Description and validation of the OMI very fast delivery products

S. Hassinen,[1] J. Tamminen,[1] A. Tanskanen,[1] G. Leppelmeier,[2] A. Mälkki,[1] T. Koskela,[1] J. M. Karhu,[3] K. Lakkala,[3] P. Veefkind,[4] N. Krotkov,[5] and O. Aulamo[3]

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[1] The Dutch-Finnish Ozone Monitoring Instrument (OMI) is on board the NASA's Earth Observing System (EOS) Aura satellite. The Aura satellite has a so-called direct broadcast (DB) capability to broadcast the measurements to ground stations at the same time as the measurements are being stored in the spacecraft's memory for later transmission to Earth. The Finnish Meteorological Institute's very fast delivery (VFD) processing system utilizes this direct broadcast to produces maps of total ozone and ultraviolet radiation over Europe within 15 min after the satellite overpass Sodankylä ground station in northern Finland. The VFD products include maps of total ozone, ultraviolet index, and ultraviolet daily dose. The aim of this service is to provide up-to-date information on the ozone and ultraviolet situation for the general public and snapshots of the current situation for scientists. The accuracy of the VFD products compares well with standard off-line OMI ozone products as well as ground-based Brewer measurements. After the VFD update in May 2006, the differences with Brewer measurements are -1.0 ± 7.2 DU for Sodankylä and -0.6 ± 8.0 DU for Jokioinen. Differences to OMDOAO3 and OMTO3 products are 2.1 ± 3.3 DU and 1.6 ± 6.6 DU for Sodankylä and 1.7 ± 2.0 DU and 0.0 ± 6.1 DU for Jokioinen, respectively. Between the VFD and Brewer measured UV daily dose products the relative error is generally less than 30%, which compares well to the global off-line OMUVB product.

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1. Introduction

[2] The Ozone Monitoring Instrument (OMI) is a Dutch-Finnish contribution to NASA's EOS Aura satellite [*Levelt et al.*, 2006a]. OMI is a nadir-viewing instrument that measures scattered sunlight over a spectral range of 250–500 nm, from which one can derive information on atmospheric composition, such as the content of ozone, NO_2, SO_2, HCHO, aerosols, cloud heights and fractions, and surface UV radiation. The Sun-synchronous orbit together with the broad swath (2600 km) ensures daily coverage of the entire sunlit globe and the small ground pixel size (13 × 24 km at nadir) presents detailed spatial distribution not available from earlier missions. For details of the OMI mission and scientific objectives, see *Levelt et al.* [2006b].

[3] There are two global ozone column products based on the OMI measurements. The OMTO3 product is based on the Total Ozone Mapping Spectrometer (TOMS) algorithm, which is further optimized for OMI [*Bhartia and Wellemeyer*, 2002]. The second product is OMDOAO3, which is based on the DOAS algorithm [*Veefkind et al.*, 2006]. Furthermore, there exist two additional ozone products, KNMI's near real time (NRT) ozone and FMI's very fast delivery (VFD) product, which both are based on the same DOAS algorithm as the OMDOAO3 product.

[4] The UV algorithm used in the VFD processing is the same algorithm that is used in the OMI global surface UV processing (OMUVB) and is based on the TOMS UV algorithms with further optimization for OMI [*Krotkov et al.*, 2002; *Tanskanen et al.*, 2006]. In the VFD processing system the total column ozone retrieved with the DOAS algorithm [*Veefkind et al.*, 2006] is used as an input for the OMI surface UV algorithm. Additionally, the OMI measured 360 nm radiance to solar irradiance ratio is used for estimation of the attenuation effect of clouds on surface UV.

[5] The VFD processing uses the EOS-Aura satellite's capability to send direct broadcast (DB) data [*Leppelmeier et al.*, 2006]. DB means the ability to broadcast data at the same time as they are being measured and stored in the spacecraft's memory for later transmission to Earth. Thus, the ground station can receive the data only when the satellite is visible from the ground station, which restricts the area that is covered by the VFD system. The OMI-VFD receiving station is located at Sodankylä (67.4°N, 26.6°E), in the northern Finland and is currently the only ground station that exploits the DB capability of the Aura satellite. OMI VFD provides measurements over Europe, typically

[1]Finnish Meteorological Institute, Helsinki, Finland.
[2]G&S Associates, Espoo, Finland.
[3]Finnish Meteorological Institute, Sodankylä, Finland.
[4]Royal Netherlands Meteorological Institute, De Bilt, Netherlands.
[5]GEST Center, University of Maryland, Baltimore County, Baltimore, Maryland, USA.

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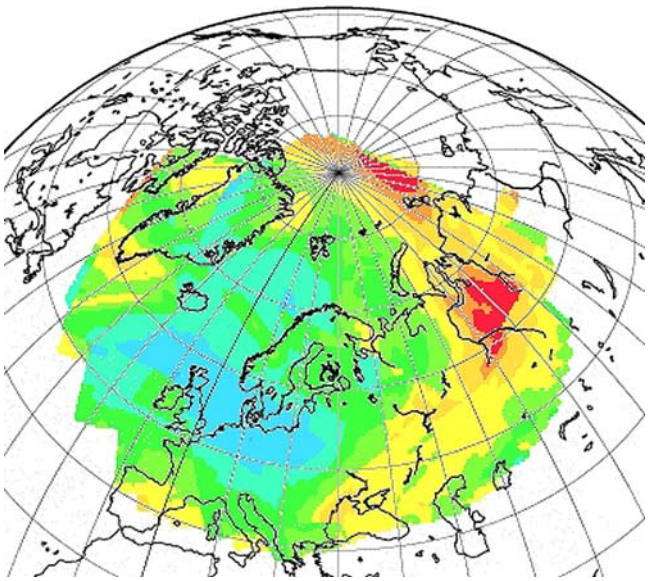

Figure 1. Composite image of the total column ozone measured by OMI for the 10 day period ending 10 April 2007. Later images are pasted on top of the previous ones. The image shows the geographical extent of direct broadcast receiving in Sodankylä and can be used to show the latest ozone situation over Europe and the Arctic Ocean.

from central Italy to the North Pole (Figure 1). The VFD products are maps of total ozone, UV Index and the daily erythemal surface UV dose (Figure 2). They are made publicly available 15 min after the satellite overpass. The products are provided as images at http://omivfd.fmi.fi. The service has been operational since March 2006. Data from two to six orbits are received and processed daily depending on the season and receiving geometry.

