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Atmospheric Measurement Techniques
Discussions

Interactive comment on "Validation of TROPOMI Surface UV Radiation Product" *by* Kaisa Lakkala et al.

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Final Author comments

Authors' response to Referee #1, Referee #2 and Referee #3 comments on " Validation of TROPOMI Surface UV Radiation Product" by Kaisa Lakkala et al.

The authors thank the Referees for constructive comments and reply to all comments here below. The answer is structured as follow: (1) comments from Referee, (2) author's response, (3) author's changes in the manuscript.

Referee #1

Main comments

(1) 1. The question naturally arises whether the validation results improve for such a high-resolution satellite instrument like TROPOMI as compared to those of coarser resolution instruments like OMI or GOME-2. At high resolution the specific site conditions are more representatively measured from space: the homogeneity should improve. On the other hand, the cloudiness conditions for larger pixels may be more representative. A comparison of the TROPOMI validation results with OMI and GOME-2 UV validation would be useful. This topic would deserve more attention in discussion and conclusions.

(2) The authors agree with the comment and comparison with OMI and GOME-2 validation results has been added and discussed.

(3) Tables has been added to compare validation results between TROPOMI, OMI and GOME-2. A new section has been added with the following text: "5.1 Comparison with other satellite surface UV products TROPOMI is planned to continue OMI surface UV time series. A detailed comparison analysis of OMI and TROPOMI surface UV product is needed and it is a subject for future study. Many publications have discussed OMI surface UV products, but only few included same sites and same UV parameters. In Tables 7–8 TROPOMI surface UV product validation results are shown together with those from OMI and GOME-2 satellite instrument studies at sites having comparable results. When interpreting the results, one should keep in mind, that each study has different data time period, spatial and time difference, quality criteria and the overpass time of the day vary between satellites. In addition, the pixel size of each satellite instrument is different. These suggest that results depend on actual cloudiness and other atmospheric conditions like aerosols at polluted sites or sites affected by seasonal aerosol or dust events, as well as surface albedo conditions.

In Table 7 GOME-2 stands for the EUMETSAT Surface UV Data Record 2007-2017 generated in the framework of the Satellite Application Facility on Atmospheric Composition Monitoring (AC-SAF) (Kujanpää, 2018). It is a multimission product which is produced using as input total ozone column from GOME-2/Metop-A and/or GOME-

2/Metop-B, and cloud optical depth from AVHRR-3 onboard Metop-A, Metop-B, NOAA-18 and NOAA-19. The difference to the EUMETSAT operational OUV product is that one uniform algorithm version is used for the whole time period, and that climatological aerosol optical thickness and surface UV albedo inputs are changed from climatological values to actual daily values. The effect of using surface albedo which corresponds better to actual conditions at the site is seen for Palmer (Table 7), where the median relative difference between TROPOMI data and ground-based measurements is 6%, while for TROPOMI and OMI data it is -49% and -33%, respectively, for snow free conditions.

Fioletov et al. (2002) showed that TOMS overestimated surface UV on average by 9-10%, Tanskanen et al. (2007) found OMI to have median overestimations between 0-10% and this study shows that TROPOMI median relative differences to ground-based measurements is within ±5% at several sites even if TROPOMI surface UV tends to be lower than ground-based data. The smaller pixel size of TROPOMI compared to OMI suggest that validation results of TROPOMI are more representative of ground-based measurement conditions, e.g., regarding cloudiness. As summary, TROPOMI and OMI validation results are of same magnitude (within ±10% for sites with homogeneous conditions), but OMI usually overestimates while TROPOMI underestimates. Further analyses are needed to detect the effects of, e.g., differences in radiative transfer models and the way they take into account cloudiness. Studies should be done with spatially and temporally corresponding data sets."

New References: Fioletov, V., Kerr, J. B., Wardle, D. I., Krotkov, N., and Herman, J. R.: Comparison of Brewer ultraviolet irradiancemeasurements with total ozone mappingspectrometer satellite retrievals, Opt. Eng., 41, 3051–3061, 2002.

Kujanpää, J.: OUV Algorithm Theoretical Basis Document, SAF/O3M/FMI/ATBD/001, Issue 2.1, 15.1.2018, 2018.

Lakkala, K., Kalakoski, N., and Kujanpää, J.: AC SAF VALIDATION REPORT, SAF/AC/FMI/V&V/RP/001, Issue 1/2019, 19.2.2019, 2019.

(1) 2. Which TROPOMI UV algorithm improvements are needed? Clearly the surface albedo of TROPOMI should be improved and should have a time-component because of the snow variability. Are there more improvements needed as follow from this validation study?

