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Abstract

Validation of ultraviolet radiation budgets using satellite observations from the OMI instrument

Satellite retrieval of ozone, clouds, aerosols and ground albedo allows the modelling of ultraviolet (UV)-doses received at the ground. UV-doses derived from satellite observations are highly useful in analyzing regional differences in the effects of ozone depletion and climate change on the biologically effective UV-radiation levels. RIVM has developed and used UV-mapping and UV-risk mapping techniques in environmental assessments in evaluating the effects of ozone depletion and climate change. This project provides a validation study on the OMUVB product by means of a comparison with ground-based measurements. This validation should demonstrate if the OMUVB product can be used from the perspective of long-term environmental trend assessments.

Comparing ground-based UV-measurements with the OMUVB product, we show that the product consistently overestimates the UV-doses received at the ground in Europe. The systematic comparison with data from 8 European sites shows on average a 15% overestimate in the yearly integrated UV with a site-to-site variability of around 8%. For four of the more northern sites the overestimation in yearly doses is between 5-10%, and for the four sites that are more southern the deviation is 20-27%. Using the ozone and reflectivity data from the OMI-instrument in combination with the AMOUR-algorithm shows smaller overestimates of on average 5-6% with a similar variability between the sites. The variability between sites is largely caused by aerosol and albedo effects and is reduced to 3% if local data on aerosol and albedo are used. The overestimates in the OMUVB product are primarily due to too low (tropospheric) aerosol loads used for the European sites. In addition, our comparison shows that under heavy clouded conditions the cloud modification factors are too high. This contributes to the overall too high UV-doses of the OMUVB product.

Environmental assessments of long-term changes in the biologically effective UV require calculated UV-data using different satellite instruments. We previously showed that RIVM's AMOUR-algorithm in combination with data from the TOMS-instruments compared well with ground-based yearly doses. It was also shown that the influence of clouds were, on average, well accounted for using the TOMS-reflectivity dataset. Results using the OMI produced ozone and reflectivity data do not agree as well with ground-based data as was previously demonstrated for TOMS. Using OMI-data in combination with the AMOUR-algorithm provided better agreement with the ground-based UV-measurements in Europe than the OMUVB product. The analysis documented in this report involves mainly the data version that was operational until the first of February 2008. In view of the preliminary results with the new operational products of OMI, further improvements of the OMUVB product and the use of OMI-ozone and radiative cloud fraction are required and should be possible.

Key words: ultraviolet, UV-radiation, ozone depletion, climate change, UV-mapping, UV-retrieval, validation, satellite observations

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Executive summary

Satellite retrieval of ozone, clouds, aerosols and ground albedo allows for modelling of the UV-doses received at the ground. UV-doses derived from satellite observations are useful in analyzing regional differences in the effects of ozone depletion and climate change on the biologically effective UV-radiation levels. RIVM has developed and used UV-mapping and UV-risk mapping techniques in environmental assessments for the evaluation of the consequences of ozone depletion and climate change on UV-radiation budgets and UV-related risks. These methods and techniques were developed, demonstrated, validated, and embedded in previous BCRS/NIVR projects, and have lead to implementation in the AMOUR-model. This AMOUR-model uses satellite observations on ozone and clouds to determine the UV-doses on the ground. The developed methods and techniques are thus far mainly based on the use of the TOMS-instruments. However, the TOMS dataset is now discontinued due to degradation of the last TOMS-instrument. New satellite instruments have become available in recent years, and it is necessary to include those instruments and methods in the environmental assessments. This project provides a validation study on the operational OMUVB product by means of a comparison with ground-based measurements. This should demonstrate if the OMUVB product can be used from the perspective of long-term environmental trend assessments.

