.4)"
Everybody knows, what to do with references. Please avoid clutter.

[done]

page 7754:

line 5: "at spatial" -> "at a spatial" line 7: "introducing correction" -> "introducing empirical correction" line 8: "that a" -> "that, a" line 9: What is an "extensive" validation versus a not extensive one. See comment above. line 22: Delete "hile on short time scales, w" or rephrase.

page 7755:

line 7: "over land is" -> "over land, however, is" line 8: "However, t" -> "T" line 9ff:

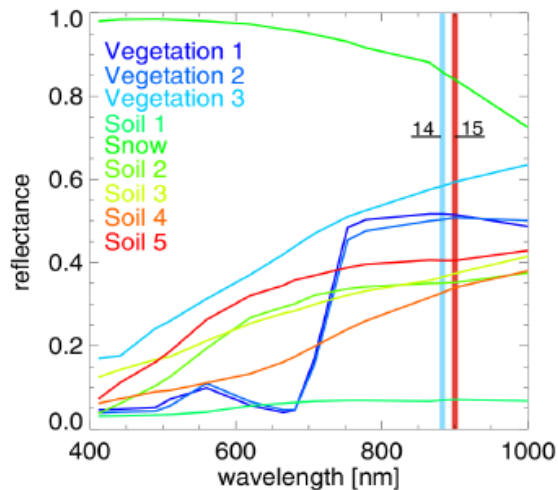
[done]

Please include some further references, at least[.]

[done]

line 12: What do you mean with "very" suitable? line 13: "all surface types are sufficiently bright" -> the surface brightness only weakly depends on surface type

Actually the surface brightness in the 900 nm region highly depends on the surface type as you see in the Figure below:



From: Leinweber, R., 2010: Remote sensing of atmospheric water vapor overland areas using MERIS measurements and application to numerical weather prediction model validation. Ph.D. thesis, Institute for Space Science, FU Berlin.

line 13:

delete " in this spectral interval" line 14: let "Lindstrot et al. (2012) introduced a procedure" begin a new paragraph line 15: delete "extensive" line 17: Is the other band literally without "any" absorption? Is there the possibility of interference? Please specify! line 22: insert "applying MERIS measurements" after "time series"

[done]

line 28: Give figures/reasons why "the accuracy of this product" is limited! For which applications would it be sufficient?

We provide a validation against MWR, GNSS, (and now additionally AERONET) ground-based measurements in this paragraph (Figure 1).

page 7756:

line 5: Please specify, why an overestimation is unsatisfactory when investigating trends. In principle, a constant offset does not change the derivative.

As you can see in Figure 1 it is not a constant offset it is rather a relative error (slope of the plotted line: 1.15 -1.16). It indicates that there is something going wrong in the operational MODIS TCWV retrieval. When analyzing trends you can not tell whether it is true or just due to an error in the retrieval (e.g. not accounting for aerosols could introduce a trend when the AOD is changing in a special area)

line 10: "in comparison" -> "compared" line 21: "pixel by pixel" -> "pixel-by-pixel" to be consistent with the rest of the text line 23: "However, an empirical factor accounting for ... is needed."

[done]

page 7757:

line 4: Is global coverage gained in one or two days? On what does this depend upon? line 14 move "in band 18" between "pronounced" and "and"

page 7758:

line 7: What is a "good" background? Please provide a reference. line 12f: "approximated as (simplified form) :" -> "simplified to:" line 16: use abbreviation: "top-of-atmosphere solar flux" -> "TOA solar flux" line 23: What is the exact meaning of "air mass"? Please specify its definition (there are several "air masses") and why it is dimensionless. line 25: insert "a" after "of"

page 7759:

line 7: "actual" Specify, that the surface temperature needs to be inferred from a meteorological model. line 18: insert "only by water vapour" after "pure absorption" to specify "pure" line 21: "f is increased" -> "f increases"

[done]

page 7760:

line 3: insert "without H2O absorption" after bands. to specify "window" line 7: Please specify, why the "secant method" is no longer applicable. line 12: How was this issue solved by Lindstrot et al, 2012? The list is intended to describe the differences. Line 12: Is this an improvement? line 20ff: Please provide already defined symbols yet again in order to improve readability of formula (4).