[6] In this paper the VFD total ozone and UV erythemal daily dose products are validated using Brewer measurements from Sodankylä and Jokioinen as well as standard off-line OMI total ozone products. First the validation setup and data products are described. Then follows the validation. The validation discussion focus on the reasons behind the found discrepancies.

2. VFD Validation

[7] The validation data consist of OMI-VFD values, Brewer ground-based measurements for ozone and UV radiation, and OMI OMTO3 and OMDOAO3 off-line data. The Brewer stations are located at Sodankylä (67.4°N, 26.6°E) and Jokioinen (60.8°N, 23.5°E) in Finland. Consistency between different algorithms was studied using the OMI OMTO3 and OMDOAO3 global ozone data. The total ozone overpass values of these products for Sodankylä and Jokioinen were obtained from the Aura Validation Data Center (AVDC).

[8] The validation period presented in this paper is from 1 April until 30 August 2006. The time frame was chosen so that the solar zenith angle (SZA) is small enough to ensure good quality of the data. Furthermore, OMI does not measure over Sodankylä or even Jokioinen during winter months because of very high solar zenith angle (polar night in Sodankylä). The second data set is for the period 15 October to 6 November 2007. This period was selected

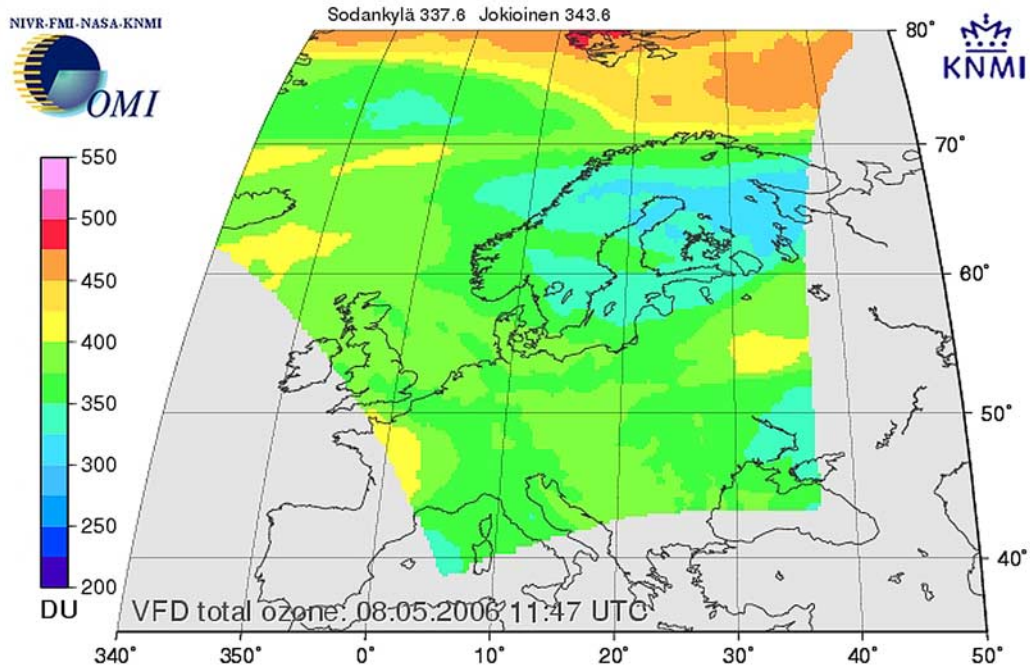

Figure 2. An example of the OMI-VFD total ozone product on 8 May 2007 at 1147 UTC. Note the ozone minimum area over Northern Europe. This minimum is seen also in Figures 3, 4, and 5 around the Julian day number 127. The corresponding UV maximum is visible in Figure 7 on the same days.

because the processing chains have been stable long time and this makes possible to reveal any small accumulating differences between products. The second reason is that the SZA values are much larger than during the summer period and this can be used to study SZA dependency of the algorithms.

3. OMI Very Fast Delivery Data

[9] The VFD products are available when the satellite is above the horizon as seen from the Sodankylä ground station. From two to six DB overpasses are received daily in Sodankylä, depending on the season. However, the amount of the data over a predefined base map must exceed a certain limit before processing is initiated. Therefore, from 2 to 5 orbits are accepted for detailed VFD maps, like in Figure 1, depending on season. In addition to the detailed maps, all the received DB data from the last 10 days are used to produce a composite image which shows the overall UV and total ozone fields over Europe (Figure 2).

[10] OMI-VFD overpass data for the locations of Sodankylä and Jokioinen Brewer stations are not available for every received orbit. There are two reasons: the stations can be outside the measurement area although the satellite is visible from the Sodankylä ground station or the DB is turned off while the satellite is transmitting data to the ground station located at Spitzbergen. The transmission of the memory and DB cannot take place at the same time. Generally, the location of Sodankylä is measured two or three times per day because of its high latitude, whereas Jokioinen only once or twice. The difference in measurement frequency between ground stations is explained by the polar orbit of the satellite and the broad swath (2600 km) of OMI. The successive orbits overlap each other and locations further north are seen by OMI more often than southern locations. This means that the poles are measured on every orbit whereas location at equator only once per day. Sodankylä is located about 7° northward from Jokioinen and this makes the difference in measurement frequency.

4. Validation Data

[11] The validation data consist Brewer ground-based total ozone and UV erythemal dose measurements, and OMI OMTO3 and OMDOAO3 standard off-line data.

4.1. Brewer Total Ozone and UV Daily Dose Data

[12] The Brewer instrument in Sodankylä is a MKII type, while Jokioinen's is a MKIII [*Lakkala et al.*, 2003]. Only direct Sun (DS) measurements were used for validating ozone measurements in order to ensure the best quality of the ozone data. However, in partly cloudy conditions the Brewer and OMI measurements can be different: Brewer instruments may be able to produce DS measurements, while the spatially large OMI pixels are contaminated by clouds. With the UV daily dose values the method has been different. The Brewer daily dose values are obtained using all of the Brewer measurements for that day, including both DS as well as zenith measurements.

[13] The time selection criterion for ozone ground measurements has been chosen to be 30 min around the actual measurement time of the OMI instrument. Inside that window the cloud situation is first determined with the Brewer data and the closest DS measurement is chosen for comparison. If there is no DS measurement, the VFD data point is rejected from further analysis.