Comparing ground-based UV-measurements with the OMUVB product, we find that the product consistently overestimates the UV-doses received at the ground in Europe. The systematic comparison with data from 8 European sites shows on average a 15% overestimate in the yearly integrated UV with a site-to-site variability of around 8%. For four of the more northern sites the overestimation in yearly doses is between 5-10%, and for the four sites that are more southern the deviation is 20-27%. Using the ozone and reflectivity data from the OMI instrument in combination with the AMOUR-algorithm shows smaller overestimates of on average 5-6% with a similar variability between the sites. The variability between sites is largely caused by aerosol and albedo effects and is reduced to 3% if local data on aerosol and albedo are used. The overestimates in the OMUVB product are primarily due to too low (tropospheric) aerosol loads used for the European sites. In addition, our comparison shows that under heavy clouded conditions the cloud modification factors are too high, also contributing to the overall too high UV-doses of the OMUVB product.

Environmental assessments of long-term changes in the biologically effective UV require calculated UV-data using different satellite instruments. We previously showed that the AMOUR-algorithm in combination with data from the TOMS instruments compared well with ground-based yearly doses, and that the influence of clouds were, on average well accounted for using the TOMS-reflectivity dataset. We now show that using the OMI produced ozone and reflectivity data do not agree as well with ground-based data as was previously demonstrated for TOMS. Therefore, part of the overestimations found for the OMUVB product under heavy clouded conditions may be attributed to the underlying cloud reflection data. The analysis documented in this report involves mainly the data version that was operational until the first of February 2008. In view of the preliminary results with the new operational cloud effect product of OMI, further improvements of the OMUVB product are required, and the use of OMI-ozone and radiative cloud fraction should be possible.

Samenvatting

Satellietwaarnemingen aan ozon, bewolking, aerosolen en grondalbedo maken het mogelijk om de UV-straling op grondniveau te modelleren. Aldus verkregen UV-doses op de grond zijn waardevol voor het analyseren van regionale verschillen in de effecten van aantasting van de ozonlaag en klimaatverandering op de UV-stralingsbelasting. Het RIVM heeft technieken ontwikkeld om UV-kaarten en UV-risicokaarten te produceren voor milieuevaluaties voor het inschatten van de gevolgen van ozon en klimaatverandering voor UV-stralingsniveaus en de ermee samenhangende risico's. Deze methoden en technieken zijn ontwikkeld, gedemonstreerd, gevalideerd en ingebed op basis van eerdere BCRS/NIVR projecten in het kader van de gebruikersondersteuning, en hebben geleid tot toepassing in het AMOUR-model. Het AMOUR-model koppelt satellietgegevens over ozon en bewolking aan berekeningen over UV-straling op de grond. De ontwikkelde methoden en technieken zijn toegepast in (inter-)nationale milieuevaluaties. Tot dusver werd daarbij vooral gebruikgemaakt van TOMS-instrumenten. Echter, metingen met het laatste TOMS-instrument zijn, door degradatie van het instrument, niet langer beschikbaar. Nieuwe instrumenten moeten de rol van TOMS overnemen. Dit project is gericht op de validatie van methoden die gebruikmaken van waarnemingen met het OMI-instrument. Daartoe is ondermeer het recent beschikbaar gekomen OMUVB-product systematisch vergeleken met metingen van de UV-stralingsdoses op diverse Europese grondstations. De analyses moeten duidelijkheid geven over de bruikbaarheid van de OMI UV-dataproducten voor milieuevaluaties.

Wanneer we het huidige operationele UV-product (OMUVB) vergelijken met de grondwaarnemingen van acht Europese sites dan vinden we een consistente overschatting van de waargenomen UV-dosis. Gemiddeld bedraagt die overschatting 15% in de over een jaar geïntegreerde UV-dosis, met een standaarddeviatie van 8% voor de verschillende stations. Voor de vier meest noordelijke stations bedraagt de overschatting 5-10%, en voor de zuidelijker stations 20-27%. Wanneer we de ozon en reflectiviteit van het OMI-instrument gebruiken in het AMOUR-algoritme dan is de gemiddelde overschatting niet meer dan 5-6% met een vergelijkbare variabiliteit tussen de verschillende stations. Indien lokale data over aerosol en grondalbedo worden gebruikt dan wordt de variabiliteit gereduceerd tot slechts 3%.

