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Discussions

Interactive comment on "Validation of SCIAMACHY O$_2$ A band cloud heights using Cloudnet radar/lidar measurements" *by* P. Wang and P. Stammes

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Reply to referee 1

We would like to thank referee 1 for the helpful suggestions and comments. The paper is revised and more explanations are added in the results and methodology sections. New simulations about the SCIAMACHY FRESCO cloud height retrievals at different cloud optical thicknesses and heights are performed and one new figure (Fig. 2) is added. The quality of the figures are improved. We have answered all the questions and revised the paper according to the comments and suggestions. The revised texts

are in blue color in the paper. The answers of the questions are started with a 'A:'.

Anonymous Referee 1 Received and published: 27 November 2013 General comments This paper reports on the comparison between two satellite cloud height retrieval algorithms and ground-based measurements. Satellite input data comprises cloud height data products based on SCIAMACHY measurements and the SACURA and FRESCO algorithms, respectively. Both are compared to ground-based lidar profiles inferred from measurements at Cabauw and Lindenberg. The scope and content of the paper matches those of AMT and the paper is therefore recommended for publication. The paper is well structured and the language may be easily understood by non-native speakers like me. The selection of plots is appropriate to illustrate this difficult matter. In my opinion, however, especially the discussion of both the methodology and results requires thorough revision.

Specific comments 1) In the abstract (p.8604, l.8), the Authors claim that their method to collocate satellite and ground-based measurement achieves "an optimal temporal and spatial match". In the entire manuscript, it is never discussed, why the selection scheme chosen (ranges plusminus 1h the satellite overpass time) should be optimal. Merging data is never trivial. The parameters for the applied merging scheme appears arbitrary and the influence of their choice is not discussed. From a technical paper like the one presented, I expect an appropriate discussion of the involved parameters. How do the results change when, e.g., the time window for averaging the lidar measurements is modified. Is there a flag indicating how representative a point measurement is for the entire SCIAMACHY pixel? What if the SCIAMACHY pixel just scratches Cabauw/Lindenberg? I am confident that a discussion of this matter would strengthen the paper. The discussion may be added to Section 3.

A: We have revised the sentences about the collocation of the satellite and ground-based data in section 3. We do not intend to study the optimal method for the collocation but rather using some selection criteria from the literature. The mean time of the ground-based radar/lidar data is within +/- 30 minutes of the SCIAMACHY overpass

time. Assuming the wind speed is 10 m/s, the clouds can move 36 km in an hour which is about the pixel size of SCIAMACHY (30 x 60 km). The mean distance between the center of the SCIAMACHY pixels and the Cloudnet sites is about 17 km. It is possible in some cases that the Cabauw or Lindenberg sites are at the edge of the SCIAMACHY pixel but most of the cases would have a reasonable collocation.

2) The essential results of this study are the deviations of FRESCO/SACURA compared to Cloudnet cloud profiles. The figures for this deviation given in the abstract are (0.44 ± 2.07) km (p.8604, l. 13-14) and (-0.14 ± 1.88) km (l. 16-17). I do not believe it is serious to give more than one significant decimal in this context. Apparently, the deviations between the satellite measurement and ground-based measurement are not significant at all since they agree much better than 1 sigma. Please

A: The SACURA algorithm claims that the error is 0.25 km for full convergence, which is two decimals, therefore we used two decimals in the abstract. The deviation is not significant for all the clouds, because the positive and negative biases cancel. The Cloudnet cloud top height covers the range from 0.5 to 15 km, it is too coarse to use one mean value for all clouds. The comparison for the cloud heights in 1-km bins gives more insight into the cloud height differences. The abstract has been revised.

3) In the introduction it is stated "It is a challenge to retrieve cloud information from SCIAMACHY because of its large pixel size." (p. 8605, l. 6-8) There are algorithms taking advantage of the increased spatial resolution of the PMDs, like OCRA and HICRU for instance. Algorithms using PMDs are not mentioned before p.8610. Please discuss.