(2) The authors agree that improvement on the surface albedo input are needed. The improvement should be both in time and spatial resolution. In addition to improving the treatment of albedo, corrections for mountainous regions could be improved, in particular in the presence of clouds. For example, when processing UV data for this study, the cloud optical depth was forced to zero when the UV product quality flag showed rough terrain. Following previous experience this has worked for mountain sites, e.g. Tibet region, where the site is most of the time above the clouds. However, this study showed that there are big challenges e.g., in the Alps, where the topography is strongly non-homogeneous and the site is locate in the valley, e.g., Aosta and Davos. The satellite pixel, which is around 7x4 km^2 can include in such mountainous area high elevation differences, with one part of the pixel being inside the cloud and the other one outside the cloud. However, estimating UV radiation from space at locations with non-homogeneous terrain will always be challenging. Secondly, aerosol absorption is taken in account by a post-correction using an aerosol climatology. Even if no need for improvement was detected in this specific study, actual aerosol data from e.g. satellite retrievals would be a good improvement for taking into account local aerosol anomalies.

(3) The following texts have been added to address the time resolution improvement in surface albedo input: "In the ideal case, the surface albedo input would have the same space resolution as the TROPOMI and follow actual albedo changes in time." "In this study, the cloud optical depth was forced to zero when the UV product quality flag showed rough terrain. Following previous experience this has worked for mountain sites, e.g. Tibet region, where the site is most of the time above the clouds. However, this study showed that there are big challenges e.g., in the Alps, where the topography

is strongly non-homogeneous and the site is locate in the valley, e.g., Aosta and Davos. The satellite pixel, which is around 7x4 km^2 can include in such mountainous area high elevation differences, with one part of the pixel being inside the cloud and the other one outside the cloud. However, estimating UV radiation from space at locations with non-homogeneous terrain will always be challenging." and "Even if no need for improvement was detected in this specific study, actual aerosol data from e.g. satellite retrievals would be a good improvement for taking into account local aerosol anomalies. "

Detailed comments

(1) Abstract, l. 1-5: Those instrument details on TROPOMI do not belong in the abstract.

(2) The authors think that the details are interesting for the readers who want quickly to know what is the paper about: 1) Start date of TROPOMI measurements, 2) Polar orbit and resolution information are important to know when considering the potential application of the data.

(3) No changes in the manuscript.

(1) Abstract: Please mention which UV retrieval algorithm was used.

(2) The TROPOMI UV algorithm (Lindfors et al., 2018).

(3) The following text has been added to the abstract: "The Finnish Meteorological Institute (FMI) is responsible for the development of the TROPOMI UV algorithm and the processing of the TROPOMI Surface Ultraviolet (UV) Radiation Product which includes 36 UV parameters in total."

(1)Abstract l. 13: Please clarify: TROPOMI UV is too low?

(2) Yes, too low. The text has been clarified.

(3) The text has been changed to: "Generally median relative differences between TROPOMI data and ground-based measurements were a little biased towards negative

values (i.e. satellite data < ground-based measurement), but at high latitudes where non-homogeneous topography and albedo/snow conditions occurred, the negative bias was exceptionally high, from -30% to -65%."

(1) l. 72: On the surface albedo data base: which spatial resolution? based on which satellite instrument?

(2) The surface albedo data is taken from a climatology generated for the OUV algorithm (Kujanpää and Kalakoski, 2015) which is provided on a 0.5°x0.5° latitude-longitude grid. It uses the monthly minimum Lambert equivalent reflectivity (MLER) climatology (Herman and Celarier, 1997) for regions and time periods with permanent or negligible snow/ice cover, while elsewhere a climatology from Tanskanen 2004 is used, which better captures the seasonal changes in the surface albedo during the snow/ice melting and formation periods. The following data sets were used to determine the regions and time period with permanent or negligible snow/ice cover: Northern hemispheric monthly snow cover extent data (Armstrong and Brodzik, 2010) from the International Satellite Land-Surface Climatology Project, Initiative II (ISLSCP II) (Hall et al., 2006) together with the monthly masks of maximum sea ice extent derived by the National Snow and Ice Data Center (NSIDC) from the sea ice concentrations obtained from passive microwave data (Cavalieri et al., 1996). The climatology of Tanskanen 2004 is calculated from TOMS 360 nm Lambertian Equivalent Reflectivity (LER) time-series 1979-1992 using the moving time-window method presented in Tanskanen et al. 2003. The data is available in a 1°x1° latitude-longitude grid from http://promote.fmi.fi/MTW_www/MTW.html .

(3) The above text has been added to the manuscript.

New References: Armstrong, R. and Brodzik, M. J.: ISLSCP II Northern Hemi-sphere monthly snow cover extent, ISLSCP Initiative II Collec-tion, in: ISLSCP Initiative II Collection. Data set, edited by:Hall, R. G., Collatz, G., Meeson, B., Los, S., Brown de Col-stoun, E., and Landis, D., available at: http://daac.ornl.gov/ from Oak Ridge

National Laboratory Distributed Active Archive Cen-ter, Oak Ridge, Tennessee, USA, doi:10.3334/ORNLDAAC/982,2010.

