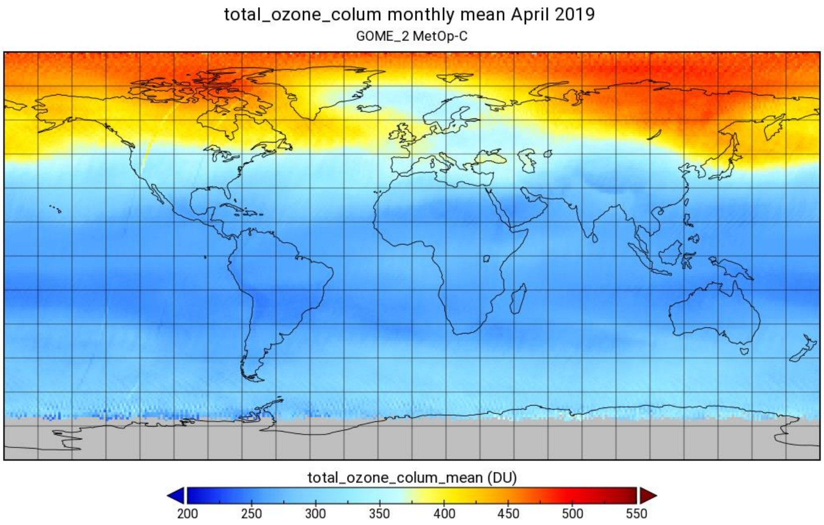
AC SAF VALIDATION REPORT

Validated products:

Identifier	Name	Satellite
O3M-301	Offline total ozone	GOME2/Metop-C
O3M-300	NRT total ozone	GOME2/Metop-C



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Reporting period: February 2019 – July 2019

Input data versions: GOME-2 L1b version 6.3

Data processor versions: GDP 4.9, UPAS version 1.4.0

Introduction to EUMETSAT Satellite Application Facility on Atmospheric Composition monitoring (AC SAF)

Background

The monitoring of atmospheric chemistry is essential due to several human caused changes in the atmosphere, like global warming, loss of stratospheric ozone, increasing UV radiation, and pollution. Furthermore, the monitoring is used to react to the threats caused by the natural hazards as well as follow the effects of the international protocols.

Therefore, monitoring the chemical composition and radiation of the atmosphere is a very important duty for EUMETSAT and the target is to provide information for policy makers, scientists and general public.

Objectives

The main objectives of the AC SAF is to process, archive, validate and disseminate atmospheric composition products (O_3, NO_2, SO_2, BrO, HCHO, H_2O, OClO, CO, NH3), aerosol products and surface ultraviolet radiation products utilising the satellites of EUMETSAT. The majority of the AC SAF products are based on data from the GOME-2 and IASI instruments onboard Metop satellites.

Another important task besides the near real-time (NRT) and offline data dissemination is the provision of long-term, high-quality atmospheric composition products resulting from reprocessing activities.

Product categories, timeliness and dissemination

NRT products are available in less than three hours after measurement. These products are disseminated via EUMETCast, WMO GTS or internet.

- Near real-time trace gas columns (total and tropospheric O_3 and NO_2, total SO_2, total HCHO, CO) and high-resolution ozone profiles
- Near real-time absorbing aerosol indexes from main science channels and polarization measurement detectors
- Near real-time UV indexes, clear-sky and cloud-corrected

Offline products are available within two weeks after measurement and disseminated via dedicated web services at EUMETSAT and AC SAF.

- Offline trace gas columns (total and tropospheric O_3 and NO_2, total SO_2, total BrO, total HCHO, total H_2O) and high-resolution ozone profiles
- Offline absorbing aerosol indexes from main science channels and polarization measurement detectors
- Offline surface UV, daily doses and daily maximum values with several weighting functions

Data records are available after reprocessing activities from the EUMETSAT Data Centre and/or the AC SAF archives.

- Data records generated in reprocessing
- Lambertian-equivalent reflectivity
- Total OClO

Users can access the AC SAF offline products and data records (free of charge) by registering at the AC SAF web site.

More information about the AC SAF project, products and services: https://acsaf.org/

AC SAF Helpdesk: helpdesk@acsaf.org

Twitter: https://twitter.com/Atmospheric_SAF

Contents

ACRONYMS AND ABBREVIATIONS

AUTH	Aristotle University of Thessaloniki
BDM	Brion, Daumont, Malicet
BUFR	Binary Universal Form for the Representation of meteorological data
CDOP	Continues Development and Operations Proposal
DLR	German Aerospace Center
DOAS	Differential Optical Absorption Spectroscopy
GDP	GOME Data Processor
GOME	Global Ozone Monitoring Experiment
HDF	Hierarchical Data Format
MetOp	Meteorological Operational satellite
NRT	Near-real-time
NTO/O3	Near-real-time Total Ozone Product
O3MSAF	Ozone Monitoring Satellite Application Facility
OMI	Ozone Monitoring Instrument
OTO/O3	Offline Total Ozone Product
SZA	Solar Zenith Angle
TOC	Total Ozone Column
WOUDC	World Ozone and UV Data Center

Applicable AC SAF Documents

[ATBD] Algorithm Theoretical Basis Document for GOME-2 Total Column Products of Ozone, NO_2, BrO, SO_2, H_2O, HCHO and Cloud Properties (GDP 4.9 for AC SAF OTO and NTO), SAF/AC/DLR/ATBD/01, 3/B Rev.1, Valks, P., et al., June 2019.

[PUM] Product User Manual for GOME-2 Total Column Products of Ozone, NO_2, BrO, SO_2, H_2O, HCHO, OCIO and Cloud Properties (GDP 4.9 for AC SAF OTO and NTO), SAF/AC/DLR/PUM/01, 3/B Rev.1, Valks, P., et. al., 2019.

[PRD] Product Requirements Document, Issue 1.5, SAF/AC/FMI/RQ/PRD/001, Issue 1.5, D. Hovila, S. Hassinen, P. Valks, J., S. Kiemle, O. Tuinder, H. Joench-Soerensen, June 2019.

Document change record

Issue	Date	Section	Description of Change
1/2019	18-11-2019	All	Initial version

Technical information

Satellite ID: M01

Product type: O3MOTO, O3MNTO

Validation reporting period **February – July 2019**

Level-2 processor version **GDP 4.9, UPAS version 1.4.0**

Internal product ID's for project control

Product ID	***Name***	***Satellite***	***Acronym***
O3M-300	NRT total ozone	GOME-2/Metop-C	MCG-N-O3
O3M-301	Offline total ozone	GOME-2/Metop-C	MCG-O-O3

Input GOME-2/MetOp-C Level-1B data version table

Start Date	*Start Orbit*	*Level 1B Version*
February 1, 2019	01222	6.3.0

1. INTRODUCTION

The main aim of this report is to validate the GOME-2/MetopC, hereafter GOME-2C, offline and NRT total ozone column (TOC) product against the Dobson and Brewer spectrophotometer ground-based networks. In addition, we directly compare GOME-2C TOCs with other sensors that are processed by the same or very similar algorithms, such as GOME-2/MetopA and MetopB, hereafter GOME-2A and GOME-2B respectively, and TROPOMI/S5P NRTI TOCs.

In Section 2 the satellite and ground-based datasets used in this report, are presented. In Sections 3.1 and 3.2 we present summary global averages of the statistics from the comparisons between the GOME-2C total ozone product and the ground-based instruments, separately performed for the Dobson and Brewer spectrophotometers. In Section 3.3 the GOME-2C TOCs are compared to GOME-2A and GOME-2B via their comparison to ground-based measurements, while in Section 3.4 the GOME-2C and GOME-2B TOC measurements are directly compared for one month.

In this report, the following analysis was utilized to result to the global statistics that are summarized in Section 3.4:

- Time series of the monthly mean percentage differences between ground-based and GOME-2C instruments.
- Histograms of the differences.
- Scatter plots of the data series
- Pole-to-pole plots of the mean differences per ground-based station.
- Pole-to-pole plots of the percentage differences averaged in 10º latitude bins
- Solar zenith angle dependence of the differences.
- Dependence of the percentage differences on other influence quantities, such as different cloud parameters.
- Maps of global representation of the percentage differences between two sensors.

Finally, the conclusions of the current report are presented in Section 5.

2. DATA SOURCES AND CO-LOCATION METHODOLOGY

2.1 Data sources

2.1.1 GOME2/Metop-C

The GOME2/Metop-C (hereafter GOME-2C) offline total ozone column (TOC) product has been processed with the DOAS algorithm version GDP4.9. The main differences between GDP4.8, which is the previous operational algorithm used for the GOME-2/MetopA and MetopB processing, and 4.9 concern the SO_2 vertical column retrieval. For ozone only minor updates have been performed:

For the analysis of GOME-2C the slit function was optimized based on the existing slit function file and spectral observation. The changes in the slit function were small but led to an improvement of the DOAS fit. Another improvement was achieved by introducing a pseudo absorber for possible orbital variations of the resolution. The ozone retrievals use the same fitting window (325 to 335 nm), the same cross section files for NO_2 and O_3, the same temperatures and the same AMF retrieval. For the other two instruments, GOME-2B and GOME-2A, the data retrieval is the same in GDP 4.8 as in 4.9. Therefore, the O_3 columns from GOME-2C can be assumed to be similar to the respective data from GOME-2 on MetOp-B, analyzed with the previous version of the algorithm.

During the analysis of the GOME-2C data it was decided to apply a filtering criterion for the total ozone error, which must be less than 2%. This filter excludes from the validation dataset a very limited number of co-locations (~ 1 %) and results to excluding some extreme values of the comparisons. All data files have been stored locally and have been separately compared with ground-based data.