A: A discussion of the PMD algorithm (OCRA) is added in the introduction. Please note that OCRA and HICRU retrieve only effective cloud fraction from the PMDs but not cloud height. HICRU retrieves cloud height from the O_2 B band spectrum (at about 630 nm) which has the same ground pixel size as the O_2 A band.

4) Please discuss the advantage of using ground-based lidar measurements to "val-

idate"satellite cloud products. I expect satellite measurements (e.g. CALIOP) to be much better suited. These match the SCIAMACHY observation much better in coverage and resolution. Especially for thick clouds, satellite observations will be better suited to detect the upper boundary of the cloud.

A: We agree with referee 1 that it would be better to compare SCIAMACHY cloud height with lidar and radar measurements from satellites. However, CALIOP and Cloudsat have an overpass time at about 13:30 LT, which is 3.5 hours later than SCIAMACHY. It is difficult to find CALIOP/Cloudsat and SCIAMACHY measurements at similar time and location.

5) Cloud heights retrieved from satellite are compared to ground-based lidar observations. I have the following concerns regarding the ground-based measurements applied which should, in my opinion, be discussed in the paper. a) What is the maximum cloud optical thickness the applied lidar can measure? b) How do optically thick clouds influence the comparison between observations from the surface and from space? c) Please discuss whether a limitation of the maximum column optical thickness can result in a systematic bias towards lower clouds (both top and middle heights)? d) Is there a reason why only observations from Cabauw/Lindberg are included in this study? As far as I know, also the other Cloudnet sites feature lidars. e) In this paper, the authors demonstrate a possible yet sophisticated approach to compare satellite and groundbased cloud data. The discussion towards a global perspective is based on satellite observations alone. What about extending this study using ground-based lidar observations also from other regions on the globe. This would strengthen the claim of validating satellite cloud products in this paper.

A: We have clarified in sect. 2.3 that the comparison is performed with the ground-based Cloudnet cloud classification product which is derived from both lidar and radar measurements.

a) As referee 1 has pointed out, the lidar measurements can be easily blocked by

optically thick clouds. The maximum cloud optical thickness that can be measured by lidar is 2–3. For optically thick clouds, the cloud height is derived from the radar measurements.

b) According to simulations (Fig. 2 in the revised paper) and references, the SCIA-MACHY cloud height should be more close to the cloud top height for optically thick clouds. We expect that the SCIAMACHY and radar measured cloud top height will have better agreement for optically thick clouds. If the cloud optical thickness is very thick, say > 100, the ground-based radar signal may not reach the cloud top; however, this is rather unusual at Cabauw and Lindenberg.

c) The cloud top heights of optically thick clouds are determined from radar measurements. The Cloudnet radar can measure up to 15 km, usually, the radar will not miss the optically thickness clouds. The optically thin clouds can be detected by the lidar. We do not think that in the selected cloud cases, the Cloudnet cloud top heights are limited by the optically thick clouds.

d) We choose Cabauw and Lindenberg because they cover a longer time period and have less missing measurements (days) than other stations between 2002 and 2011. There are some Cloudnet target classification products from other stations but their data mainly start from 2011.

e) We are aware that there are lidar networks and radar networks in other regions and Cloudnet has more sites. Some SCIAMACHY validations have been done before using the ARM site lidar/radar measurements. We choose the Cloudnet product because we have not yet used the Cloudnet product for validation and we have better support from our colleagues who work on the Cloudnet data. The Cabauw and Lindenberg sites have the longest data records and least missing data. Because SCIAMACHY had an overpass over Cabauw or Lindenberg only every 6 days, with missing ground-based data, we would have less collocated data.

6) Why is it important that the ground-based measurements cover "the whole SCIA-

MACHY mission period" (p.8611, l.21)? What is the specific benefit? Now you have the data at hand, it would also be possible to study whether there are trends in the satellite cloud products from 2003 through 2011.

A: We agree that we could study the trends in the cloud product but it is not the aim of this paper. The aim of this paper is to evaluate the SCIAMACHY cloud height products, but not only the algorithms. Although the cloud algorithms do not change with time, some instrument features can occur (optical degradation, detector degradation), which will impact the retrieved products. For SCIAMACHY instrument degradation is a potential issue, therefore we would like to check the cloud height products in the whole mission period. We have revised the texts.