Cavalieri, D. J., Parkinson, C. L., Gloersen, P., and Zwally, H.:Sea Ice Con-centrations from Nimbus-7 SMMR and DMSPSSM/I-SSMIS Passive Microwave Data, NASA DAAC at theNational Snow and Ice Data Center, Boulder, Colorado, USA,doi:10.5067/8GQ8LZQVL0VL, 1996.

Hall, F. G., Brown de Colstoun, E., Collatz, G. J., Lan-dis, D., Dirmeyer, P., Betts, A., Huffman, G. J., Bounoua, L.,and Meeson, B.: ISLSCP Initiative II global data sets: sur-face boundary conditions and atmospheric forcings for land–atmosphere studies, J. Geophys. Res.-Atmos., 111, D22S01,doi:10.1029/2006JD007366, 2006.

Herman, J. R. and Celarier, E. A.: Earth surface reflectivity clima-tology at 340 nm to 380 nm from TOMS data, J. Geophys. Res.,102, 28003–28011, 1997.

Tanskanen, A., A. Arola, J. Kujanpää, Use of the moving time-window technique to determine surface albedo from the TOMS reflectivity data, In: Proc. SPIE Vol. 4896, p. 239–250, 2003.

Tanskanen, A., Arola, A., and Kujanpää, J.: Lambertian surfacealbedo climatology at 360 nm from TOMS data using movingtime-window technique, in: Proc. XX Quadren-nial Ozone Sym-posium, Kos, Greece, 1–8 June 2004, 1159–1160, 2004

(1) l. 81: Is there a manual (PUM) to explain all the 36 parameters?

(2) Yes, The reference of the PUM was added.

(3) The TROPOMI L2 UV product (Kujanpää 2020) contains 36 UV parameters in total (Table 1), including irradiances at four different wavelengths and dose rates for erythemal (Commission Internationale de l'Eclairage, 1998) and vitamin D synthesis (Bouillon et al.,2006) action spectra.

(1) l. 372: please clarify on the topic how the UV processor deals with clouds

(2) For Aosta, which is a challenging mountainous site, the UV product quality parameter flags “rough terrain” which, in the UV algorithm version used for satellite data calculation of this study, sets automatically cloud optical thickness to zero, meaning no clouds. This results in satellite UV data that are too high, especially when heavy clouds are present, which would lead to low UV dose rates measured at the ground. The same applies for Izana which, depending on the TROPOMI pixel position, can be flagged as rough terrain.

(3) Text has been changed to “Large positive biases in TROPOMI UV data occur over these mountainous regions during cloudy conditions when the "rough terrain" quality flag is active and cloud optical depth is set to zero in the UV algorithm.”

(1) Caption Figure 5: “Red diamonds...”: but such conditions are not all exclusive: site scan be both clear-sky and snow-free. How to indicate that?

(2) Here clear-sky means that the cloud optical depth retrieved from the first LUT of the TROPOMI UV algorithm is less than 0.5. It doesn't tell about the actual conditions at the measurement site. To distinguish between snow and snow-free, the input of TROPOMI albedo is used, which is based on albedo climatology, and neither tells about actual albedo conditions of the site. This means that if TROPOMI data with COD<0.5 (in the first manuscript version called “clear sky”) agree well with ground-based measurements, most probably the albedo climatology is representative for actual surface albedo conditions, assuming there is no problem with other input parameters (e.g. aerosols). The authors are aware that the wording “clear sky” can be misleading and it has been changed in the whole manuscript to “cloudfree”.

(3) The following text has been added to the manuscript:” Results for the cloudfree datasets, with cloud optical depth input parameter of the TROPOMI UV algorithm lower than 0.5, were also included in the plot. Cloudfree criteria is not reflecting actual cloudiness conditions, but the cloud optical depth retrieved from the first LUT in the TROPOMI UV algorithm. If a perfect agreement between satellite and ground-based

data is found, most probably also the surface albedo climatology represents actual surface albedo conditions and the aerosol climatology actual aerosol conditions. ”

(1) l. 425: in function of > as a function of

(2) Text changed as suggested.

(3) Text changed as suggested.

(1) l. 485: check spelling: homogeneous

(2) Text changed as suggested.

(3) Text changed as suggested.

Referee #2

(1) Abstract line 13 For compete clarity please state ‘relative differences...were a little biased towards negative values (i.e. ground-based measurement > satellite data).

(2) Text changed as suggested.

(3) Text changed as suggested.

(1) Line 40-41 This somehow implies that there is no more chemical ozone depletion. Please rephrase.

(2) The text has been rephrased.

(3) The text has been changed to: “The international Montreal Protocol was signed in 1987 to protect theÂăozone layerÂăby phasing out the production of ozone-depleting substances (ODS). As a result, the ozone layer is now starting to recover (WMO, 2018). However, the removal process of ODS will take several decades and UV levels at the ground will therefore remain elevated for the foreseeable future (Petkov et al., 2014; Fountoulakis et al., 2020).”

(1) Line 53-54 Provide resolution of e.g. OMI UV products to give context to the claim of better resolution.