The main characteristics of the satellite instruments used in this validation report, namely GOME-2C and those presented in the following sections (2.1.2 and 2.1.3), are shown in Table 1.

Table 1: Main characteristics of the GOME2/MetOp-A, GOME2/MetOp-B, GOME2/Metop-C and TROPOMI/SP instruments affecting the total ozone column products.

	GOME-2/ METOP-A	GOME-2/ METOP-B	GOME-2/ METOP-C	TROPOMI/S5P
PRINCIPLE	UV/VIS grating spectrometer	UV/VIS grating spectrometer	UV/VIS grating spectrometer	UV/VIS/NIR/SWIR push broom grating spectrometer
DETECTORS	Reticon linear diode array	Reticon linear diode array	Reticon linear diode array	2-dimentional CCD
SPECTRAL RESOLUTION	0.26 nm	0.26 nm	0.26 nm	0.55 nm
SPATIAL RESOLUTION (DEFAULT)	80 x 40 km^2 40 x 40 km^2 since July 15, 2013	80 x 40 km^2	80 x 40 km^2	7 × 5 km^2 7 × 3.5 km^2, since August 2019
SWATH WIDTH	1920 km 960 km since July 15, 2013	1920 km	1920 km	2600 km
EQ. CROSSING TIME	09:30 LT	09:30 LT	09:30 LT	13:30 LT
LEVEL-0-TO-1B ALG.	GOME2 PPF 6.3.0	GOME2 PPF 6.3.0	GOME2 PPF 6.3.0	v01
LEVEL-1-TO-2 ALG.	GDP 4.8	GDP 4.8	GDP 4.9	NRTI

2.1.2 GOME2/Metop-A and GOME2/Metop-B

To assess the consistency of GOME-2C to its predecessors, the GOME2/Metop-A and GOME2/Metop-B (hereafter GOME-2A and GOME-2B) TOC products, processed with the GDP4.8 version of the algorithm (ATBD, Valks et al., 2017) for the time-period examined in this report, were used. The latter sensors were successfully validated, and their validation report is published in Koukouli et al., 2015b. In the plots where they are used as a comparison basis for the GOME-2C sensor, only their temporally common co-locations are utilized to have comparable datasets.

2.1.3 TROPOMI/S5P

In this report, we also compare the GOME-2C TOC data with TROPOMI/S5P total ozone data using its NRTI product, which has a retrieval algorithm very similar to the GDP4.8 algorithm (ATBD, Spurr et al, 2018). The differences between GDP4.8 and NRTI algorithms and the filtering criteria applied on the TROPOMI measurements are thoroughly described in Garane et. al, 2019. The Level-2 TROPOMI NRTI TOC data are available through the Sentinel-5P Pre-Operations Data Hub (https://s5phub.copernicus.eu/) and, as mentioned above, only common co-locations to GOME-2C are utilized here.

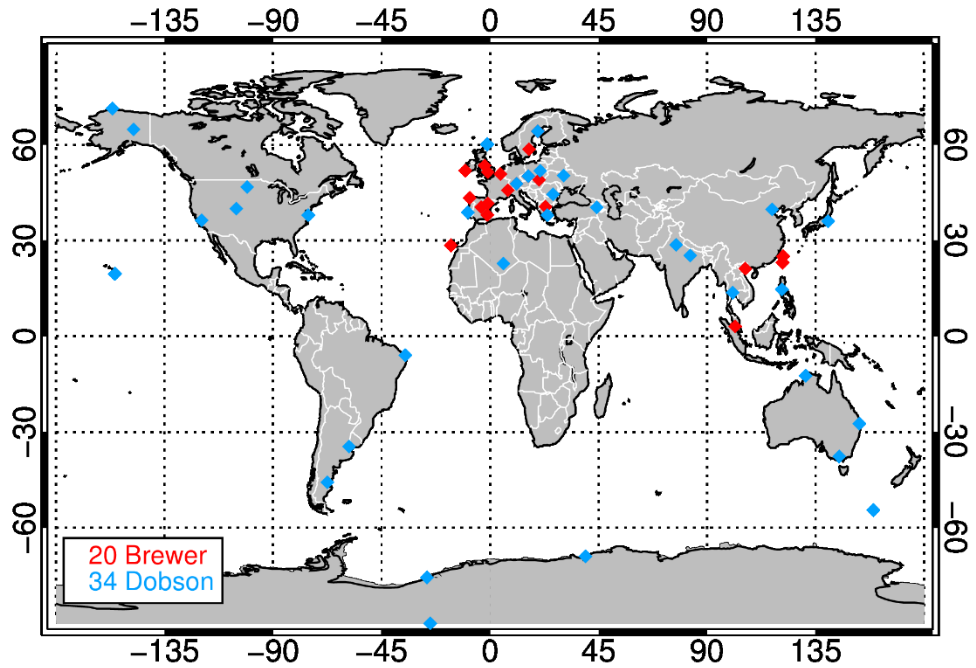

Figure 1: Spatial distribution of the Brewer and Dobson ground-based stations used for the comparisons.

2.1.4 Ground-based observations

The ground-based validation database used for this report consists of archived Brewer and Dobson daily total ozone data that are downloaded from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC, http://www.woudc.org). WOUDC is one of the World Data Centres, which are part of the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO). These data are not randomly and automatically archived; instead, they are quality controlled, first by each station and, secondly by WOUDC.

For the quality of the reference ground-based data, used for the validation of the total ozone products, updated information were extracted from recent inter-comparisons and calibration records. This continuously updated selection of ground-based measurements has already been used numerous times in the validation and analysis of global total ozone records, such as the inter-comparison between the OMI/Aura TOMS and OMI/Aura DOAS algorithms (Balis et al., 2007a), the validation of ten years of GOME/ERS-2 ozone record (Balis et al., 2007b), the validation of the updated version of the OMI/Aura TOMS algorithm (Antón et al., 2009), the GOME-2/Metop-A validation (Loyola et al., 2011; Koukouli et al., 2012), the GOME-2/Metop-B validation (Hao et al., 2014), the evaluation of the European Space Agency's Ozone Climate Change Initiative project (O3-CCI) TOCs (Koukouli et al., 2015, Garane et al., 2018) and the validation of the TROPOMI/S5P total ozone column products (Garane et al., 2019). In all the aforementioned works, LAP/AUTH assumes the leading role in the validation efforts.

In this report, we use archived daily total ozone measuremnts for the comparisons covering the period **February to July 2019,** depending on the availability of data for each individual station. Most stations upload their data to the WOUDC database two to four months after observation, which is the reason for the limited number of available co-locations especially for the most recent months of the validation and mainly for the Southern Hemisphere where the number of available stations is smaller. The WOUDC stations considered for the comparisons are listed in Tables A.1 and A.2 (Appendix I) and they are also spatially depicted in Figure 1.

2.2 Co-location methodology

After the generation of the satellite overpass files for each station including all relevant parameters for each measurement, a co-location methodology is applied using direct-sun GB measurements from Dobson and Brewers for the comparisons. Specifically, pairs of co-located satellite and daily-mean ground-based measurements are formed and their percentage difference is calculated using the simple formula:

$$Diff\ (\%) = \frac{(satellite - ground)}{ground}\%$$

The co-location criteria applied to minimize the noise of the comparisons are:

- the satellite and groud-based daily total ozone measurements have to correspond to the same day, and
- the maximum search radius between the ground-based stations and the centre coordinates of the satellite pixel is set to 150 km. The spatially closest satellite observation is paired with the ground-based station's daily-mean measurement. Due to the different spatial resolution of TROPOMI (see Table 1) the search radius for the respective co-locations is set to 10 km, (Garane et al., 2019).

In all comparative plots and statistics presented in this report only the direct sun (DS) Brewer and Dobson observations are used for the computation of the percentage differences between satellite and ground-based measurements, since they are considered of higher accuracy than all the other types of ground-based observations. This is the reason that some of the plots in the following figures are denoted as “DS only”.

The monthly means that are shown in the respective time-series plots are calculated by averaging the total number of available co-locations per month.The error bars in the plots (where they are shown) stand for the 1σ standard deviation of the means. The mean values are always extracted from averaging of all individual daily measurements that fall within the bin in question.

Finally, only Northern Hemisphere Brewer ground-based stations are considered, because the number of stations in the Southern Hemisphere is very limited and they are mainly located on Antarctica.

3. VALIDATION ANALYSIS

3.1 Global comparisons between GOME-2C and Dobson ground based TOCs

In this section, the archived and quality-controlled Dobson total ozone data, for the period February – July 2019, are used for the validation of GOME-2C TOCs. Figure 2 shows the monthly mean time series of the percentage differences between GOME-2C and co-located (in space and in time) ground-based measurements. In the left panel the Northern Hemisphere (NH) time series is shown, while to the right the respective comparisons for the Southern Hemisphere (SH) are depicted. The mean bias of the percentage differences for the NH was found to be 1.7 ± 0.9 % and the respective mean standard deviation of the available monthly means is 3.4 %. This suggests that GOME-2C has an offset relative to Dobson readings by ~ 1.7 %. In the SH, the mean bias is smaller, 0.9 ± 0.9 %, but that timeseries is noisier, giving a higher mean standard deviation, 4.1%, which is mostly due to the limited availability of the ground-based measurements in this part of the globe. Since it is expected that the GOME-2C/Dobson comparisons will have an enhanced seasonal dependence (due to the well-known dependency of Dobson measurements on effective temperature, see Koukouli et al. (2016)), these numbers (i.e. the mean bias of the percentage difference) are expected to change significantly when a full year of comparisons will become available.