[14] The Brewer instruments measure the spectral irradiance on the surface under actual cloud conditions, from which the corresponding UV Index is calculated using the erythemal action spectrum, while the UV Index value provided by the VFD system is for the clear sky conditions and projected to time of the local solar noon on that day. Therefore, the UV Index data are comparable only in occasional middle day clear sky conditions, and the validity of the VFD UV Index product was not studied. However, the daily surface UV doses can be compared, as the VFD algorithm uses the "snapshot" of the cloud situation of the measurement pixel as representing an average for the whole day. This is one of the reasons why the VFD algorithm may overestimate or underestimate the actual radiation if the cloud conditions change during the day. The Brewer-derived daily dose is calculated using all the available spectra of the day, measured on average every half an hour. Also in that case, the unknown cloud conditions between the measurements causes some uncertainty, but less than for the satellite-derived doses.

4.2. OMDOAO3 and OMTO3 Data

[15] The off-line OMDOAO3 data set is processed with the ozone and cloud algorithm versions 1.0.1, OPF (Operation Parameter File) version 31 and GDPS (Ground Data Processing Software) version 0.9.15. However, the VFD processing was based on the OMI-DOAS ozone and cloud algorithm versions 1.0 until they were upgraded to versions 1.0.1 at 3 May. Furthermore, OPF and GDPS were upgraded to the same versions (31 and 0.9.15) as OMDOAO3 was using at 4 May. Therefore 3 May is an important date for validation of the VFD products. The cloud and ozone algorithms are not consistent between the VFD and OMDOAO3 processing chains before the 3 May 2006. The data prior and after that day should be studied separately.

[16] The OMTO3 product version number is 0.9.45. The OMDOAO3 and OMTO3 overpass data was obtained from the Aura Validation Data Center (AVDC). The OMDOAO3 and OMTO3 orbit data was obtained from the DAAC (GES Distributed Active Archive Center). The number of OMDOAO3 and OMTO3 overpasses is grater than the number of VFD overpasses. That is because the off-line processing of the standard products does not suffer of the memory transmissions to the ground stations as VFD does.

5. Validation Results

[17] Validation is divided into six sections. First VFD ozone values are compared separately against OMDOAO3 and OMTO3 values as well as against Brewer measurements. Then the erythemal daily surface UV dose values of the VFD product are compared to daily doses determined from the Brewer measurements. After that, the internal consistency of the VFD total ozone is studied. The validation results are discussed in the last subsection.

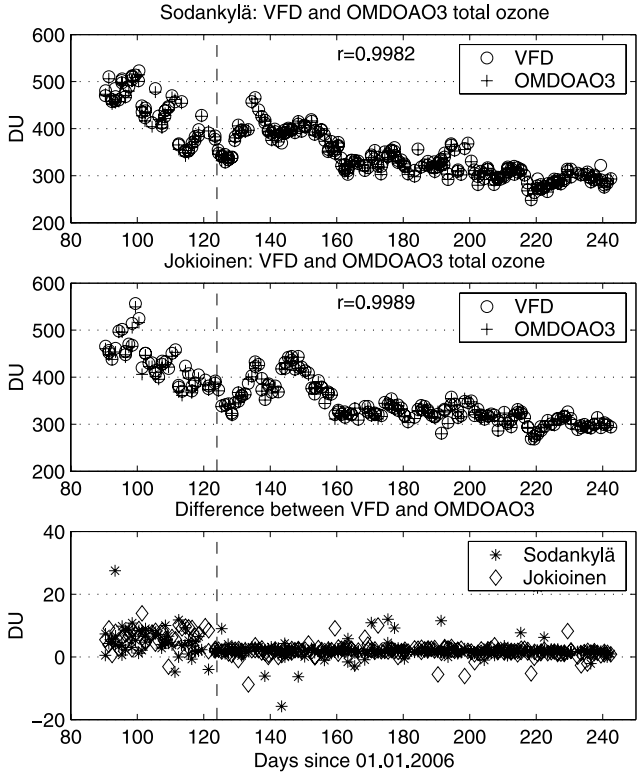

Figure 3. OMI-VFD and OMDOAO3 total ozone values in Sodankylä and Jokioinen over the time period of April–August 2006. The *x* axis shows the day of the year. The upgrade time of the VFD SW components is shown as the dashed vertical line on day 122.

5.1. Comparison of the VFD and OMDOAO3 Total Column Ozone

[18] The VFD and OMDOAO3 data sets for the summer 2006 validation period have been shown in Figure 3. The correlation coefficient between VFD and OMDOAO3 for Sodankylä is 0.9893 and for Jokioinen 0.9848 which are remarkably good although some individual measurements show large discrepancies.

[19] The differences of the means of OMDOAO3 and VFD total column ozone values are 4.4 DU (one Dobson unit is 2.69×10^{16} ozone molecules per square centimeter) for Sodankylä and 6.2 DU for Jokioinen for the period before 3 May (Table 1) and VFD producing larger values. After the upgrade of the VFD algorithms the differences of the means are 2.1 and 1.7 DU, respectively. This means that the relative difference between the VFD and OMDOAO3 total ozone is less than 1% in summer. The standard deviation of the difference is of the order of 2–3 DU.

[20] The old cloud and ozone algorithm versions of the VFD system explains the deviation between VFD and OMDOAO3 product in April. After the upgrade, the results are almost the same although some point-to-point variability remains. Before the upgrade the VFD values are about 4 to 6 DU larger than OMDOAO3 values whereas after the upgrade the difference is only about 2 DU. However, old algorithms do not satisfactorily explain why VFD overestimates total ozone values in April because OMDOAO3 does it too, although in somewhat lesser amount. Furthermore, the difference becomes smaller already before the upgrades of the algorithms have been implemented, so other reasons must be found.

5.2. Comparison of the VFD and OMTO3 Total Column Ozone

[21] Comparison of the VFD total ozone with the OMTO3 total ozone data obtained with the TOMS processing algorithm shows large difference in April 2006, but it is almost negligible in summer (Figure 4). The VFD mean for Sodankylä is 18.8 DU larger than OMTO3 mean before 3 May, whereas in summer only 1.6 DU. For Jokioinen, these values are 10.1 DU and 0.0 DU, respectively. The correlation coefficient between VFD and OMTO3 total column ozone values is 0.9883 for Sodankylä and 0.9848 for Jokioinen showing strong correlation between products.