(2) The OMI pixel size is 13 km× 24 km at nadir.

(3) The text has been changed to: “The ground resolution of the UV product was 7.2x3.5 km^2 at nadir until 6 August 2019, and is now 5.6x3.5 km^2, while the OMI pixel size was 13x24 km^2 at nadir.”.

(1) Line 95-97 Are the changes in ozone product version and aerosol index product version significant? Please comment in either case.

(2) Changes in version numbers do not significantly impact the surface UV product. However, there are signs of degradation in the UV solar irradiance measurement of TROPOMI. We do not see any trend in our cloud optical depth retrievals using the 354 nm reflectance, but further analysis is needed in any UVtrend study."

(3) The following text has been added to the manuscript: “Changes in version numbers do not significantly impact the surface UV product. However, there are signs of degradation in the UV solar irradiance measurement of TROPOMI (Rozemeijer and Kleipool, 2019). We do not see any trend in our cloud optical depth retrievals using the 354 nm reflectance, but further analysis is needed in any UV trend study.”

Reference: Rozemeijer, N. C. and Kleipool, Q., S5P Mission Performance Centre Level 1b Readme, S5P-MPC-KNMI-PRF-L1B, issue 2.2.0, 31.10.2019, 2019, available at http://www.tropomi.eu/sites/default/files/files/publicSentinel-5P-Level-1b-Product-Readme-File.pdf

(1) Section 2.2 The sites are well described, but quantification of the uncertainty in measurements from each site is inconsistent or missing. Ideally all uncertainties would be described in the same way, and added to tables 3 and 4 after the traceability column. Please do what is possible in this respect (at the least provide uncertainties in the text, for those sites currently without).

(2) The authors agree with the Referee and comparison against QASUME and ex-

panded uncertainties are included in Tables 3 and 4 when available.

(3) The following text has been changed: “Many of the spectroradiometers have participated in on- site quality assurance of spectral solar UV measurements performed by the traveling reference spectroradiometer QASUME since 2002 (Gröbner et al., 2005), and the average offset of all instruments is within ±5% from the reference instrument with a diurnal variability typically less than 5%. The reports of the site visits can be found at https://www.pmodwrc.ch/en/world- radiation-center-2/wcc-uv/qasume-site-audits/ and the comparison results of the latest QASUME comparisons are shown in Table 3. In addition, available estimates of expanded uncertainties of ground-based measurements are shown in Tables 3 and 4. The expanded uncertainties of spectroradiometers and broadband / multiband radiometers are less than 6% and less than or equal to 9%, respectively.”

(1) Please provide a summary statement about the uncertainties in the ground-based data. It is important to know how the ground based data compare as a benchmark for the satellite data comparison. For example, do all instruments that have been compared with the QASUME instrument fall within x% of this world calibration standard? Or, are all expanded uncertainties within y%?

(2) The authors agree with the Referee and a summary statement about the uncertainties is added.

(3) Please see answer to the question above.

(1) Line 338 Please state which method was then used for the rest of the analysis.

(2) The text has been modified to include the method used in the rest of the analysis: 1) Each TROPOMI pixel was treated as individual measurement.

(3) The modified text is now: “The spatial resolution of TROPOMI data is very high compared to older generation satellite instruments. This leads to huge amount of data and at most sites several satellite pixels fulfilling the selection criteria were colocated

with the same ground-based measurement. For example, at high latitudes, this increased the number of data to include more than 5 pixels for each overpass. Thus, the sensitivity of the results was studied by comparing three different data selection methods for Villeneuve d’Ascq measurements: 1) Each TROPOMI pixel was treated as individual measurement, 2) the pixel nearest of the site was chosen, 3) the average of the TROPOMI pixels meeting the chosen limitations (time difference, SZA, altitude, distance) was used. The results did not differ significantly between the methods, and in this study the results were calculated for each pixel separately. Results are shown in the Fig. S13 and Table S6 of the Supplement material.”

(1) Line 398 Comment briefly on how this improved the relative difference statistics for Davos. For this, and the previous comment, readers should not have to go to supplementary material to find the outcome, only to see the detail.

(2) Comment on the changes in statistics has been added. The results of the “pixel test” are addressed in the response of the previous comment.

(3) The corresponding chapter if now: “The effect of taking into account quality flags was evaluated for the site of Davos. Data for which the quality value number UVQAV was less than 0.5 were excluded (see Section 2.1 for explanation of UVQAV). This removed e.g., unreliable values when the cloud optical depth was set to 0 due to the flagging. Indeed, as mentioned in Section 2.2, Davos is a mountainous site with heterogeneous albedo during the winter. Setting a limit of 0.5 for the UVQAV, results in removing satellite observations with at least two of the following warnings: "rough_terrain", "alb_hetero" or "clearsky_assumed". This procedure reduced the number of data points by around half, and removed most data points where satellite estimates exceed the ground measurements. This resulted in a shift of median relative differences towards more negative values: From -24% to -57% and from -6% to -13 % for snow cover and snow free conditions, respectively. The statistics and scatter plots of the study are shown in Supplement material Table S7 and Fig. S14.”