De overschatting van de UV-doses door het operationele OMUVB-product wordt veroorzaakt door te lage waarden voor het troposferische aerosol voor de Europese grondstations. Bovendien blijkt uit een meer gedetailleerde analyse dat onder zwaar bewolkte condities de inschatting van het bewolkingseffect leidt tot een te hoge inschatting van de UV-belasting. De bewolkingsmodificatiefactoren zijn te hoog.

Voor evaluaties van biologische effecten is het van belang inzicht te hebben in de langetermijnontwikkelingen van de UV-stralingsniveaus, en daarbij moet gebruikgemaakt worden van satellietwaarnemingen met verschillende instrumenten. We hebben in eerdere validatiestudies laten zien, dat het AMOUR-algoritme gevoed door satellietwaarnemingen met het TOMS-instrument goed vergeleek met de grondwaarnemingen, en dat met behulp van de TOMS-reflectiviteitsmeting het gemiddelde bewolkingseffect goed kon worden ingeschat. Op dit moment voldoet het gebruik van de OMI-waarnemingen nog niet zo goed als de eerdere TOMS-waarnemingen waar het gaat om het gebruik van de informatie voor het inschatten van de bewolkingseffecten. De analyses gerapporteerd in dit rapport betreft voornamelijk de OMI producten die operationeel waren tot 1 februari 2008. Voor dit rapport konden we slechts voorlopige resultaten presenteren met het nieuwe bewolkingsproduct van OMI, waaruit het mogelijk blijkt om de bewolkingsanalyses verder te verbeteren en te gebruiken.

1 Introduction

Ozone depletion and climate change have an impact on the biologically effective ultraviolet (UV) radiation received at the ground (De Gruijl and Van der Leun, 1994; Slaper et al., 1996; Herman et al., 1996; UNEP, 1998; WMO 2003). Exposure to UV-radiation can lead to a variety of health and ecological effects. Health effects include short-term effects such as sunburn or snow blindness, and long-term effects such as skin cancer, skin ageing, and cataract formation (NRPB 2002; Parkin et al., 2002). UV-exposure of the skin leads also to the production of vitamin-D3, which is relevant for bone formation, and might have protective effects for some internal cancers (Reichrath, 2006). Different effects are associated with different spectral weighting functions, action spectra, and therefore spectral information on the UV-radiation is required.

Long-term changes in the received UV-radiation can most accurately be assessed using ground-based spectrally resolved measurements. High spectral resolution measurements are required especially in the short wavelength part of the UV where the combination of the wavelength dependent ozone absorption and the biologial effectiveness of the UV-radiation enhance the overall wavelength dependency. These time series can often be extended beyond the starting point of UV-measurements through modelling making use of ground-based total column ozone data and cloud information (Madronich, 1992; Kaurola et al., 2000; Den Outer et al., 2005). However, such measurements and modelling can only give local information. In order to assess long-term regional changes in the UV-radiation, a high-density network of measurements would be required. Satellite observations have been shown to provide a valuable complementary source of information that can be used to analyse the regional and global patterns in the UV-climate and the changes therein. Methods have been developed to use satellite observations on ozone, clouds, aerosols and albedo to calculate the regional and global UV-climate on the ground (Eck et al., 1995; Herman et al., 1997 and 1999; Krotkov et al., 1998; Kalliskota et al., 2000; Matthijsen et al., 2000; Slaper et al., 2001; Kelfkens et al., 2001; Williams et al., 2004; Van Dijk et al., 2008).

RIVM has developed and used UV-mapping and UV-risk mapping techniques using satellite observations in environmental assessments for the evaluation of the consequences of ozone depletion and climate change on UV-radiation budgets and UV-related risks (Bordewijk and Van der Woerd, 1997; Van Dijk et al., 2008) The UV-mapping and risk-mapping techniques are integrated in the Assessment Model for Ultraviolet radiation and Risks (AMOUR), which also allows for scenario evaluations of possible future developments (GRID, 2007; MNP, 2007; Van Dijk et al., 2008). These methods were developed, demonstrated, validated, and embedded in previous BCRS/NIVR projects (Bordewijk and Van der Woerd, 1997; Kelfkens et al., 2001; Slaper et al., 2001; Van Dijk et al., 2008).