[22] OMDOAO3 and OMTO3 comparison against VFD can be used to study the behavior of the DOAS and TOMS-based algorithms generally. Although the OMDOAO3 total ozone values are smaller than VFD values in April, they are still remarkably larger than values taken from the OMTO3 product. This shows general discrepancy between TOMS and DOAS-based OMI algorithms in spring. An interesting point is that there is no such large discrepancy between different products in summer time. Furthermore, the OMTO3/VFD discrepancy is larger in Sodankylä, which is located in northern Finland, whereas Jokioinen is about 7° southward.

5.3. Comparison of the VFD and Ground-Based Total Ozone

[23] Comparison of the OMI data processed with the VFD system against the Brewer DS measurement data is shown in Figure 5. The VFD system overestimates the ozone values in spring when the difference of means is 19.4 DU for Jokioinen and 10.3 DU for Sodankylä before 3 May 2006. The smaller difference for Sodankylä is caused by the data points in the end of April. Furthermore, the small number of data points for Jokioinen can cause the large mean difference. The column ozone values are about 400–500 DU in April 2006 which means that the relative difference is less than 5% in average. The situation

Table 1. Differences Between the Mean VFD and OMDOAO3, OMTO3, and Brewer Total Column Ozones[a]

	OMDOAO3 April (72/42)	OMDOAO3 (200/159)	OMTO3 April (51/41)	OMTO3 (217/159)	Brewer April (35/11)	Brewer (139/61)
Difference of means	4.4/6.2	2.1/1.7	18.8/10.1	1.6/0.0	10.3/19.4	−1.0/−0.6
SD of difference	4.3/3.2	3.3/2.0	12.6/4.8	6.6/6.1	13.9/5.0	7.2/8.0

[a]Unit is Dobson units. The first value in the table cells is for Sodankylä, and the second is for Jokioinen. Each comparison is divided into two parts, the first showing the values of the data before 4 May and the second for the rest of the data set. The number of data points of both locations are shown in the header row, the first for Sodankylä and the second for Jokioinen.

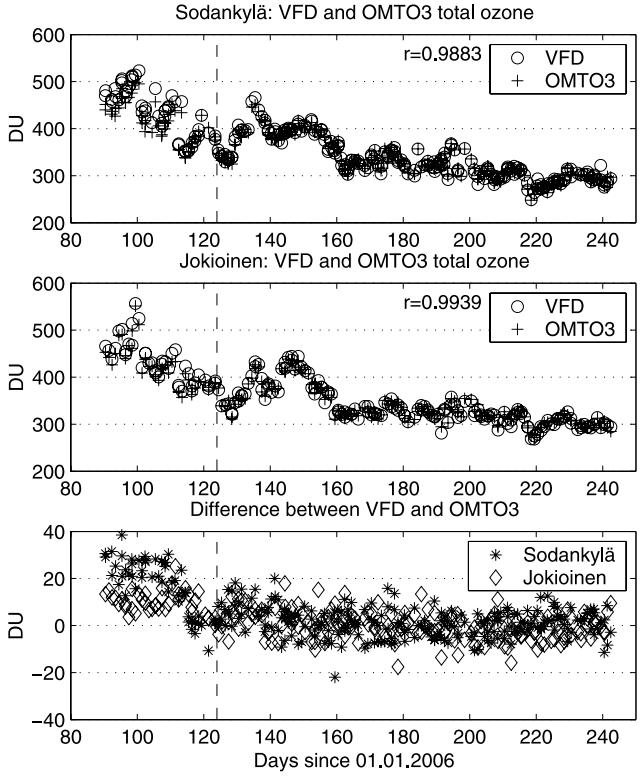

Figure 4. OMI-VFD and OMTO3 total ozone values in Sodankylä and Jokioinen over the time period of April–August 2006. The *x* axis shows the day of the year. The upgrade time of the VFD SW components is shown as the dashed vertical line on day 122.

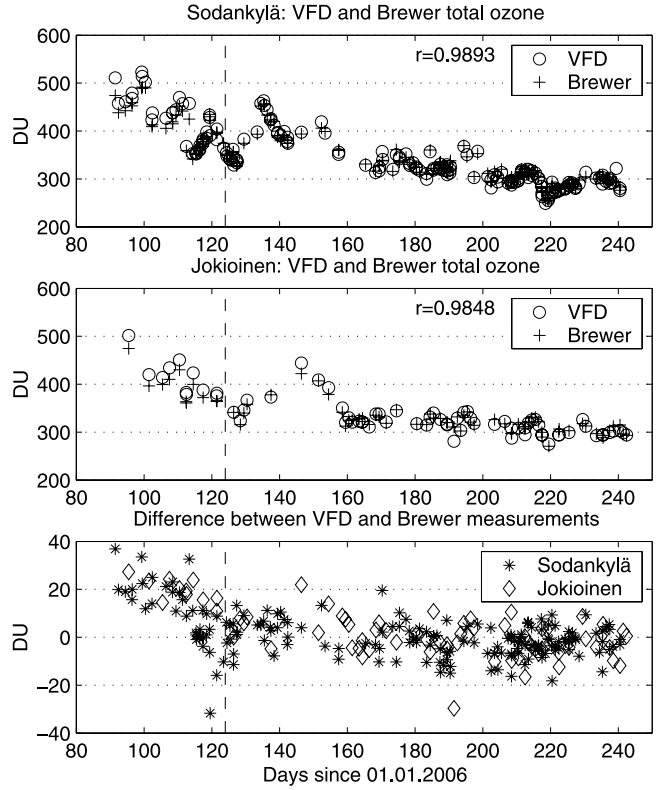

Figure 5. OMI-VFD and Brewer total ozone values in Sodankylä and Jokioinen over the time period of April–August 2006. The *x* axis shows the day of the year. The upgrade time of the VFD SW components is shown as the dashed vertical line on day 122.

changes in summer, the relative difference between the VFD and Brewer values is almost negligible: for Sodankylä −1.0 DU (∼0.25%) and for Jokioinen −0.6 DU. The correlation coefficients between products are 0.9893 and 0.9848, respectively.

[24] The effect of the solar zenith angle between algorithms in summer 2006 was studied by correlating SZA and the difference between OMDOAO3 and OMTO3 algorithms. The correlation was −0.56 which reveals small correlation. However, this correlation can be overestimated because the large OMDOAO3 values in April causes the same effect as larger SZA values. Furthermore, the Brewer air mass was utilized to study the SZA-total ozone relationship by comparing the Brewer air mass and VFD-Brewer total ozone difference because the Brewer air mass is as an function of the SZA. The air mass was in the range 1.35–2.1. However, basically no correlation (r = −0.17) was found. These findings shows the fact that the very large solar zenith angles were absent in the summer 2006 data set and therefore the dependency between the algorithms and SZA values could not be found.