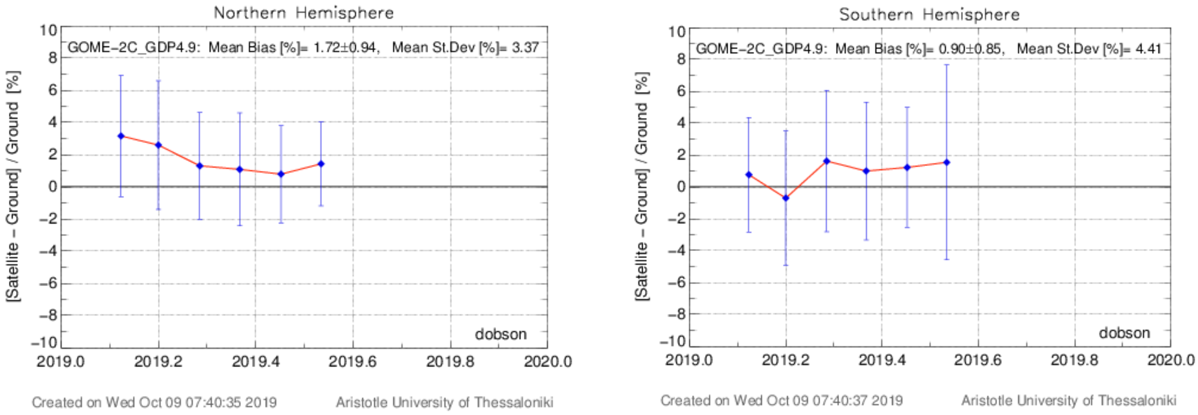

Figure 2: The time series of the monthly mean percentage differences between GOME-2C and ground-based Dobson measurements, shown for the Northern (left panel) and the Southern Hemisphere (right panel).

In Figure 3, left panel, the nearly normal distribution of the percentage differences between GOME-2C and the Dobson ground-based measurements, for the 2219 co-locations, is shown. The average overall difference between GOME-2C and Dobson observations is 1.3 ± 3.5%. The two data sets show a remarkably high correlation coefficient of 0.971 as shown in Figure 3, right panel, with small scatter, due to the use of the archived and quality assured ground-based data and the high quality of the GOME-2C data.

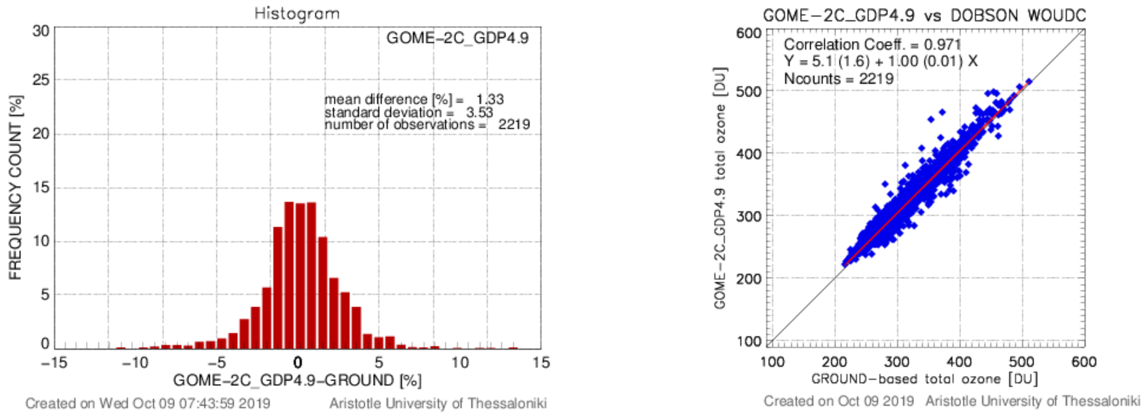

Figure 3: Left panel: the distribution of the percentage differences between GOME-2C and Dobson TOCs for the total number of co-locations found. Right panel: a scatter plot of the co-located total ozone values measured by GOME-2C and Dobson instruments.

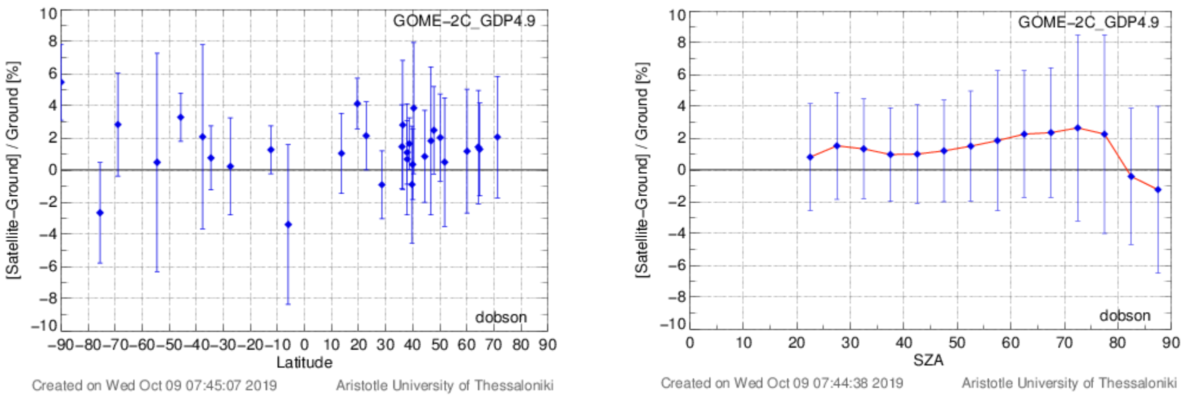

Figure 4: The percentage differences between co-located GOME-2C measurements and TOCs from Dobson instruments plotted versus the latitude of each ground-based station (left panel). To the right, the dependency of the percentage differences on solar zenith angle.

In Figure 4, left panel, the mean percentage differences per station with available ground-based data are shown, versus the latitude of the stations' locations. It is clear here as well that the NH ground-based stations have a positive mean bias and a moderate variability, whereas in most of the SH stations the variability is ~ 5-6%. The mean bias of each station cannot not be attributed to GOME-2C only, since it is well known that some ground-based stations overestimate or underestimate ozone systematically. Some of them are usually left out of our validation exercises, but in this case where a temporally limited data set is available for validation, all ground-based stations were used to increase the number of co-locations. Nevertheless, it is important to note that there is no clear pattern in the dependency of the percentage differences on latitude.

To the right panel of Figure 4, the dependency of the percentage differences on solar zenith angle is shown. GOME-2C reports higher TOCs than Dobson by ~1% for SZAs below 50°, and their difference increases with SZA, reaching +2.5 % for SZAs 60° - 70°. Based on the previous validation reports of GDP4.X TOC products, the comparisons of GOME-2C are expected to show such a dependency. However, the current, rather short, sampling of data, especially for the large zenith angles, does not allow us to quantify this dependence in a significant way.

Finally, the Dobson station of Tamanrasset, Algeria, is used as an example of the comparisons of the overpasses of GOME-2C to ground-based measurements. This particular station was chosen because of its high number of co-locations during the time-period of interest. In Figure 5, the time series (left panel) and the respective scatter plot (right panel) of the available co-locations show that, even though there is a bias of ~+2% between the two instruments, it remains stable for the time period under consideration and the correlation coefficient (0.94) is very satisfying for such a limited dataset.

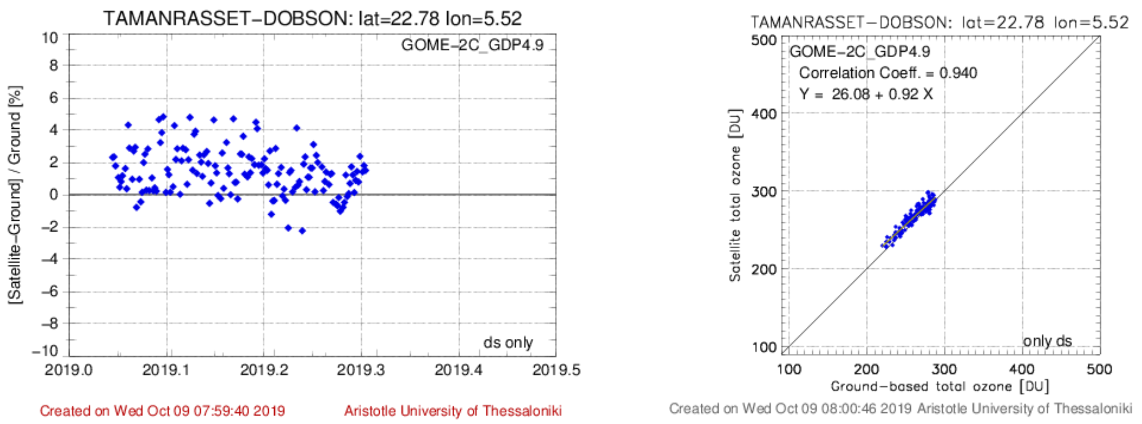

Figure 5: Time series of the percentage differences (left panel) and the respective scatter plot (right panel) for the TOC measurements of GOME-2C and the Dobson instrument operated at Tamanrasset, Algeria.

3.2 Global Comparisons between GOME-2C and Brewer ground based TOCs

In accordance with the previous section, the archived and quality-controlled Brewer total ozone data, for the period February – July 2019, are used here for the validation of GOME-2C TOCs. In Figure 6, the time series of the monthly mean percentage differences between GOME-2C and co-located (in space and in time) Brewer ground-based measurements, is shown for the NH only, because the ground-based stations equipped with Brewer spectrophotometers are extremely limited in the SH and mainly located at the Antarctica. The mean bias of the percentage differences for the NH was found to be 0.5 ± 0.6 % and the respective mean standard deviation of the available monthly means is 2.9 %, which indicates a very good agreement between the two instruments. The seasonal variability cannot be commented using a dataset that covers less than a full year of observations, but in any case, it is expected to be very small for the Brewer comparisons.