Previous environmental assessment studies have thus far focused on the use of the TOMS instruments, which provided data over the period 1979- 2002. The OMI-instrument, on board the AURA satellite is following up on the TOMS-data record. The list of products of OMI include (slant) column of gases O_3 SO_2 NO_2, HCHO, BrO, OClO, ozone profile, Radiance and Surface UVB flux, and day sums of the erythemal weighted UV, i.e. the OMUVB product.

It is well recognized that satellite observations and modelling of the UV-climate requires continuous validation using ground-based measurements to assure the continuity and homogeneity of the satellite derived UV-maps over time. A European international collaboration joined in one OMI-validation project, OMI Cal/Val proposal nr. 2945 by NIVR, KNMI, ESA, aims at a direct validation of the UV products of OMI, using ground-based spectrally resolved observations at several stations over Europe.

The OMI and UV-maps validation project (OMI_UV_val projectnummer GO-2005/90) is the Dutch contribution to this European validation project, the results of which are given in this report. The focus is on the validation of UV-products derived from the OMI observations, which is the OMUVB product as such, and AMOUR derived UV using OMI total column ozone and cloud information. The satellite-based daily, monthly, and yearly integrated UV-sums are systematically compared with ground-based UV-measurements, or model result using ground-based observations on ozone and clouds. Ground-based UV-measurements, and ancillary measurements were obtained from several European monitoring stations with quality controlled UV-measurements.

The outline of this report is as follows: chapter 2 focuses on the cost benefit analysis for the use of satellite derived UV-maps. Chapter 3 provides detailed information on the datasets used. During the finalisation of this project, 'Collection 3'-calibrated data and a new developed data product became available which could only partly be incorporated in this report. In chapter 3, a short discussion is given on possible consequences of these new data sets on the derived results. In chapter 4, the OMUVB product is assessed with ground-based measurements. The satellite derived UV-budgets obtained from the operational OMUVB product are also compared with the budgets calculated using the AMOUR-model with input form the OMI-ozone and reflection measurements. This is done in chapter 5.

2 Cost-benefit analysis of satellite-based UV-assessment

Ozone depletion and climate change lead to changes in the biologically effective UV-radiation levels received at the ground. The UV-climate and the changes therein show relevant regional variations. In order to evaluate risks associated with the environmental changes it is important to analyse regional variations and changes. In a previous report, we have more extensively indicated the relevance and cost-effectiveness of satellite-based observations in obtaining knowledge of the regional UV-climate and the changes therein (Van Dijk et al., 2008). Here we briefly focus on the major aspects. The major advantage of satellite observations in the calculation of the UV-climate is the fact that a full global coverage can be obtained. However, it should be recognized that the satellite-based approach is indirect and requires modelling of the UV-climate.

To be able to assess risks in relation to ozone and climate changes it is necessary to have knowledge of the long-term changes in the UV-climate, because many of the effects, such as skin cancer, cataracts, and skin ageing are related to exposures received over prolonged periods. From this perspective it is important to have accurate long-term trend information. Satellite instruments tend to degrade, and the combination of different platforms and instruments is necessary to obtain the long-term accuracy that is required. Therefore, satellite-based approaches should always be validated and combined with ground-based methods to allow for the continuity and accuracy assessment that is required from the perspective of long-term risk assessments.

Three major approaches can be used to study the UV-climate and the UV-climate changes.

- ground-based measurements of UV, either spectrally resolved or with broad band sensors
- modelling of the UV at the ground using ground-based measurements on ozone, clouds, aerosols and albedo
- modelling of the UV-radiation at the ground using satellite-based observations on ozone, clouds, aerosols and albedo

Spectrally resolved UV-measurements with well-maintained and quality controlled spectroradiometers on the ground offer the most accurate determination of the local UV-climate. Such measurements require skilled personnel for maintenance and calibrations and are thus expensive. Broadband sensors are more easy to use and cheaper to operate, but the difficulty is to maintain certainty about the long-term characteristics of the spectral response and the stability of the irradiance calibration. Thus, the broadband measurements are probably less certain in long-term evaluations. Another disadvantage of the broadband sensors is that they provide limited information on the spectral composition of the UV and thus it is more difficult to transfer the measured UV to the weighted UV that is required for different effects (where different spectral weighting functions are required). Both ground-based measurements can have a high temporal resolution and thus the integration to daily, weekly, and monthly sums is straightforward and accurate. Thus, they offer high accuracy, but strictly local information and the production of a UV-map is only possible with a very high number of stations.