[25] By comparing Figures 4 and 5 it can be concluded that the OMTO3 product shows much better agreement with the Brewer measurements than with VFD in April. This is shown also in Figure 6. The difference of mean values between OMTO3 and Brewer is only −1.8 DU for Sodankylä and 3.7 DU for Jokioinen before 4 May. After 3 May the OMTO3–Brewer difference is −4 DU for Sodankylä and −1.4 DU for Jokioinen which indicates small negative bias for the OMTO3 total ozone.

[26] The effect of the cloudiness was studied using synoptic cloud amounts as well as cloud fractions of the

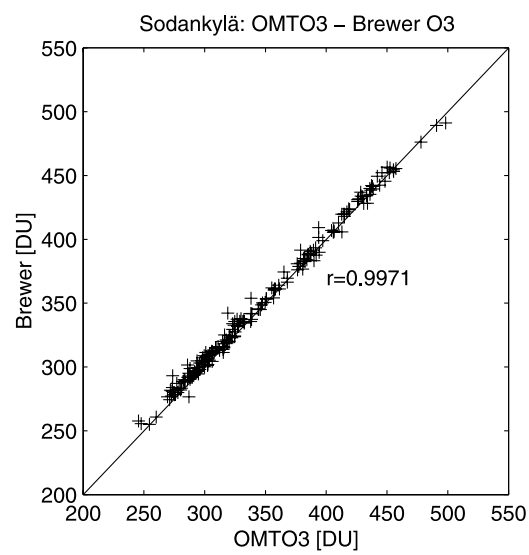

Figure 6. OMI total ozone overpass values from the standard OMTO3 product as a function of the values measured with the Brewer instrument in Sodankylä, northern Finland.

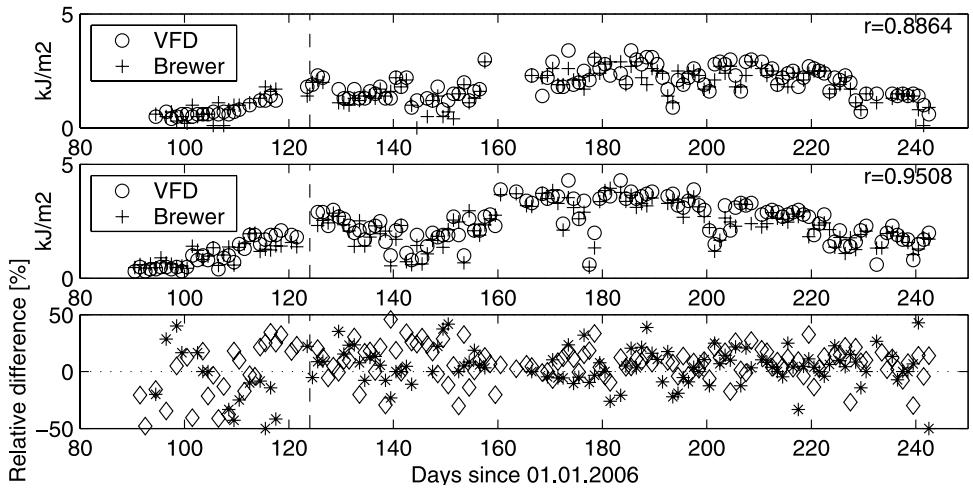

Figure 7. Erythemal daily surface UV dose in (top) Sodankylä and (middle) Jokioinen calculated from the Brewer instrument measurements and derived from the OMI-VFD overpass measurements. The figure shows clear seasonal cycle of the surface UV related to the seasonal variation of the solar elevation. The large local minima in erythemal daily dose values in the end of May and beginning of June (days 140–160) is caused by high ozone values together with thick cloud cover. The effect of thick clouds are seen also around days 175–180 and 200–205. (bottom) The VFD-Brewer relative difference with diamonds for Jokioinen and asterisks for Sodankylä. The upgrade time of the VFD SW components is shown as the dashed vertical line on day 122.

OMI pixels and comparing these to the Brewer-OMDOAO3 difference. The correlation between these variables was almost zero. Thus, no dependency between cloudiness and total ozone differences was found. The same conclusion is valid for Brewer-VFD total ozone also.

5.4. Comparison of the VFD and Ground-Based Surface UV Doses

[27] OMI very fast delivery UV erythemal daily dose values are compared with Brewer measurements. Because of the strong seasonal dependency on UV radiation the winter erythemal daily dose values are practically zero, whereas they are about 2–3 kJ/m^2 in Sodankylä and 3–4 kJ/m^2 in Jokioinen in midsummer. In the first part of April the daily dose is about 0.5 kJ/m^2 at both locations, rising rapidly to the level of 1–2 kJ/m^2 toward the end of the month. The effect of clouds is clearly visible in Figure 7. The large minimum around days 130–150 as well as smaller minimums on days 175–180 and 200–205 in Jokioinen, are caused by thick cloud covers.

[28] The systematic differences between the Brewer and VFD erythemal daily doses in Jokioinen and Sodankylä values are close to zero except in April (Figures 7 and 8). The absolute variation of the VFD-Brewer difference is about the same throughout the validation period for both locations. The relative difference between the VFD and Brewer values is largest in spring, exceeding 100% in some cases. However, in midsummer, the difference is less than 50%, apart from just a few cases, and generally less than 30%. The biased surface UV radiation values in April are caused by the biased total ozone values described in sections 4.1–4.2. The ozone column is used in the UV processing and therefore too high ozone values lead to unrealistically low UV values. The summer UV validation results agree with the results obtained by *Tanskanen et al.* [2007] by comparing global OMUVB product to 16 ground based spectroradiometers.

[29] The interesting fact is that the strong effect of clouds as seen as minimums in absolute daily dose values do not produce any deviation between VFD and Brewer UV products.