Results / Conclusion

(1) Please provide a summary of comparative results for OMI and TOMS UV products. Specific cases are detailed in the results – mainly those with large relative differences. Please also give the comparators for the 'easier' sites. From what is provided it appears that TROPOMI results are similar to those for OMI – this is important with respect to the final paragraph of the manuscript and the desire for a longtime series of satellite derived UV data. Please summarise whether this is the case, or whether significant improvements have been made.

(2) The authors agree with the comment and comparison with OMI and GOME-2 validation results has been added and discussed, and a summary sentence with TOMS results have been added to the Discussion section.

(3) Please see changes in the manuscript from the first answer to Referee #1.

Referee #3

(1) A more thorough outline review of the algorithm used

(2) The used TROPOMI UV algorithm has already been published in Lindfors et al. 2018, so the authors think that a restricted amount of details is sufficient for this paper. Details which are important for discussion on results have been included. As suggested more details on cloud optical depth retrieval and aerosol correction are included. Also the albedo climatology has been discussed in more details.

(3) Albedo related changes: See response to Referee#2.

Cloud optical depth: The paragraph describing the cloud optical depth retrieval has been modified to:"The TROPOMI UV algorithm is based on two pre-computed lookup tables (LUT) in order to save computing time compared to explicit radiative transfer calculations. The first LUT is used to retrieve the cloud optical depth from the measured 354 nm reflectance using SZA, viewing zenith angle, relative azimuth angle, surface pressure and surface albedo as other inputs. Details on the cloud optical depth retrieval

can be found in Sect. 3.3 of Lindfors et al, 2018s. The measured 354 nm reflectance together with the angles and surface pressure are obtained from the TROPOMI L2 aerosol index (AI) product (Stein et al, 2018) as they are used for the calculation of the AI product. The LUT was pre-generated by radiative transfer calculations. The reflectance and 354 nm was calculated using different combinations of cloud optical depth, SZA, viewing zenith angle, relative azimuth angle, surface pressure and surface albedo. The outcome is a LUT from which the cloud optical depth can be retrieved when all other input parameters are known. For radiative transfer calculations, a homogeneous water cloud layer is considered at 1-2 km height in the atmosphere. Thus, the retrieved cloud optical depth can be considered to be an effective optical depth for the whole satellite pixel which best corresponds to the measured 354 nm reflectance. 3D effects due to partial cloudiness are ignored. "

Aerosol absorption: The following has been added to the text of the manuscript:"The correction for absorbing aerosols follows the approach developed earlier to the OMI algorithm (Arola et al. 2009). It is based on aerosol absorption optical depth (AAOD), which is taken from the monthly aerosol climatology by Kinne et al. (2013). The correction factor and its dependence on AAOD was first suggested by Krotkov et al. 2005 and applied in Arola et al. 2009."

(1) Adding comparison with the OMI product.

(2) The authors think that a detailed comparison between TROPOMI and OMI is a subject for another study. However discussion on comparison of published validation results of different satellite instruments has been added as a new section to the manuscript.

(3) Please see the first answer to Referee #1.

(1) There are problems with comparisons with broad-band instruments Table 4 that are not discussed in this paper. Broad-band instruments do not have a spectral response that matches the erythemal action spectrum used. Figure 5 suggests the difficulty of

using broad-band instruments. Instead of scatter plots that clearly indicate problems, time series would be much more revealing of the deficiencies of broad-band analysis, especially the seasonal differences.

(2) The broadband instruments have a spectral response close to the erythemal action spectrum, but it is true that it is not perfectly the same. This difference is taken into account during the calibration procedure of broad band instruments, as the calibration coefficient is provided as a function of SZA and total ozone. Data from broadband instruments can agree within ±2% with measurements of well- calibrated spectroradiometers (Hülsen et al. 2008 and Hülsen et al. 2020). The authors don't see that Figure 5 suggest difficulties using broadband instruments. The broadband instruments used in the study are from Davos (DBB), the Israeli sites (BET, JER, EIL), Australian site (ALI) and the Indian Ocean sites (MAH, ANT, SDT, ROD). From those, the Israeli sites and the Australian site don't show seasonal dependence. The discrepancies between TROPOMI and ground-based measurements in Davos are similar to those found by performing the 310 nm irradiance comparison against the spectral instrument (DAV), where the median relative differences are -39% (snow cover) and -8% (snow free) and -38% (snow cover) and -5% (snow free) for DBB and DAV, respectively. The clear seasonal dependency is due to problems of TROPOMI surface UV product for non-homogenous topography sites, not because of problems with broadband instruments. For the Indian Ocean sites, there is no clear reason for the underestimation of TROPOMI UV at extreme UV levels. The biggest differences is seen for three Indian Ocean sites and the possible explanation is discussed in the manuscript: " The same applies for the impact of cloudiness when clouds are non-uniformly located around the site due to topography or changes in surface (e.g. sea/ground). For example the site itself is free from clouds but there can be small cumulus clouds at the edge of the pixel which increase the reflection towards the satellite. In that case the TROPOMI would most probably underestimate the UV irradiance as the small fraction of clouds is considered as cloudiness of the whole pixel. Under scattered clouds, the UV radiation at the surface can be larger than during clear skies (Calbó et al., 2005; Jégou