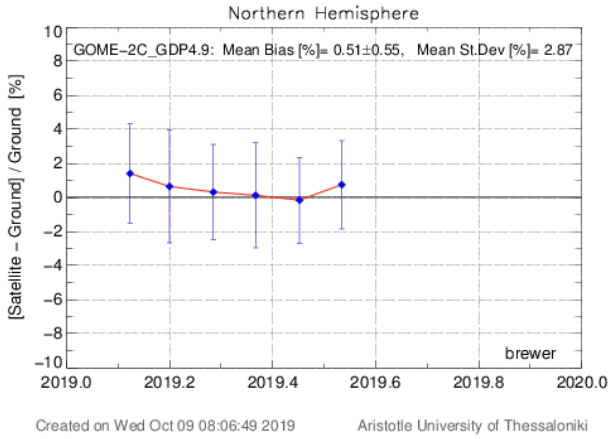

Figure 6: The time series of the monthly mean percentage differences between GOME2C and ground-based Brewer measurements, shown for the Northern Hemisphere only.

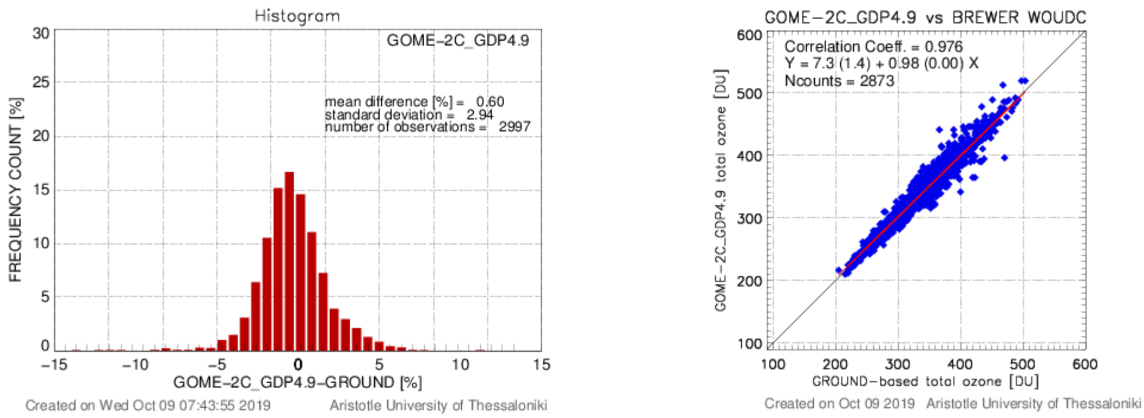

Figure 7: Left panel: the distribution of the percentage differences between GOME2C and Brewer TOCs for the total number of co-locations found. Right panel: a scatter plot of the co-located total ozone values measured by GOME2C and Brewer instruments

In Figure 7, the almost normal distribution of the percentage differences between GOME-2C and the Brewer ground-based measurements, for the total number of 2997 co-locations that were found, is shown. The average difference between GOME-2C and Brewer observations is 0.6 ± 2.9 %. The correlation coefficient between the two data sets is remarkably high (0.976), as it shown in Figure 7, right panel, with small scatter due to the use of the high-quality ground-based and satellite data.

To the right panel of Figure 8, the dependency of the percentage differences on solar zenith angle is shown. For SZAs up to 50° the GOME-2C TOC values are almost the same to Brewer measurements. For SZAs above 50°, GOME-2C reports higher TOC values than Brewer, reaching +2.5 % for SZAs 70° - 80°. In the current data set, the available number of co-locations with SZA less than 25° and more than 70° is very limited, therefore it is not safe to quantify this dependence in a significant way. Nevertheless, based on previous validation reports of GDP4.X TOC products, the comparisons of GOME-2C are expected to show a dependency similar to the curve seen in Figure 8 (right panel).

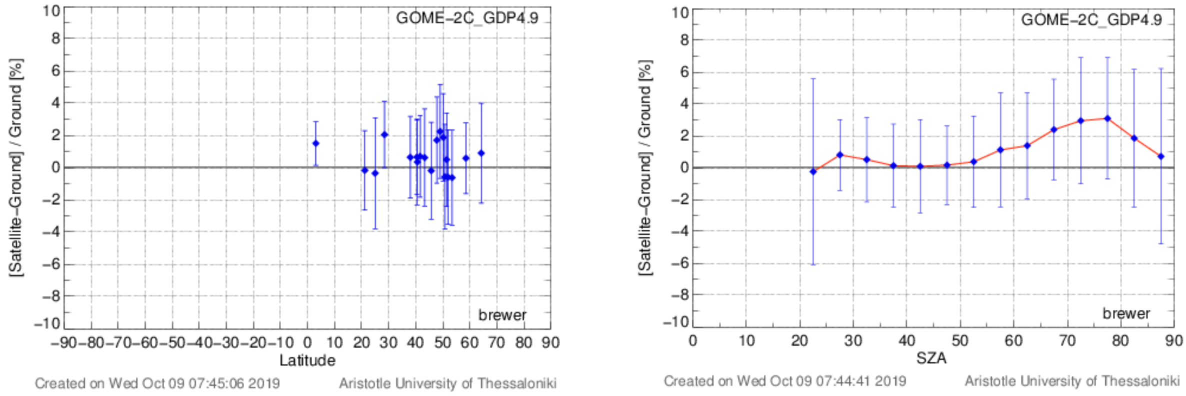

Figure 8: The percentage differences between co-located GOME2C measurements and TOCs from Brewer instruments plotted versus the latitude of each station (left panel). To the right, the dependency of the percentage differences on solar zenith angle, is shown.

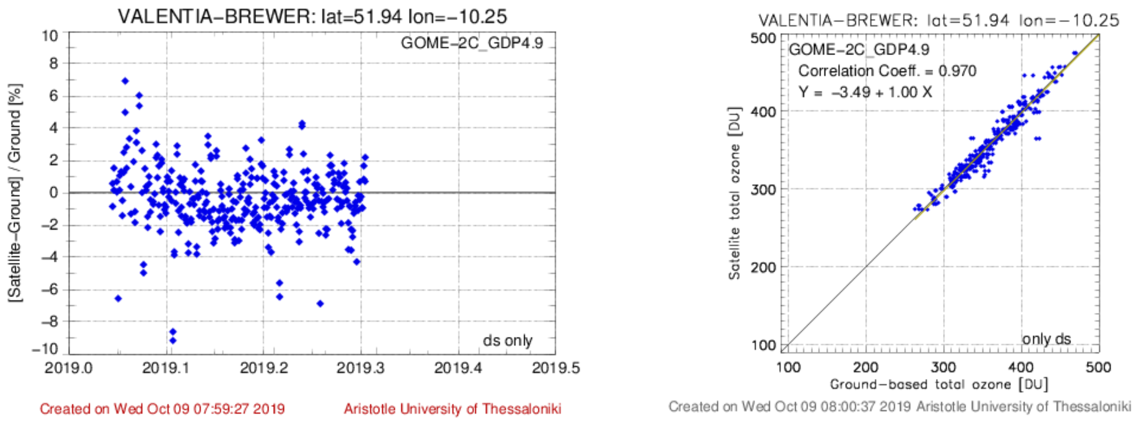

Figure 9: Time series of the percentage differences (left panel) and the respective scatter plot (right panel) for the TOC measurements of GOME2C and the Brewer instrument operated at Valentia, Spain.

In Figure 9, the Brewer station of Valentia, Spain, is used as an example of the comparisons between the overpasses of GOME-2C to ground-based measurements. The time series (left panel) and the respective scatter plot (right panel) show that there is a very small bias, ~ -0.5 %, between the two instruments which remains stable for the most part of the time period under consideration and the correlation coefficient (0.970) is very satisfying for such a limited dataset.

3.3 Comparisons of GOME-2C with GOME-2A, GOME-2B and TROPOMI total ozone columns against co-located ground-based measurements

In this section, GOME-2C is compared to GOME-2B, GOME-2A (both processed with the algorithm GDP4.8) and TROPOMI/S5P NRTI TOC products. In the following, we show comparisons of all sensors with respect to ground-based data (separately for Dobsons and Brewers), temporally restricted only to common days of operation of all sensors. Note that, for reasons of brevity, the respective plots with the Brewer comparisons are displayed in the Appendix II. A global direct comparison between the GOME-2C and GOME-2B instruments' estimates is presented in section 3.4.

In Table 1, we presented the instrument characteristics of each satellite sensor considered in the comparisons that will be used in this section. Apart from algorithm issues, differences in the estimated total ozone can be also a result of differences in the Level-1 products, in the instruments and satellites themselves and therefore such differences should be considered when comparing different satellite datasets. In addition to the parameters listed in Table 1, the differential signal-to-noise characteristics of the instruments can have an impact on the total ozone column retrieval, as well.

Discussion on the consistency of GOME-2C with other satellite TOC data sets

The time series of the monthly mean percentage differences between the three GOME-2 sensors compared to Dobson ground-based measurements, are displayed in Figure 10, left panel for the Northern Hemisphere comparisons and right panel for the Southern Hemisphere. The whole time period of operation of each satellite sensor is used for these plots, namely GOME-2A (orange line and symbols) since 2007, GOME-2B (green line and symbols) since mid-2013 and GOME-2C (blue line and symbols) for the time period under validation. The respective time-series for the Brewer comparisons are shown in Figure A. 1.