7) Please specify, how "pixels with out snow/ice on the surface"(p.8613, l.10-11) are identified.

A: The snow/ice pixels are determined using the flag in the FRESCO data. In FRESCO the snow/ice pixel is determined using the TOMS monthly climatological surface albedo map. The texts are revised.

8) On "More statistics of the comparison between SCIAMACHY cloud heights and Cloudnet cloud heights for multi-layer clouds is given in the Appendix in Tables A5-A8." p.(8619, l.17-19) Please specify, what the reader can expect from the tables in the Appendix. Otherwise he/she will be quite lost at this point. I suggest to either discuss the tables in an Appendix, provide a cross-reference in the captions of Figs. 7 and 11 to the respective data, or put both a description and the tables into a Supplement.

A: We added some discussions about how to use the tables. The values given in the tables are easier to read than from the figures. According to the tables, the readers/users can see the error of the SCIAMACHY cloud products for different cloud heights. Depending on the application, the users can choose SCIAMACHY ESA L2 or FRESCO products. For example, if the application is on low clouds, the FRESCO cloud top height can be used; if the application is on high clouds, the ESA L2 cloud top height is

a better option.

9) Conclusions (p.8620, l. 7): Please specify the similarities to and deviations between the presented study/data and Lelli et al., 2011. What do we learn from this study using SCIAMACHY data?

A: Lelli et al. compared GOME cloud heights derived using the SACURA algorithm with ground-based measurements. The similarity is that the SACURA algorithm is used both for SCIAMACHY ESA L2 and GOME. We have performed comparisons for the SCIAMACHY FRESCO product which is not presented by Lelli et al.. They showed selected cases in their comparison which has less data points. They showed that the SACURA cloud top height and the ground-based lidar/radar cloud top height have better agreement for deep (geometrically thick) clouds than for shallow (geometrically thin) clouds. We have seen similar results in our analysis: ESA L2 cloud top heights have more scatter for low clouds than for height clouds. Here the low clouds are mostly geometric thin clouds. However, we also showed comparisons for optically thin and thick clouds. We have added some discussion in the conclusions.

10) Conclusions (p.8620, l. 10-12): a) How "accurate" are the FRESCO cloud middle heights? b)Is the ESA L2 cloud top height "on average reliable" or does it merely have "a large scatter"? Please be more specific.

A: We have revised the texts and used cloud height values.

11) Conclusions (p.8620, l. 13-14): How "limited" is the number of ground-based radar/lidar measurement sites world-wide? There are certainly more.

A: We have revised the texts. This sentence could be misleading. We would like to explain that it is not possible to validate the SCIAMACHY cloud product globally by using ground-based lidar/radar measurements. Therefore, this sentence is removed.

12) Conclusions (p.8620, l.21-22): What are "other satellite cloud height products"? Please specify.

A: We have revised the texts. "...other satellite cloud height products..." is removed.

13) Conclusions (p.8620, l. 24): What does "accurate" in "FRESCO cloud height is accurate for low clouds" mean? Within 1 sigma?

A: We revised the texts and gave numbers.

14) Comparing the last columns of Tables A1 and A2 reveals that the pixel selection for FRESCO and ESA L2 cloud products are different. Why?

A: If the ESA L2 cloud products are flagged as "not converged" or cloud optical thicknesses are too thin for the cloud top height retrievals, then there are no data. This explanation is included in the text in Sect. 4.2.1.

15) The captions of Figs. 4, 5, and 8 state whether the plotted correlations are significant or not. What does that mean? I suggest to calculate p-values and define, below which value significant correlation may be assumed for this kind of data. Furthermore, I suggest to put this information as well as a discussion in the main text body.

A: The p-values are almost 0 for the significant cases. We defined p-value < 0.01 as significant correlation. We have added discussions about the correlation coefficient and the significance of the correlation in sect. 4.2. The texts about the significance of the correlation are removed from the captions of the figures.