et al., 2011). This phenomenon occurs when the direct radiation from the Sun is not obstructed and additional radiation is scattered by clouds to the radiometer at the surface. The TROPOMI algorithm does not consider these situations, resulting UV levels that are too low. This phenomenon is likely one reasons for the underestimation found in the TROPOMI UV dose rates during high UV levels at tropical sites." Plots of time series will not help to identify the reason of the discrepancies, as the self-evident noise due to how TROPOMI algorithm handle cloudiness (scattered cloudiness not detected by TROPOMI) will mask other reasons.

(3) Text has been added about the uncertainties related to broadband measurements and uncertainties have been added to the manuscript (Table 4). Please see answer to Referee #2.

New Reference: Hülsen, G., Gröbner, J., Bais, A., Blumthaler, M., Diémoz, H., Bolsée, D., Diaz, A., Fountoulakis, I., Naranen, E., Schreder, J., Stefania, F., and Guerrero, J. M. V.: Second solar ultraviolet radiometer comparison campaign UVC-II, Metrologia, 57, 035 001, https://doi.org/10.1088/1681-7575/ab74e5, https://doi.org/10.1088%2F1681-7575%2Fab74e5, 2020.

(1) Problems with snow covered conditions are to be expected and are not indicative of problems with TROPOMI. However, the O2 A-band information from TROPOMI can detect clouds over snow and ice and perhaps improve the results.

(2) The authors thank for the suggestion.

(3) None.

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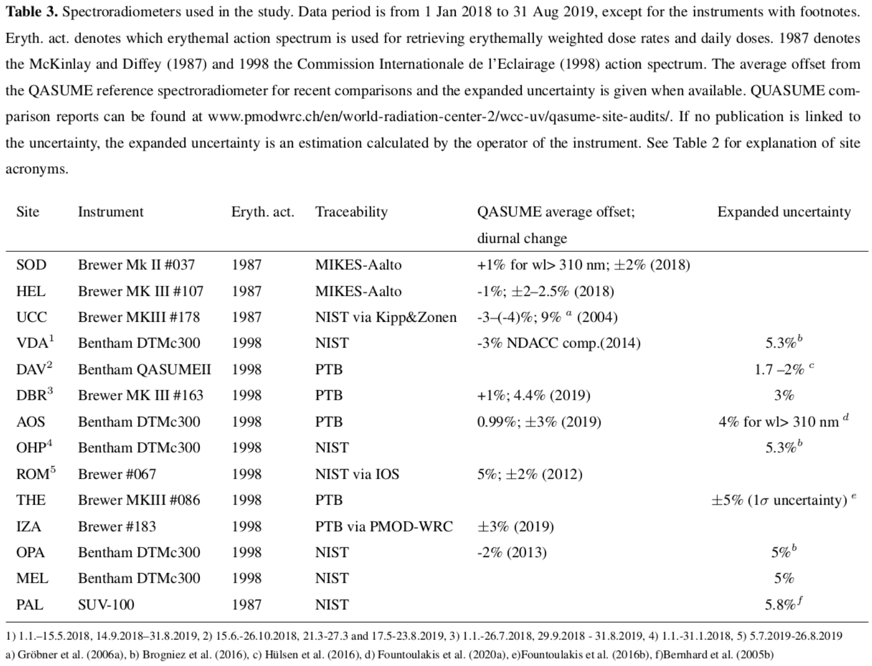

Table 3. Spectroradiometers used in the study. Data period is from 1 Jan 2018 to 31 Aug 2019, except for the instruments with footnotes. Eryth. act. denotes which erythemal action spectrum is used for retrieving erythemally weighted dose rates and daily doses. 1987 denotes the McKinlay and Diffey (1987) and 1998 the Commission Internationale de l'Eclairage (1998) action spectrum. The average offset from the QASUME reference spectroradiometer for recent comparisons and the expanded uncertainty is given when available. QUASUME comparison reports can be found at www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits/. If no publication is linked to the uncertainty, the expanded uncertainty is an estimation calculated by the operator of the instrument. See Table 2 for explanation of site acronyms.