Even though the differences in the time periods of operation are major, the continuity of the TOC record and the good consistency between the three sensors is evident. The mean bias of their datasets for the NH are almost the same (~+ 1.5 %), which is also true for the mean standard deviation of their means (~ 3.5%). This is a very encouraging result, showing that GOME-2C is already in the same quality path as the rest of the GOME-2 family. In the SH, the mean bias for all three sensors is ~ 1.1 – 1.4 % and the mean standard deviation is higher than it is in the NH, ~4.1%, but as it was said in Section 3.1, the number of co-locations with Dobson ground-based measurements in the SH is rather limited, which justifies the greater variability.

It can be seen already from this figure (Figure 10) that GOME-2C agrees well with GOME-2B and shows differences to GOME-2A during early 2019, due to some calibration issues of the latter. Specifically, GOME-2A lost solar visibility since January 2019 until mid-March 2019 and a solar model was switched on in order to substitute the solar measurements. Based on this, in the following figures, where we will focus exclusively on the time period of the GOME-2C operation, mainly GOME-2B and secondly TROPOMI NRTI TOC products will be used to validate our sensor of interest.

In Figure 11, the monthly mean time series of the percentage differences to ground-based measurements is shown for GOME-2C (blue line and symbols), GOME-2B (red line and symbols) and TROPOMI NRTI TOC comparisons. Here, the GOME-2B and TROPOMI time series are temporally limited to the time period of operation of GOME-2C, to ensure the comparability between each pair of sensors. As it can be seen, GOME-2C reports higher TOC values than GOME-2B and the mean difference in bias is + 0.5 % for the NH and the SH (see also Figure A. 2). The increasing difference between GOME-2C and GOME-2B with time is an interesting feature, but at least one full year of data is needed to conclude to a possible pattern or seasonality for the overestimation of GOME-2C the NH. The mean standard deviation of the comparisons is smaller for GOME-2C than GOME-2B for this time period, showing that the latter is noisier. Besides this small difference in the bias of the two sensors, the consistency between them, during this period of common operation, is very good.

Comparing GOME-2C to TROPOMI NRTI TOC, we can see a very good consistency as well, except for the Dobson comparisons during March and April in the NH. As discussed in Garane et al. (2019), this is an effect of the surface albedo climatology used by the TROPOMI NRTI TOC retrieval algorithm which causes large discrepancies mainly in the Northern high latitudes. No such discrepancy is seen in the Brewer comparisons, because there are no co-locations available for latitudes higher than 70°N.

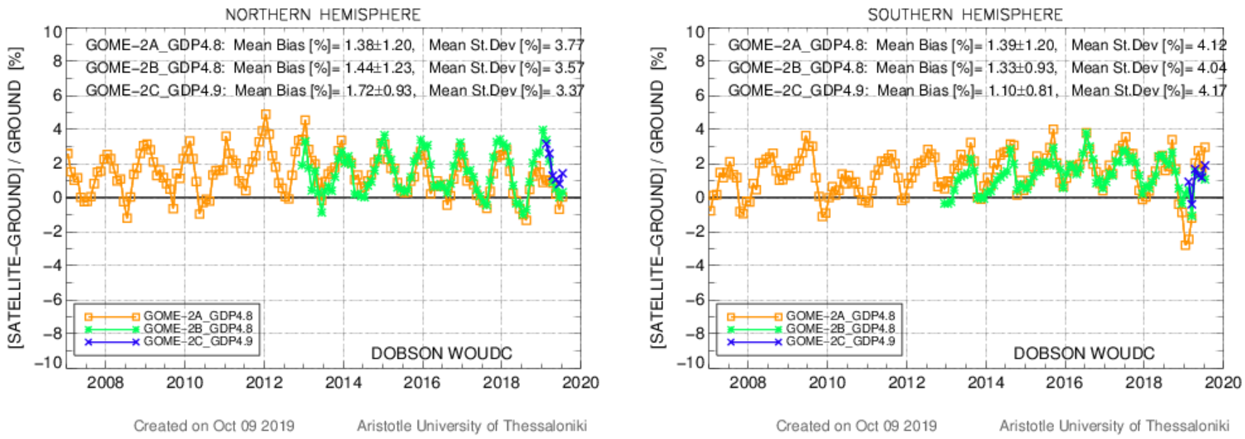

Figure 10: Time series of the monthly mean percentage differences between the three GOME-2 sensors and Dobson ground-based measurements, for the NH (left panel) and the SH (right panel). The blue line and symbols show the GOME-2C comparisons, the green line and symbols show the GOME-2B comparisons and the orange line and symbols show the GOME-2A comparison, for the respective total time period of operation.

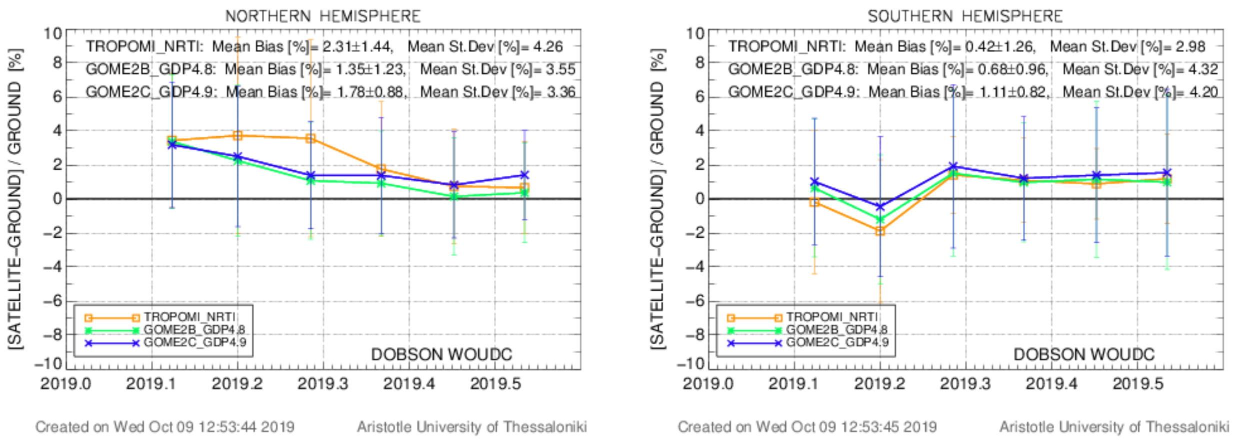

Figure 11: Time series of the monthly mean percentage differences between GOME-2C (blue line), GOME-2B (red line) and TROPOMI vs Dobson ground-based measurements, for the common time period of operation and at the two hemispheres (NH in the left panel; SH in the right panel).

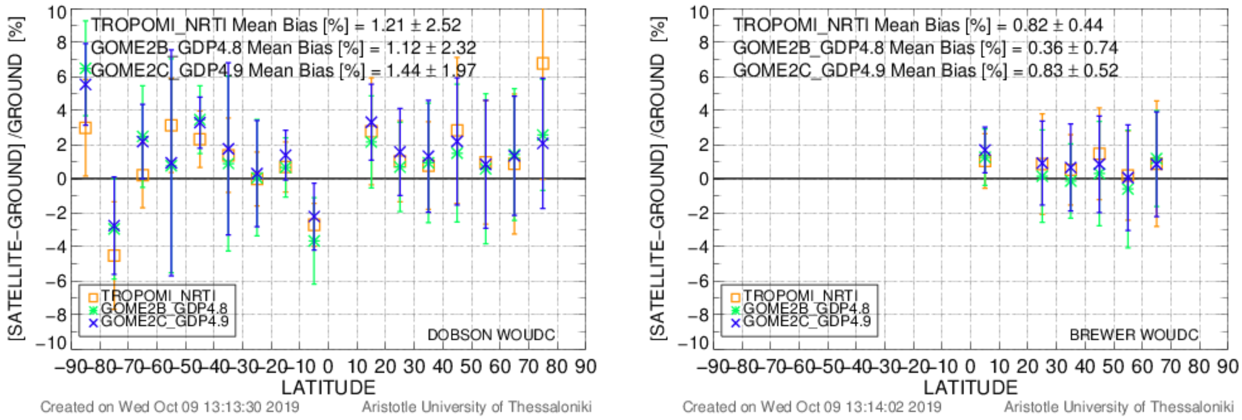

Figure 12: The pole-to-pole diagrams of the percentage differences of the three satellite sensors for the Dobson (left panel) and the Brewer (right panel) comparisons.

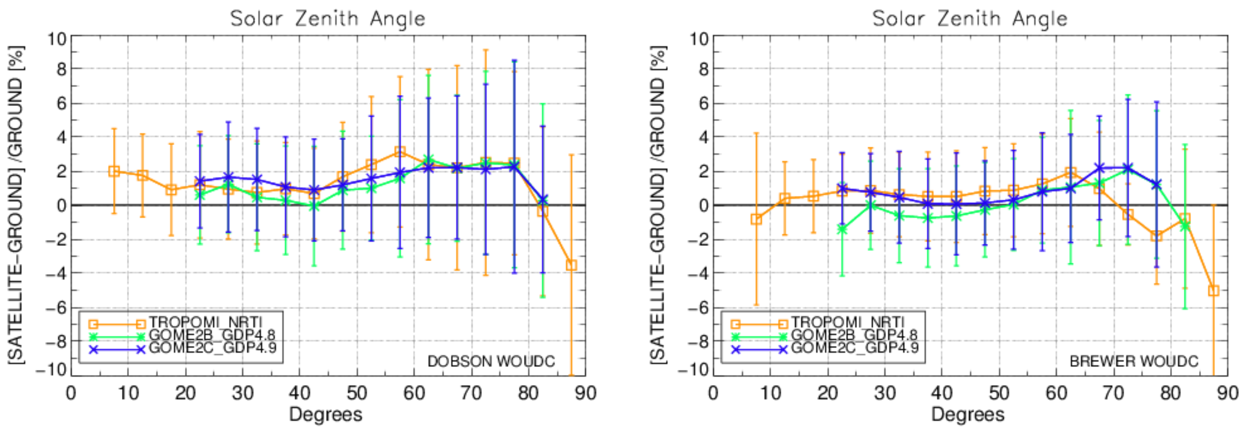

Figure 13: The dependency of the percentage differences on SZA for the Dobson (left panel) and the Brewer (right panel) comparisons.