[done]

line 23: How is the simulation of T noscat performed anyway? What model is used to calculate the LUTs?

This part was omitted in order to remove redundancies with the reference of Lindstrot et al., 2012 (claimed by the quick-reviews). Nevertheless, that sentence has been extended:

"The pure absorption part of the simulated transmittance T_{noscat} is derived from pre-calculated absorption coefficients using an advanced k-distribution method (Bennartz et al., 2000). The coefficients are calculated from the HITRAN2008 line database (Rothman et al., 2010) using the AER LBLRTM code (Clough et al., 2005). The optical depth values are stored in look-up tables on 27 different pressure levels for 6 standard profiles McClatchey1972."

Is the choice of atmospheric parameters sufficient? Is the number of simulated atmospheric conditioned justified? Please give more details here! Nobody will be able to reproduce your results otherwise.

page 7761:

line 2: How is the interpolation in the LUTs performed? Is it linear? Is the method sufficient?

Here again we want to refer to Lindstrot et al., (2012). The referees of the quick-reviews demanded to omit redundant parts of the description of the forward model.

line 4: "highly" -> "sufficiently" line 7: Why not taking the surface pressure from ECMWF as well? It may also be possible to infer the surface pressure on the more detailed GTOPO30 model using our knowledge on adiabatic expansion. If not, please explain why different sources are used for the different surface meteorology parameters.

As stated in the text, we use GTOPO30 for that purpose. The spatial resolution of ECMWF is not sufficient for a pixel size of 1 x 1 km.

line 15: insert "," after values

page 7762:

line 6ff: Please provide enumerated formulas. line 14f: Please define, what "ci" are and in which

formula they appear. Please be more specific.

[done]

page 7763:

line 15: erase "-" before optical, or replace it by "aerosol" line 19: Please justify the parameters of the default aerosol profile chosen. How does it look like? What is the presumed phase function?

Inserted in Section 3.1:

"The scattering correction factor f has been calculated beforehand from radiative transfer simulations and stored in look-up tables presuming a continental aerosol layer (Hess et al., 1998) with an exponential increase from 1000 m to the bottom.

...

The phase functions were calculated with the Mie code based on (Wiscombe, 1980). "

Inserted in this Part:

"Consequently, f^* was calculated presuming an aerosol layer at 6000 m with a thickness of 500 m.

page 7764:

line 7: insert ", " after "Finally"

page 7765:

line 6: insert plural "s" after "author" line 11: Please provide citation/URL of the DWD archive.

Unfortunately, we can not provide a citation or an URL as it was distributed internally.

page 7766:

line 14: "has a built-in so-called" -> "features a"

page 7767:

line 2: omit " the following" line 3ff: Maybe use an enumerated list to improve readability of the outcomes. line 5: "Additionally" will be obsolete, then.

[done]

line 16f: The sentence starting with "Here, ..." is unclear. Please rephrase and be more specific.

Inserted before:

"..as a function of the considered central wavelength for each of the 10 detectors of the three absorption bands (represented by 10 black graphs)."

Changed to:

"Here, one detector drops out significantly."

line 22: What is "fairly constant"? Is it "sufficiently constant"? What would "sufficient" then be?

We changed it to "sufficient constant" . It is sufficient constant because it is in a sufficient bright range with a small difference of just 0.1.

page 7768:

line 1: "not shown here" -> Why?

It is hard to illustrate as it is only the maximum of the difference between simulated TOA radiances presuming two different aerosol models.

line 16: omit "beforehand" line 16: "optimizing" → How is the optimization performed? What is the cost function? I presume minimisation taking place?

Yes, you are right. We omitted a description of the way of optimization to achieve readability.

page 7769:

line 1: omit "separately" after "done" line 1: "separately." -> ", respectively" line 2: "Table" -> "Tables" line 2: "5 and 6" -> "5 and 6 for Aqua and Terra instruments, respectively."