5.5. Internal Consistency of the OMI Total Column Ozone Products

[30] The consistency of the VFD total ozone is studied with four methods. First the errors caused by distances

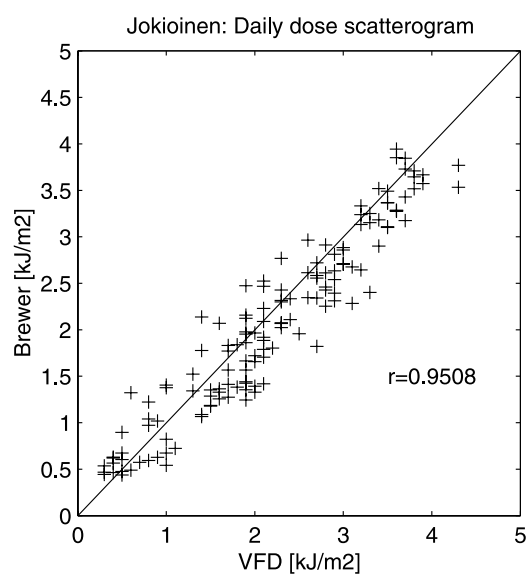

Figure 8. The Brewer UV daily dose values as a function of the VFD UV daily dose values for Jokioinen.

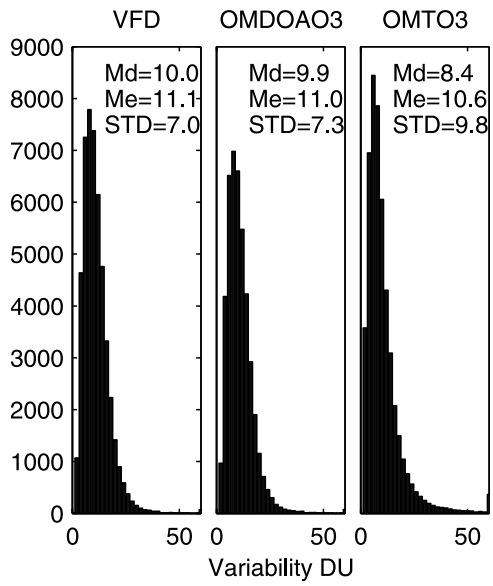

Figure 9. Small-scale total ozone variability for VFD, OMDOAO3 and OMTO3 products. Subsample of 1° in diameter has been transported over the total ozone products data with 1° steps for 20 days. The difference between maximum and minimum values are recorded. The histograms are produced using these recordings. The total areas of the OMDOAO3 and OMTO3 products are selected to be about the same size as with VFD although not exactly.

between measurement locations are estimated. Then the spatially small-scale variability of the VFD product is compared to spatial variability of the official OMDOAO3 and OMTO3 products. Furthermore, the pixel-to-pixel comparison between VFD, OMDOAO3 and OMTO3 total ozone products is done. Finally the daily overlapping VFD swaths are compared to each other as well as to Brewer measurements.

[31] The distance between the OMI measurement location and the effective Brewer measurement location can cause variation to the OMI-Brewer comparisons. The reason is that in the presence of strong total ozone gradients, the gradients are seen as disagreements between the instruments. This is studied by comparing the distance between the effective measurement point locations versus total OMI-Brewer ozone value differences. The effective location of the Brewer measurement was calculated using the solar zenith and azimuth angles and the effective ozone maximum altitude was assumed to locate at 22 km. The maximum distance between the effective location of the Brewer direct Sun measurement and the middle point of the OMI pixel is about 52 km and the average distance is 30 km. For such small distances the total ozone gradients are very small, typically 2–3 DU at most. Therefore, the fact that no correlation ($r = -0.0089$) between the VFD-Brewer differences and measurement distances was found, was as expected. This indicates that the differences does not depend on measurement geometrics. This finding is valid for the VFD data as well as for the OMDOAO3 and OMTO3 data.

[32] The spatial variability over short distances of the VFD, OMDOAO3 and OMTO3 total ozone products was studied with an moving subsample 1° in diameter and using the data set from October–November 2007. The diameter of 1° was chosen because the effective distance between measurement locations described in the previous paragraph is about the same size and the number of pixels is meaningful for this study. The subsample was moved over the whole measurement area with 1° steps and the minimum and maximum values of pixels were collected. The variation inside the subsample was taken as the difference between maximum and minimum. Then the mean, median and SD values for this difference was calculated using all the subsamples. The results are shown in Figure 9. For VFD and OMDOAO3 the mean maximum-minimum differences were 9.96 and 9.87 DU, the median differences 11.07 and 10.98 DU and finally the SD values 7.02 and 7.29 DU. The values are almost the same for these two products. The OMTO3 median (8.35) and mean (10.63) values are little smaller whereas the SD is larger (9.75) than with VFD and OMDOAO3.

[33] VFD processing uses the same DOAS algorithm [*Veefkind et al.*, 2006] as the standard off-line processing chain, However, there exists one major difference. Auxiliary data, like solar extraterrestrial irradiances, used for producing global products may include some updates that occur after measurement of the data, but before the off-line processing. These updates are missing in the VFD processing. The effect of this phenomena was studied by comparing the pixel-to-pixel difference of the VFD and OMDOAO3 products for the period 15 October to 6 November 2007. The auxiliary files for the VFD operating system was upgraded at 8 May 2007. All possible changes which are included into OMDOAO3 processing after that day are missing in the VFD processing chain except the NISE snow data which is upgraded daily. This time frame was chosen to ensure long period with stable systems. Distribution of the OMDOAO3-VFD pixel-to-pixel difference is bimodal with the peaks in 0 DU and 0.6 DU (Figure 10). We can conclude that the auxiliary files can affect total column ozone but the effect is only about 2–3 DU in maximum and in most cases

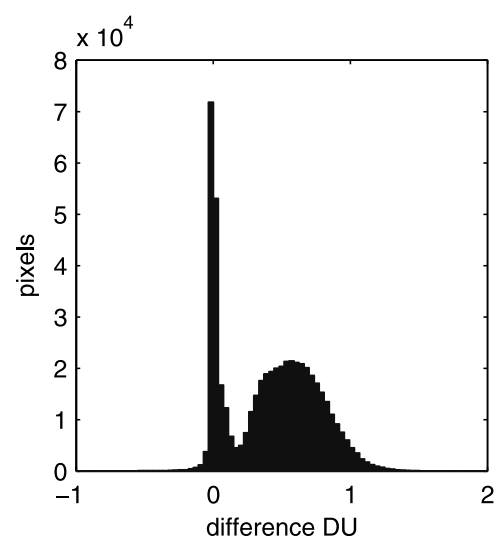

Figure 10. Pixel-to-pixel comparison of the OMDOAO3 and VFD data. The histogram shows the deviation between these products.