In Figure 12 the percentage differences between TOC retrieved by the three sensors (GOME-2C, GOME-2B and TROPOMI/S5P) and the co-located measurements performed by Dobson (left panel) and Brewer (right panel) ground-based instruments, are averaged in 10° latitude bins and displayed versus latitude. GOME-2C reports slightly higher measurements than GOME-2B, mainly in the tropics and the middle latitudes of both hemispheres. The difference is ~ 0.5 - 1 %, but it is 0% or becomes negative (up to -1%) for latitudes higher than 60° in both hemispheres.

As for the dependency of the percentage differences on solar zenith angle (SZA), in Figure 13 it is seen that the Dobson comparisons (left panel) to GOME-2C below 60° have a bias of about 1.5 - 2 %, but above 60° the dependency on SZA is stable and equal to 2 % (the number of co-locations with SZA>80° is very limited). As it was said before, this is an expected dependency for the comparisons to Dobson ground-based measurements due to their well-known dependency on effective temperature. The dependency on SZA is less pronounced for the GOME-2C to Brewer comparisons (right panel). The mean percentage differences between GOME-2C and Brewer below 60° are 0-1% and become ~1-2% for SZAs > 60°.

From this figure it is also seen that the differences between GOME-2C and GOME-2B result mostly from measurements with SZA<50°, which are the bins with the higher number of co-locations and strongly affect the overall comparison. Above 50° the consistency between the two sensors is excellent. Nevertheless, the current sampling of data, especially for higher zenith angles, does not allow us to quantify this dependence in a significant way.

Discussion on the dependence of GOME-2C on various geophysical influence quantities

For the validation of GOME-2C, many influence quantities were studied. In the following, only the parameters that are characterized by interesting features will be shown, for GOME-2C and GOME-2B. The comparisons seen here use the Dobson ground-based measurements as the ground-truth. The respective Brewer comparisons are included in the Appendix II. Note that the numbers at the top of each figure show the number of co-locations that are averaged for each bin and they appear only for those bins for which the number of co-locations is less than 3% of the total.

In Figure 14 (and Figure A. 3) the dependency of the percentage differences on scan angle is shown. The two sensors are in very good agreement for angles below 0°, but above that and up to 50°, GOME-2C reports higher TOCs than GOME-2B by up to 2%.

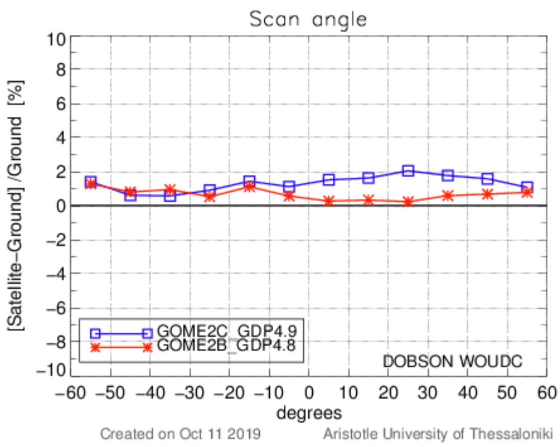

Figure 14: The dependency of the percentage differences between the two sensors (GOME-2C and GOME-2B) and Dobson ground-based TOC measurements on the scan angle.

In this context, the influence of the cloud parameters on the GOME-2C TOC retrievals was studied. In Figure 15 (and Figure A. 4), three cloud parameters are shown: cloud fraction (panel a), cloud top pressure (panel b) and cloud top albedo (panel c). As is indicated from all three figures, GOME-2C and GOME-2B do not appear to depend on these cloud parameters significantly. Nevertheless, it can be noted that for cloud top pressure values above 650 hPa the relation between the two sensors becomes stable and the 0.5-1% overestimation of TOC by GOME-2C becomes clearer. The cloud top albedo seems to have a slight influence on both sensors, as well. The percentage differences are decreasing from 2% to 0% when the albedo is increasing from 0 to 0.9, but this is also a characteristic of both GOME-2 sensors.

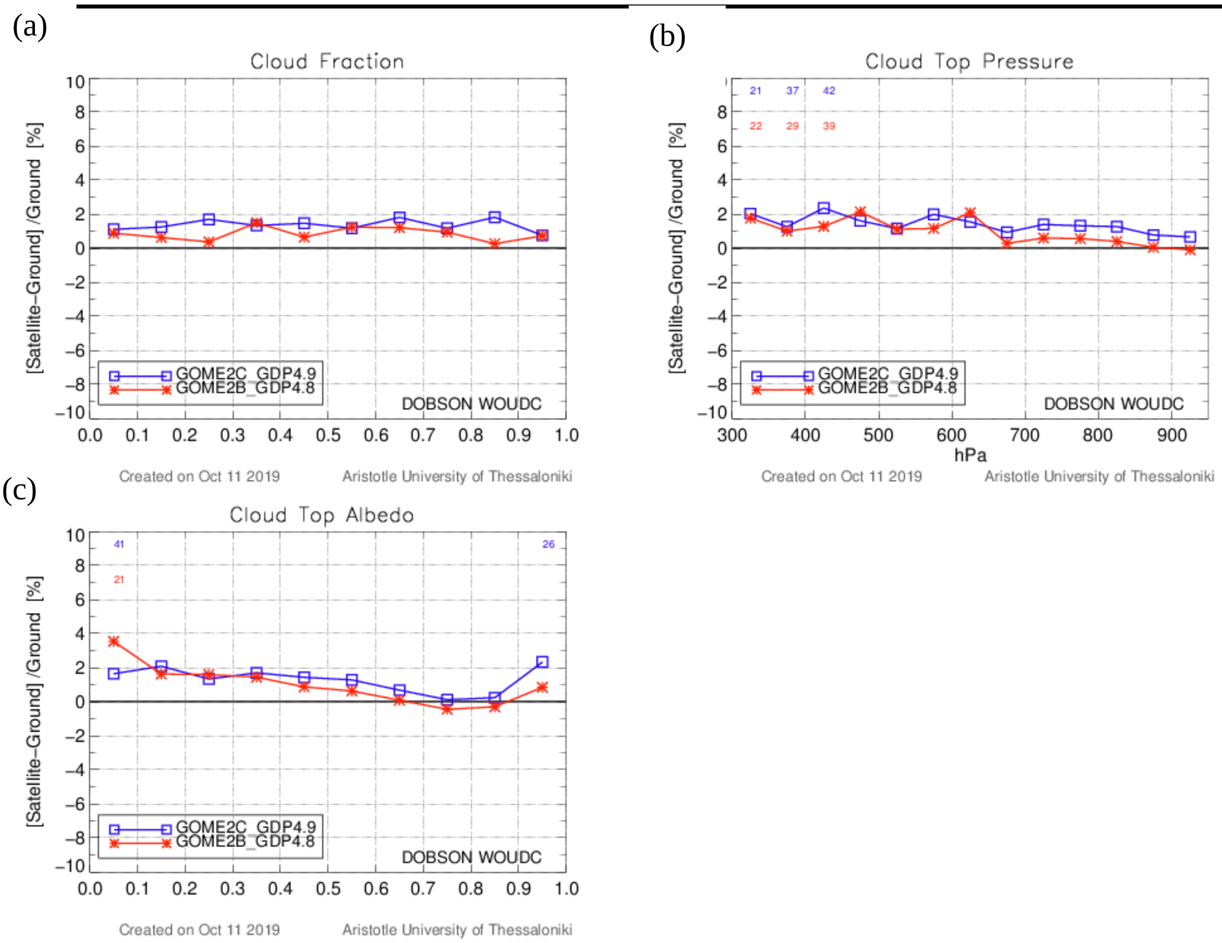

Figure 15: The dependency of the comparisons of the two sensors to Dobson ground-based measurements on three different cloud parameters, namely, panel (a) - cloud fraction, panel (b) - cloud top pressure and panel (c) cloud top albedo.

3.4 Direct comparisons between GOME-2C vs GOME-2B total ozone columns.

To avoid the problem of the non-global representation of ground-based TOC measurements, the direct comparisons of GOME-2C to GOME-2B is investigated in this section. As was discussed before, since GOME-2B is operating in parallel to GOME-2C, it can be used to validate/verify the GOME-2C total ozone columns. This comparison covers one month of GOME-2C data, namely April 2019.

In Figure 16 the global maps of the monthly mean total ozone for the month of April 2019 are shown, as reported by GOME-2C (upper left panel) and GOME-2B (upper right panel), in D.U. In the bottom panel, the global map of the relative differences (in percentages) between GOME-2C and GOME-2B is shown. The differences are negative, and go up to ~ -4%, near the South Pole, but for the most part of the SH they are positive and about +1 to +2 %, which is in accordance with the results that emerged from our latitudinal comparisons versus ground-based instruments (see Figure 12). In the NH, some negative differences up to -2% appear mainly over oceans. These negative differences are not easy to be captured when using the ground-based instruments as a means of comparison, due to their location. The global mean percentage difference between the two sensors is 0.4 %, or, in terms of absolute difference, 1.19 D.U., confirming the slightly higher TOC that is reported by GOME-2C compared to GOME-2B.