[done]

line 13: What kind of cloud data is used? What are the thresholds? Please specify.

Inserted Text:

"The cloud-mask from the MOD05-L2-data was used, which was extracted from the MOD35-L2-product. Only pixels with bit-value "100% clear" were used for our study. "

line 16: "limited accuracy of the MODIS geolocation" -> What is the accuracy? Why is it a limitation? It is certainly better than 20km.

The accuracy of the MODIS geolocation strongly depends on the scanning angle. <http://www.sat.dundee.ac.uk/modis-faq.html> stated that it is around 250m. You are right, this is not a real limitation. It is rather one reason not to just take the corresponding pixel but to calculate a mean over the surrounding area.

line 21: "Section." -> "Sect."

page 7770:

line 5: "of" -> probably "less than" line 9: How large is the number of samples? The text only states "very" high which is not very satisfactory.

Please see the plots for the number of points.

line 16ff: "In order to account for cloud contamination but also preserve a sufficient high number of data-points, only cases with less than 50 line 23: "constancy" -> "temporal consistency"

page 7771:

line 2f: "Whereas the bias between GNSS and and MODIS is shifted to negative values (meaning that MODIS values are generally higher than GNSS)." -> "Whereas, MODIS values are generally higher than GNSS."

[done]

line 5f: Why is the std. dev. so high? How high is it? Can you provide an upper limit for the maximum amplitude?

For more clarity we switched to Boxplots and added this text to the paragraph:

"The annual absolute difference between MWR and MODIS (upper panel) is less than 1 mm for both Aqua and Terra and constant over the years taking into account the scattering represented by the boxes, containing 50% of the values and the whiskers containing 75% of the values. Due to the low number of coincidences, the number of cases per year ranges between 50 and 150. The GNSS data-set provides 10 times more cases (lower panel). Considering the large variance there is no annual dependency in comparison to GNSS values, although the medians tend to be below zero which is consistent with the negative bias in the scatter plot in Fig. *.

The large area of the whiskers and the large number of outliers in the GNSS data is presumably due to the following. There are some sources of error in the retrieval of water vapour from GNSS measurements such as measurement errors, uncertainties in the mapping functions, errors due to the assumption of a mean temperature, etc. (Wang et al., 2007). These result in deviations that can vary even during one day."

line 10: "which"-> "whose" line 11f: "the surface reflectance, transmittance due to atmospheric

water vapour and the shortening" -> "(1) the surface reflectance, (2) the transmittance due to atmospheric water vapour, and (3) the shortening." line 13f: "where measurement- and forward-model-uncertainties are considered." -> "where the uncertainties of measurement and forward-model are considered, respectively."

[done]

Furthermore, please extend the summary and outlook: - Compare to operational MODIS TCWV validation. Please discuss!

The comparison to the operational MODIS retrieval is implemently done by comparing both to ground-based measurements. A comparison of TCWV fields of both retrievals the same as the scatterplots: The operational retrieval overestimates the TCWV of around 15 %. This was omitted because of the lack of additional information.

What about the retrievals in other spectral ranges mentioned in the introduction? Please discuss: accuracy, precision, differences, advantages and disadvantages!

Thank you for that suggestion! This is goint to be done in the near future when more TCWV data will be processed.

Added text:

"A first comparison to MERIS reveals a systematic difference that needs more investigation. L3-data processing and comparison to other space-borne measurements will benefit further studies of the performance of this retrieval."

Figure (pages 7782 to 7792): Figures 1, 4, 6, 7, and 10 are black and white. It would be nice to switch to colors and provide a colorbar.

page 7786:

Figure 5: It is hard to make out any information. Why not copy the style of Figures 4, 6, and 10? Please improve the readability of this plot!

page 7792:

Figure 11: Please improve the readability of this plot. The caption is confussing and needs to be rephrased. Please also increase the contrast, preferably with colors stronger than just black and blue. Another option would be, to use whiskers to better illustrate the statistical dimension of the displayed data

[done]