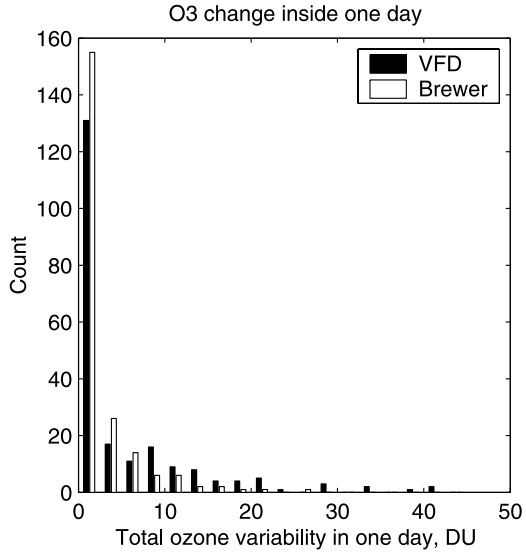

Figure 11. Total ozone variability in 1 day for VFD and Brewer instruments. The Brewer data times are selected to be the same as with VFD to produce comparable results. Only the days with more than one VFD measurements are used.

less than one DU in seven months. The OMTO3-VFD pixel-to-pixel comparison reveals a different situation. The distribution is symmetric with a mean of −6.25 DU (median −6.60 DU) and SD 12.09 showing larger VFD values. The study period was in late autumn, early winter and the SZA values were very high ranging from below 50 up to almost 90°. TOMS algorithm starts to use wavelength 313 nm at large solar zenith angles (Parthia 2002). This causes reduced total ozone and stepwise structure to the OMTO3 total ozone field. The effect of the SZA and this stepwise structure can be seen as discrepancy between VFD-OMTO3 pixel-to-pixel values. The stepwise structure is one example that the satellite algorithms have difficulties with very large solar zenith angels.

[34] The variability between daily overlapping swaths for VFD was studied by taking the VFD minimum and maximum total ozone values for Jokioinen and Sodankylä and the difference between them for each day with more than one measurement. The corresponding values were taken also for the Brewer measurements and they present the natural variability. The agreement of distributions is good, although the VFD data is more spread (Figure 11). The daily maximum variability for the Brewer data is about 27 DU whereas for the VFD data that is about 40 DU. The Brewer and VFD variabilities presents the maximum total ozone change in 5 h which is the longest time difference between the first and the last VFD measurements in 1 day.

5.6. Discussion of the Validation Results

[35] The most important findings of this validation work can be summarized as:

[36] 1. Difference between VFD and OMDOAO3 total column ozone products is quite large (about 5 DU) before 3 May because of different algorithm versions. The upgrade of the VFD algorithms improved the coincident to be almost perfect.

[37] 2. Large systematic discrepancy between the OMDOAO3 product and Brewer and OMTO3 values occurred before 3 May.

[38] 3. All OMI total column ozone products (VFD, OMTO3 and OMDOAO3) agree very well with each other as well as with the Brewer measurements in summer 2006. The mean deviation between products is less than 2 DU.

[39] 4. The erythemal daily surface UV dose product of the VFD processing chain compares well with the ground-based Brewer measurements and the difference between VFD and Brewer is generally less than 30% in summer.

[40] There exist several possible reasons for difference between the products in April. The old cloud and ozone algorithm versions of the VFD system explains the deviation between VFD and OMDOAO3 product in April as shown in section 4.2. After the upgrade, the results are almost the same although some point-to-point variability remains. However, old algorithms do not satisfactorily explain why VFD overestimates total ozone values in April because OMDOAO3 does it too, although not as clearly. The fact that the OMTO3 total ozone values corresponds well with the Brewer measurements in April, as shown in section 4.2, indicates that the problem is related to the DOAS algorithm itself or caused by external data which are used in the processing, like snow cover data or cloud information.

[41] Albedo and cloud information in the OMDOAO3 and OMTO3 processing are different. The air mass factor in VFD processing (and OMDOAO3) is determined with the cloud fraction and cloud pressure obtained from the OMI OMCLDO2 cloud product based on O_2-O_2 absorption, while the OMTO3 algorithm computes its own cloud fraction and gets the cloud height from a climatology. These cloud products are not identical and differences in determination of cloud fraction and cloud pressure lead to different ozone estimations. However, no correlation between OMDOAO3 cloud fraction and OMDOAO3-Brewer deviation was found. Thus we can conclude that the effect is not systematic, if there is any.

[42] April is the snowmelting season in Finland and therefore the interpretation of dry snow, wet snow and moist ground is essential, and small errors in this classification can mislead the cloud/ground interpretation in ozone processing. The snow started to melt rapidly in Sodankylä around 10 April and was absent by 6 May. For Jokioinen these dates were 31 March and 17 April, respectively. The snow coverage is taken from the National Snow and Ice Data Center NISE (Near real-time Ice and Snow Extent) database for the DOAS algorithm and errors in this information may cause misleading ozone values in the VFD processing. Furthermore, the cloud/snow distinction can contain errors and the snow covered surface is treated as cloud top or vice versa because of errors in the cloud product. If the snow cover is interpreted as cloud top, the cloud correction has been made by including the estimated missing tropospheric ozone column into the end product which lead to positive bias. In summer, the albedo information is more reliable and the absence of the snow removes one error source. Therefore, the values match better and there is no difference between the data products. According to *Kroon et al.* [2008a] the OMTO3 product gives low ozone values compared to OMDOAO3 over snow

and ice surface which agrees with the results presented here. However, we could not estimate quantitatively the effect of snow because of the small number of days with snow cover.

[43] The third important reason for the discrepancy in springtime may be the fact that the satellite retrieval algorithms have difficulties with large solar zenith angles (SZA). The SZA can be quite large in the northern latitudes in April. For example, the minimum SZA is 63.1° in Sodankylä on 1 April. Generally, the OMI measurement SZA varies between 60 and 65° in Sodankylä in April. DOAS-based algorithms have seasonal dependency especially in cloudy conditions because the air mass factor used in the processing is sensitive to SZA [*Bramstedt et al.*, 2003]. Therefore, the retrieved values are more reliable in summer. Very weak SZA dependency was found also in this study, but the signal was weak and disturbed by other factors, like snow related issues. However, the pixel-to-pixel comparisons of the VFD and OMTO3 products in section 4.1 revealed large discrepancy between the products. This is caused the TOMS algorithm which starts to use wavelength 313 nm at large solar zenith angles resulting reduction in total ozone. The effect of the SZA on a global scale, is studied by *Kroon et al.* [2008a].