4. SUMMARY STATISTICS

The main purpose of this analysis is to examine the performance of GOME-2C and its consistency to ground-based measurements, as well as to GOME-2B. The comparison results of the GOME2/Metop-C product are summarized in **Table 2**, where the second column shows the percentage differences, the third is the standard deviation in % and the fourth is the correlation coefficient for each pair of compared datasets. The statistics are based only on the analysis of the period February to July 2019 and thus are not comparable with similar tables that appeared in previous reports, which analyzed GOME-2A and GOME-2B results for larger time periods and for complete years of data.

According to the Product Requirement Document (PRD, Hovila et al., 2019), the target accuracy for GOME-2C TOC is 4% for SZA<80° and 6% for SZA>80°, while the optimal accuracy is 1.5%. As it can be seen in the table, the respective accuracy that resulted from our analysis is well within these targets, being less than 3.7% for SZA < 80° and less than 4.7% for SZA>80°.

5. CONCLUSIONS

The main aim of this Total Ozone Column validation report is to evaluate the first six months of operation of the new GOME-2/MetopC. Three type of comparisons were performed to assess the quality of GOME-2C Total Ozone Column datasets:

- the GOME-2C TOC data were firstly compared to archived ground-based Dobson and Brewer total ozone measurements (Sections 3.1 and 3.2),
- then it was compared to other concurrently observing satellite instruments, such as GOME2/MetopA, GOME2/MetopB and S5P/TROPOMI, over the same ground-based observational network (Section 3.3),
- and thirdly, it was globally and directly compared with the GOME2/MetopB data, analyzed with the same version of the algorithm (Section 3.4).

The average difference between **GOME-2C and Dobson observations is 1.3 ± 3.5% based on 2219 co-locations and the respective difference between GOME-2C and Brewer observations is 0.6 ± 2.9%, based on ~3000 co-locations**. Both comparisons show a remarkably high correlation coefficient of 0.971 and 0.976 respectively, with small standard deviation levels considering the rather low amount of collocated ground-based measurements. Additionally, **the accuracy target of 4% for SZA <80° and 6% for SZA > 80° is met.**

Compared to GOME-2B, it was seen that on a global scale GOME-2C is providing higher total ozone columns with a mean of 0.5-0.6% but has a lower variability by ~ 0.2 %. This is the main conclusion of this validation report and it is further supported by the direct comparisons between GOME-2C and GOME-2B, which result to a consistent outcome. Nevertheless, all latitudinal and solar zenith angle features are quite similar between the two sister instruments. In more detail, it was seen that the difference [GOME-2C - GOME-2B]:

- is up to +1% in the middle latitudes of both hemispheres and tends to be negative closer to the poles (-4% South Pole).
- is 0.5 – 1% for SZAs < 55°, but above 55° the two sensors have a very good consistency
- is ~ +2 % for positive scan angles and 0 % for negative scan angles.

Finally, many influence quantities were studied, and no particular dependencies were found, except for a dependency on cloud albedo (up to 2%) seen for both sensors.

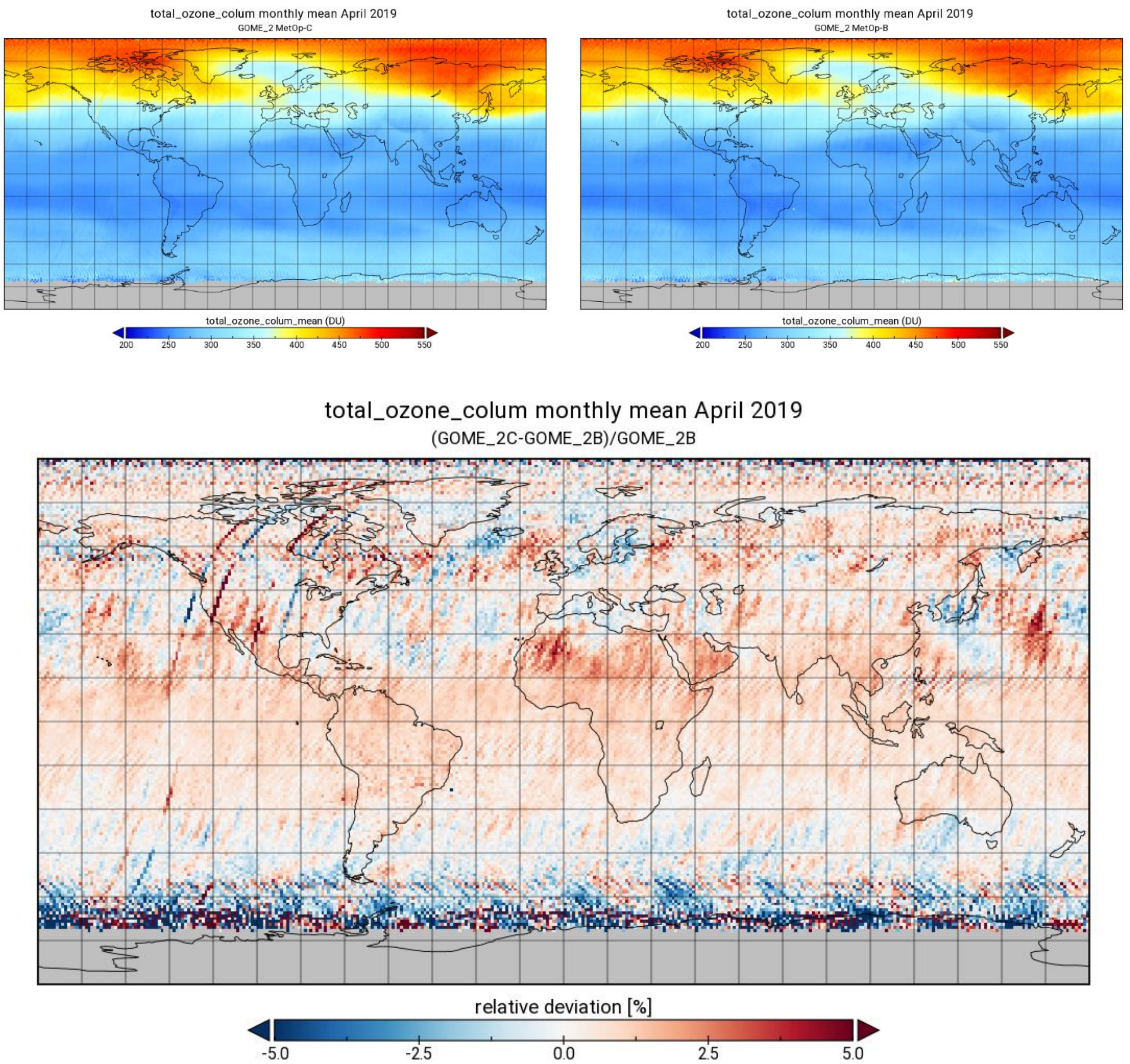

Figure 16: Global maps of the monthly mean total ozone for the month of April 2019, as reported by GOME-2C (upper left panel) and GOME-2B (upper right panel), in D.U. Below panel: the global map of the relative differences (in percentages) between GOME-2C and GOME-2B.

Table 2: Mean global percentage differences, standard deviations and correlation coefficients between the various instruments examined for coincident measurements only.

	mean diff [%]	*std [%]*	correlation
GOME2C GDP4.9 vs Dobson	**1.33**	**3.53**	**0.971**
For SZA<80° (accuracy target 4%)	1.47	**3.69**	0.971
For SZA>80° (accuracy target 6%)	-0.68	**4.59**	0.946
GOME2C GDP4.9 vs Brewer	**0.60**	**2.94**	**0.976**
For SZA<80° (accuracy target 4%)	0.67	**3.03**	0.975
For SZA>80° (accuracy target 6%)	1.47	**4.71**	0.911
GOME2C GDP4.9 vs GOME2B GDP4.8 [for co-locations with Dobsons]	**0.52**	**-0.24**	**0.972**
GOME2C GDP4.9 vs GOME2B GDP4.8 [for co-locations with Brewers]	**0.63**	**-0.26**	**0.956**
GOME2C vs TROPOMI NRTI [for co-locations with Dobsons]	0.21	-0.84	0.935
GOME2C vs TROPOMI NRTI [for co-locations with Brewers]	-0.24	0.17	0.947

With respect to S5P/TROPOMI NRTI total ozone columns, GOME-2C was found to report slightly higher TOCs, especially in the Southern Hemisphere, showing however similar dependencies on latitude and SZA. S5P/TROPOMI was used only as a supplementary means of validation, due to the small differences in the algorithm and its known issues with the surface albedo in the high latitudes.

To conclude, as shown from the validation of 6 months of available data, GOME-2C TOC measurements are of equal accuracy and precision and may continue the long-term TOC dataset provided by the GOME-2 suite of instruments since 2007.