16) Are Figures 7 and 11 really histograms as stated in the captions? In general, a histogram shows the number, occurrence, or frequency per unit interval or bin. Figures 7 and 11, however, merely illustrate statistics within each bin. I therefore suggest to use candlestick type plots instead in order to avoid confusion with histograms typically associated with bar graphs. This would also highlight that the mean FRESCO cloud height is systematically lower than the ESA L2 cloud top height (except 7-8 km bin in Fig. 7) when binned according to the respective Cloudnet cloud middle/top height.

A: Thank you for the suggestion. In the captions of Figs. 7 and 11 the word 'histogram' is changed into 'bar plot'. In the revised paper, the Figs. 7 and 11 become Figs. 8 and

12.

17) In fact, Figures 3a and 3b are histograms.

A: Thank you for the comment.

18) More on Figures 7 and 11: Do you really need the mean values for the Cloudnet data? The binning of the FRESCO/SACURA values is according to the Cloudnet data rendering the grey bars (and especially the corresponding errorbars) rather meaning-less. I suggest to remove them from the plots for the sake of clarity.

A: Thank you for the suggestion. Without the Cloudnet data the figures look more clear. However, with the bar of the Cloudnet data next to the two SCIAMACHY cloud heights, the readers can easily identify and quantify the differences/similarities between the SCIAMACHY cloud heights and the Cloudnet cloud height. We think it, therefore, helpful for the readers to include the Cloudnet data bars in the figures.

19) Could one "validate" ground-based measurements of the cloud parameters with the help of satellites?

A: It could be possible if the satellite instrument is stable and has good calibration. The pixel size of the satellite measurements should not be too big. The top height of clouds could be better observed by lidar/radar on board a satellite than by ground-based lidar/radar.

Technical corrections

p.8604, l. 2: The reference for "For the first time" is not clear (two products, SCIA-MACHY, investigated period). Please rephrase or, even better, drop this claim.

A: We dropped this claim.

p.8605, l.2: "yr" -> "years"

A: Corrected.

p.8605, l.14: Please give a more balanced selection of references to tropospheric trace gas measurements influenced by clouds.

A: a new reference is added, Bucsela et al., 2006. Bucsela, E. J., Celarier, E. A., Wenig, M. O., Gleason, J. F., Veefkind, J. P., Boersma, K. F., and Brinksma, E. J.: Algorithm for NO2 vertical column retrieval from the Ozone Monitoring Instrument, IEEE T. Geosci. Remote Sens., 44, 1245–1258, 2006.

p.8605, l.23: "accurately determined with" -> "accurately determined from space with"

A: Corrected.

p.8606, l.9: drop "as being"

A: Corrected.

p.8608, l. 4-5: "the latest SCIAMACHY ESA L1 product (version 7.04) is used" Please specify when it has been released.

A: It was released in February 2012 according to the news on the ESA web site. We included the date in the texts. https://earth.esa.int/web/guest/missions/user-services-news/-/asset_publisher/lD7r/content/sciamachy–level–1b–version–7–04–w–full–mission–re–processed–data–set–available–at–d–pac

p. 8610, l. 16: Please add the number of Cloudnet measurement sites.

A: The number of Cloudnet sites is added in the text. Around 2001, the Cloudnet started from 3 stations and later more stations joined in, especially around 2010. The texts are revised.

p.8612, l. 1: The term "pixels" is confusing with respect to satellite pixels. There are two kinds of pixels in the manuscript. Please specify.

A: We tried to revise some sentences using "pixel" for radar/lidar data.

p.8620, l. 24: insert "," between "that" and "as"

A: Corrected.

p.8626, Table 2: I suggest to divide the second hline between "Effective cloud fraction" and "Cloud (top) height (km)" (three columns each) for the sake of clarity.

A: Corrected.

Figures 7 and 11: The x-axis of the plost are unclear. Does the first bin (denoted "1") contain the measurements between 0 and 1km? Please denote the range of each bin or put the axis ticks between the bars to indicate bin limits.

A: The range of each bin is noted in the caption. The unit, km, in x-axis is removed because the x-axis is the bins. It cannot be mixed up with the range of the each bin any more.

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