[44] Three additional sources of uncertainty were identified. The auxiliary data used in the VFD processing may contain rather old data as described in section 2. Although this can cause some errors in the VFD processing it does not explain the overestimation in April or the variation in summer. The effect of the auxiliary files is 2–3 DU at most and generally less than 1 DU as shown in section 4.1. However, this can be systematic deviation. The second error source between the VFD and Brewer measurements is caused by the fact that the location of the OMI-VFD measurement is not exactly over the ground station. Furthermore, the Brewer instrument looks toward the Sun and therefore, the effective location of the Brewer measurement can be even further from the OMI location. The gradients of the ozone field can be very strong in the northern latitudes and OMI and Brewer may not measure the same air mass. This can cause small differences between the satellite and ground-based measurements, inducing small point-to-point variability into the data. However, the maximum distance between the satellite measurement point and Brewer effective location is a little over 50 km and on average only 30 km as found in section 4.1. The natural variation of total ozone can be about 10 DU in 100 km across the polar front in spring. However, the polar front is located north of Sodankylä and the gradients are far less steep in summer. Thus, the effect of the distance between the measurement points can explain only 2–3 DU at most and the effect is not systematic. Generally the effect is smaller than that in summer. Furthermore, this does not explain the variability between satellite algorithms because the measurement pixels are the same. OMI measures in nadir geometry, although near the edge of the field of the view of the instrument, the measured column is not vertical any more. This discrepancy in geometry between nadir and edge points can cause some minor errors in retrieved values especially near the edge of the field of the view although this effect of geometry is generally corrected in the processing algorithms and can be therefore neglected. Altogether, these factors can cause total ozone difference of 4–6 DU at maximum between OMI-based total ozone and Brewer measurements if the factors are affecting to the same direction.

[45] The internal small-scale variability of the VFD, OMDOAO3 and OMTO3 total ozone products was studied by moving a small subsample, size of 1°, over a data. This revealed the random pixel-to-pixel variability of the ozone products of about 10 DU inside a 1° area. This is a larger variability than the natural ozone gradients can usually cause over a 100 km distance. Therefore, the subsample variability does not represent natural variability but must be caused by other factors like instrument properties and algorithms.

[46] Large differences between VFD and Brewer UV daily doses are expected because the Brewer measurements are time integrations over the whole day, consisting several individual measurements, while VFD produces an estimate of the erythemal daily dose using just one snapshot of the ozone situation and cloudiness. This snapshot is used to represent the weather and ozone for the whole day. If the cloud conditions remain unchanged over the day, the Brewer and VFD values should be close to each other. However, the cloudiness usually changes over the day. The VFD UV dose measurements should be most reliable when taken around noon because most of the UV radiation are received at that time. Fortunately, the VFD measurements are taken around the solar noon. Depending on the cloud conditions, the VFD product may underestimate or overestimate the daily dose values. The differences are typically larger than the uncertainty in the ground reference induced by noncontinuous sampling [*den Outer et al.*, 2005].

[47] As stated by *Bugliaro et al.* [2006], more than one overpass per day is required to obtain correct cloud structure, and therefore, the UV daily dose value. Therefore, we could average the VFD-UV daily dose values for 1 day to increase the accuracy of the product. However, the purpose of this service is to provide fast snapshots of the current situation and therefore the daily averaging could be used as an supplementary product, not as an product to replace the current VFD-UV daily dose product. Furthermore, according this test the total cloudiness does not effect to the VFD-Brewer UV daily dose difference. In addition, the short test with the Sodankylä OMUVB data revealed that two or three overpasses is not enough to produce more accurate results.

6. Conclusions

[48] OMI very fast delivery products give fast snapshots of the total ozone and UV radiation over Europe. These images are intended for general public to fulfill the great interest in state of the ozone layer and UV radiation. Furthermore, the products are useful in providing scientists with nearly immediate online information about ozone and UV and, for example, for planning measurement campaigns. VFD products have proved that they can answer these demands.

[49] The quality of the VFD ozone product is in most cases comparable to the off-line standard products. The differences between the VFD ozone product and the off-line OMDOAO3 and OMTO3 products are usually only 1–2 DU. Furthermore, the ground-based Brewer DS measurements agree with the VFD ozone product in summer 2006 and no

systematic bias between VFD and the ground-based Brewer measurements was observed. The effects of the auxiliary files and effective location of the measurements can be estimated to be small, together generally less than 2–3 DU. The variability of the VFD–Brewer total ozone difference is mainly explained by the factors above and internal noise of the VFD total ozone product, the latter being greater. The causes for discrepancy in April have been identified and the main reasons are algorithm specific, like sensitivity to large solar zenith angles, and cloud/snow/albedo interpretation. Therefore, the future validation should focus on data with snow cover and large SZA values and processed with the new OMI DOAS algorithms.

[50] To determine the quality of the UV product of the VFD processing is not so straightforward as ozone because the measurement and processing principles of the VFD and ground-based values are fundamentally different. However, the VFD-UV erythemal daily dose values compares well to standard OMUVB product. The difference with Brewer measurements is generally less than 30% in summer, although in partly cloudy conditions this is not achieved all the time. Furthermore, the relative error of 30% is exceeded in fall, winter and spring when the absolute amount of the UV radiation is very small. The UV product usually overestimates the values measured from the ground level, because the current UV algorithm does not account absorbing aerosols or trace gases.

[51] The OMDOAO3 is further improved on the basis of the validation results like the ones presented in this paper. These improvements include a new scheme to better deal with high reflective terrain such as snow and ice cover, and a new version of the air mass factor look-up table. Test results of the improved OMDOAO3 algorithm shows significantly better behavior over ice covered surfaces [*Kroon et al.*, 2008a] and a strong reduction in the solar zenith angle dependency [*Kroon et al.*, 2008b]. In addition, all the OMI data will be reprocessed with new instrument calibration parameters. The reprocessing with the new version of OMDOAO3 is expected to be finalized in the beginning of 2008. The new algorithms will be adapted also into the VFD processing.

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O. Aulamo, J. M. Karhu, and K. Lakkala, Finnish Meteorological Institute, FIN-99600 Sodankylä, Finland.

S. Hassinen, T. Koskela, A. Mälkki, J. Tamminen, and A. Tanskanen, Finnish Meteorological Institute, FIN-00101 Helsinki, Finland. (seppo.hassinen@fmi.fi)

N. Krotkov, GEST Center, University of Maryland, Baltimore County, Baltimore, MD 21228, USA.

G. Leppelmeier, G&S Associates, FIN-02360 Espoo, Finland.

P. Veefkind, Royal Netherlands Meteorological Institute, NL-3730 AE De Bilt, Netherlands.