LAP/AUTH is announcing the upgrade of the AC SAF Ozone Validation & Quality Assessment web pages which have undergone substantial maintenance and have been moved to a newer, faster and more stable host server. The ACSAF validation webpages currently present the validation results of GOME-2A GDP4.8 and GOME-2B GDP4.8 near real-time and offline Total Ozone Data, following the availability of the ground-based observations. Furthermore, the high resolution Ozone Profile validation comparative plots are hosted here, while the links to the Trace Gas and UV validation remain the same. ***After the GOME2/MetopC ORR is complete, relevant fields that permit access to those validation results will automatically appear****.*

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APPENDIX I

Table A.1: List of Dobson ground-based stations used for the comparisons

STATION ID	NAME	COUNTRY	LATITUDE (degrees)	LONGITUTE (degrees)
2	TAMANRASSET	Algeria	5.51667	22.78333
10	NEW_DELHI	India	77.1751	28.63047
14	TATENO	Japan	140.1333	36.05
19	BISMARCK	USA	-100.75	46.76667
27	BRISBANE	Australia	153.0833	-27.4167
29	MACQUARIE_ISLAND	Australia	158.9385	-54.4985
31	MAUNA_LOA	USA	-155.576	19.53623
43	LERWICK	UK	-1.18333	60.13334
57	HALLEY_BAY	Antarctica	-26.18	-75.62
67	BOULDER	USA	-105.261	39.991
68	BELSK	Poland	20.79	51.84
74	VARANASI	India	83.01667	25.3
82	LISBON	Portugal	-9.13333	38.76667
84	DARWIN	Australia	130.8833	-12.4167
91	BUENOS-AIRES	Argentina	-58.4839	-34.59
96	HRADEC_KRALOVE	Czech_Republic	15.8386	50.1772
99	HOHENPEISSENBERG	Germany	11.00962	47.8015
101	SYOWA	Antarctica	39.58333	-69
105	FAIRBANKS	USA	-147.87	64.82
107	WALLOPS_ISLAND	USA	-75.46	37.94
111	AMUNDSEN-SCOTT	Antarctica	-24.8	-89.997
199	BARROW	USA	-156.611	71.32301
208	SHIANGHER	China	116.9618	39.754
216	BANGKOK	Thailand	100.62	13.67
218	MANILA	Philippines	121.05	14.65
219	NATAL	Brazil	-35.2	-6
226	BUCHAREST	Romania	26.13	44.48
253	MELBOURNE	Australia	144.8312	-37.6656
284	VINDELN	Sweden	19.76667	64.23333
293	ATHENS	Greece	23.73	37.98
341	HANFORD	USA	-119.63	36.32
342	COMODORO_RIVADAVIA	Argentina	-67.5	-45.7833
410	AMBERD	ARM	44.25	40.38334
498	KYIV-GOLOSEYEV	Ukraine	30.497	50.364

Table A.2: List of Brewer ground-based stations used for the comparisons.

STATION ID	NAME	COUNTRY	LATITUDE (degrees)	LONGITUTE (degrees)
53	UCCLE	Belgium	4.35876	50.7979
95	TAIPEI	Taiwan	121.48	25.02
96	HRADEC_KRALOVE	Czech_Republic	15.8386	50.1772
99	HOHENPEISSENBERG	Germany	11.00962	47.8015
261	THESSALONIKI	Greece	22.96	40.63
279	NORKOPING	Sweden	16.152	58.583
284	VINDELN	Sweden	19.76667	64.23333
306	CHENGKUNG	Taiwan	121.37	23.1
308	MADRID	Spain	-3.72	40.45
318	VALENTIA	Ireland	-10.248	51.938
322	PETALING_JAYA	Malaysia	101.65	3.1
330	HANOI	Vietnam	105.8	21.2
331	POPRAD-GANOVCE	Slovakia	20.32	49.03
346	MURCIA	Spain	-1.17	38
352	MANCHESTER	GBR	-2.23	53.47
353	READING	GBR	-0.94	51.44
401	SANTA_CRUZ	Spain	-16.2474	28.47253
405	LA_CORUNA	Spain	-8.47	43.3315
411	ZARAGOZA	Spain	-0.912	41.628
479	AOSTA	Italy	7.357	45.7422

APPENDIX II

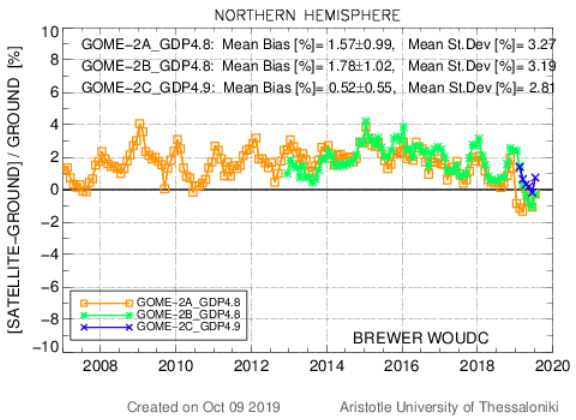

Figure A. 1: As in Figure 10, for the comparisons of the three GOME-2 sensors to Brewer ground-based measurements, for the NH only.

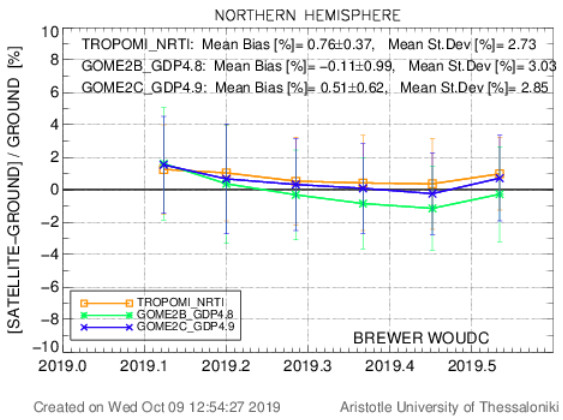

Figure A. 2: As in Figure 11 for the Brewer ground-based measurements in the NH.

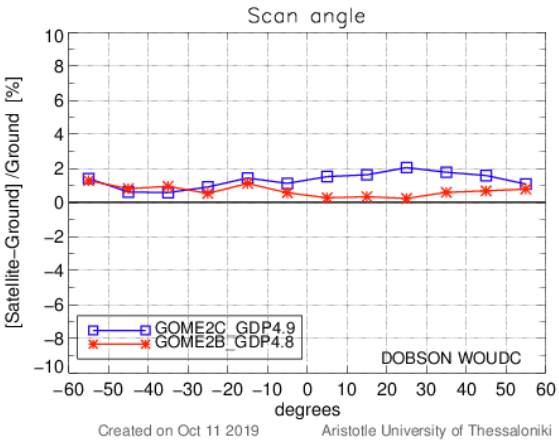

Figure A. 3: As in Figure 14 but for comparisons to Brewer measurements.

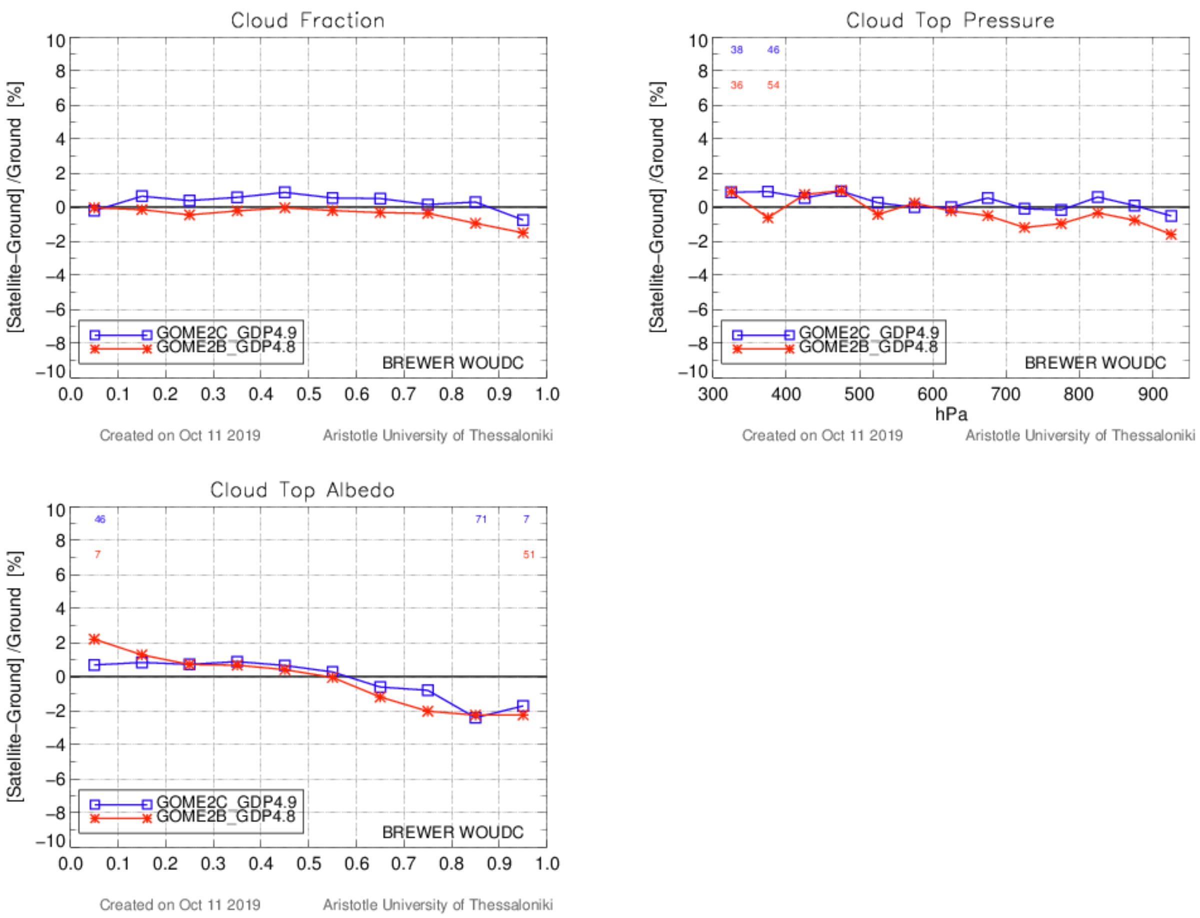

Figure A. 4: As in Figure 15 but for comparisons to Brewer measurements