Site	Instrument	Eryth. act.	Traceability	QASUME average offset; diurnal change	Expanded uncertainty
SOD	Brewer Mk II #037	1987	MIKES-Aalto	+1% for wl> 310 nm; ±2% (2018)	
HEL	Brewer MK III #107	1987	MIKES-Aalto	-1%; ±2–2.5% (2018)	
UCC	Brewer MKIII #178	1987	NIST via Kipp&Zonen	-3–(-4)%; 9% ^{a} (2004)	
VDA^1	Bentham DTMc300	1998	NIST	-3% NDACC comp.(2014)	5.3%^{b}
DAV^2	Bentham QASUMEII	1998	PTB		1.7 –2% ^{c}
DBR^3	Brewer MK III #163	1998	PTB	+1%; 4.4% (2019)	3%
AOS	Bentham DTMc300	1998	PTB	0.99%; ±3% (2019)	4% for wl> 310 nm ^{d}
OHP^4	Bentham DTMc300	1998	NIST		5.3%^{b}
ROM^5	Brewer #067	1998	NIST via IOS	5%; ±2% (2012)	
THE	Brewer MKIII #086	1998	PTB		±5% (1σ uncertainty) ^{e}
IZA	Brewer #183	1998	PTB via PMOD-WRC	±3% (2019)	
OPA	Bentham DTMc300	1998	NIST	-2% (2013)	5%^{b}
MEL	Bentham DTMc300	1998	NIST		5%
PAL	SUV-100	1987	NIST		5.8%^{f}

1) 1.1.–15.5.2018, 14.9.2018–31.8.2019, 2) 15.6.-26.10.2018, 21.3-27.3 and 17.5-23.8.2019, 3) 1.1.-26.7.2018, 29.9.2018 - 31.8.2019, 4) 1.1.-31.1.2018, 5) 5.7.2019-26.8.2019

a) Gröbner et al. (2006a), b) Brogniez et al. (2016), c) Hülsen et al. (2016), d) Fountoulakis et al. (2020a), e)Fountoulakis et al. (2016b), f)Bernhard et al. (2005b)

Fig. 1. Table 3

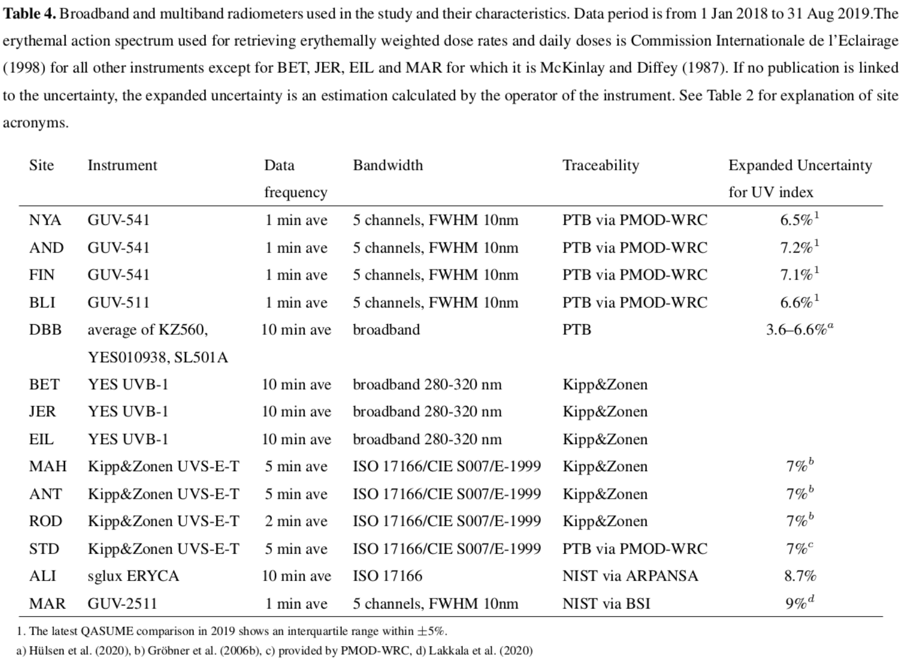

Table 4. Broadband and multiband radiometers used in the study and their characteristics. Data period is from 1 Jan 2018 to 31 Aug 2019.The erythemal action spectrum used for retrieving erythemally weighted dose rates and daily doses is Commission Internationale de l'Eclairage (1998) for all other instruments except for BET, JER, EIL and MAR for which it is McKinlay and Diffey (1987). If no publication is linked to the uncertainty, the expanded uncertainty is an estimation calculated by the operator of the instrument. See Table 2 for explanation of site acronyms.

Site	Instrument	Data frequency	Bandwidth	Traceability	Expanded Uncertainty for UV index
NYA	GUV-541	1 min ave	5 channels, FWHM 10nm	PTB via PMOD-WRC	6.5%^{1}
AND	GUV-541	1 min ave	5 channels, FWHM 10nm	PTB via PMOD-WRC	7.2%^{1}
FIN	GUV-541	1 min ave	5 channels, FWHM 10nm	PTB via PMOD-WRC	7.1%^{1}
BLI	GUV-511	1 min ave	5 channels, FWHM 10nm	PTB via PMOD-WRC	6.6%^{1}
DBB	average of KZ560, YES010938, SL501A	10 min ave	broadband	PTB	3.6–6.6%^{a}
BET	YES UVB-1	10 min ave	broadband 280-320 nm	Kipp&Zonen	
JER	YES UVB-1	10 min ave	broadband 280-320 nm	Kipp&Zonen	
EIL	YES UVB-1	10 min ave	broadband 280-320 nm	Kipp&Zonen	
MAH	Kipp&Zonen UVS-E-T	5 min ave	ISO 17166/CIE S007/E-1999	Kipp&Zonen	7%^{b}
ANT	Kipp&Zonen UVS-E-T	5 min ave	ISO 17166/CIE S007/E-1999	Kipp&Zonen	7%^{b}
ROD	Kipp&Zonen UVS-E-T	2 min ave	ISO 17166/CIE S007/E-1999	Kipp&Zonen	7%^{b}
STD	Kipp&Zonen UVS-E-T	5 min ave	ISO 17166/CIE S007/E-1999	PTB via PMOD-WRC	7%^{c}
ALI	sglux ERYCA	10 min ave	ISO 17166	NIST via ARPANSA	8.7%
MAR	GUV-2511	1 min ave	5 channels, FWHM 10nm	NIST via BSI	9%^{d}

1. The latest QASUME comparison in 2019 shows an interquartile range within ±5%.

a) Hülsen et al. (2020), b) Gröbner et al. (2006b), c) provided by PMOD-WRC, d) Lakkala et al. (2020)

Fig. 2. Table 4

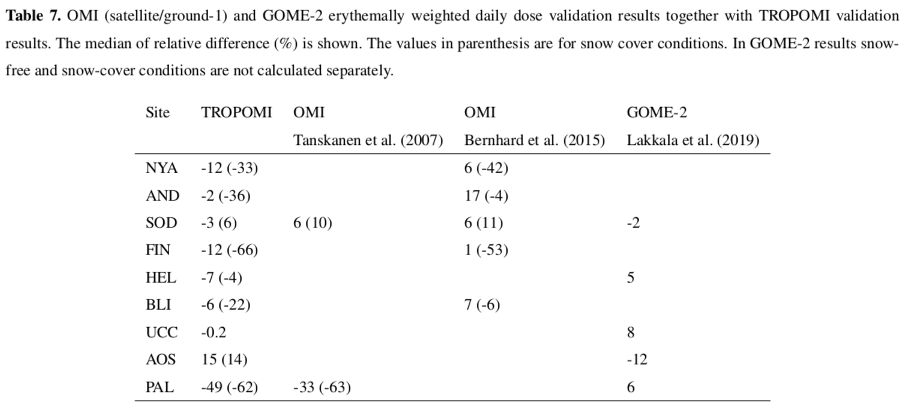

Table 7. OMI (satellite/ground-1) and GOME-2 erythemally weighted daily dose validation results together with TROPOMI validation results. The median of relative difference (%) is shown. The values in parenthesis are for snow cover conditions. In GOME-2 results snow-free and snow-cover conditions are not calculated separately.

Site	TROPOMI	OMI Tanskanen et al. (2007)	OMI Bernhard et al. (2015)	GOME-2 Lakkala et al. (2019)
NYA	-12 (-33)		6 (-42)	
AND	-2 (-36)		17 (-4)	
SOD	-3 (6)	6 (10)	6 (11)	-2
FIN	-12 (-66)		1 (-53)	
HEL	-7 (-4)			5
BLI	-6 (-22)		7 (-6)	
UCC	-0.2			8
AOS	15 (14)			-12
PAL	-49 (-62)	-33 (-63)		6

Fig. 3. Table 7

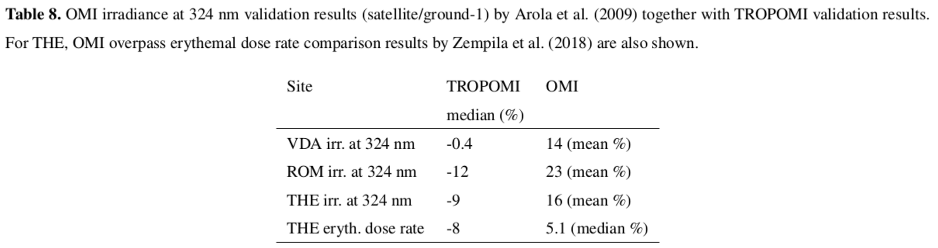

Table 8. OMI irradiance at 324 nm validation results (satellite/ground-1) by Arola et al. (2009) together with TROPOMI validation results. For THE, OMI overpass erythemal dose rate comparison results by Zempila et al. (2018) are also shown.

Site	TROPOMI median (%)	OMI
VDA irr. at 324 nm	-0.4	14 (mean %)
ROM irr. at 324 nm	-12	23 (mean %)
THE irr. at 324 nm	-9	16 (mean %)
THE eryth. dose rate	-8	5.1 (median %)

Fig. 4. Table 8