Modelling of UV using ground-based data on ozone and clouds (and aerosols and albedo) can offer on average good accuracy of the local UV. The accuracy is mainly dependent on the quality of the input data. Day sums of effective UV can be obtained with a 9% accuracy, and year sums with 2-5% (see for instance Den Outer et al., 2005). Also here the availability of input data does not easily allow the construction of UV-maps with local to regional evaluations.

Modelling of UV using the satellite-based observations on ozone, clouds, and if feasible aerosols and albedo, is less accurate than the above-mentioned approaches on the short time scale. However, it offers a unique opportunity to analyse regional variability. For day sums, the accuracy is probably around 25-30%, but monthly averages can be accurate at the 5-10% level. The largest deviations can be expected in arctic and alpine regions where snow cover leads to high albedo situations. Such high albedo situations are easily interpreted as clouds by the retrieval algorithms. However, year round analyses have been shown to give quite accurate results, even for the more northerly stations (Van Dijk et al., 2008). Since the major data are made available on the internet daily, the analysis can be performed in near real time. In order to cover prolonged periods the combination of different satellite instruments is required. Systematic comparison and validation of the analyzed UV-sums with measured ground level UV remains necessary, but his can be done with a restricted number of stations. The information obtained allows the analysis of regional changes. Despite the fact that ground-based observations on ozone led to the discovery of the Antarctic ozone ‘hole’, the satellite-based observations on the extent of the ozone 'hole' have certainly added to the sense of urgency in the public and political arena.

A cost-benefit analysis in terms of absolute costs must be regarded as indicative only.

In a previous report we estimated costs of the EP-TOMS mission at 4.4M€ per year (Van Dijk et al., 2008). Koskela et al. (2006) have estimated the overall costs related to the OMI/AURA mission (amounting to M€573), and assumed a 3.5% share of the costs as being related to the UV-related products. This implies a total cost of M€20 for the OMI UV-product. Taking 6 years of operational use this would lead to an annual cost of M€3.3. Sharing the annual costs among two continents would lead to a yearly budget of M€1.7 for Europe. This amount should be raised with an additional budget for validation analysis using ground based UV-measurements, which is not included in the estimates from Koskela et al. It should be noted that the OMI instrument provides global analysis. A network of at least 25 UV-monitoring stations for Europe would be required for the validation work, and leads to annual operational costs of M€1.5-2.5 . Thus we end up with annual costs for Europe of M€3.2 - 4.2 per year for the satellite derived UV.

If we use ground-based stations to measure the UV-budgets, the overall costs depend very strongly on the number of stations. Van Dijk et al. (2008) assumed a number of 100 stations over the European continent amounting to M€10 per year for operational costs and data-analysis. However, this number might be too low from the perspective of monitoring. Long and Ackerman (1995) have indicated that a single station is representative for an area with a radius of 75 km. This would imply that on the European continent around 1500 stations would be required to have accurate coverage and allow full continental mapping of the UV-budgets. One could argue that for many areas a full coverage is not feasible or necessary. Reducing the overall number to 500 we would end up with an estimated annual budget of M€30-50.

Thus, the combined use of satellite observations and a limited number of high quality ground-based stations is the most cost-effective approach. Satellite-based retrieval of ground level UV is a cost-effective way of analysing regional differences in the UV-climate and changes therein, and offers a unique opportunity to couple UV-budget maps and long-term risk assessments. However, in view of the limited spatial and temporal resolution and the fact that satellite instruments tend to degrade, a continuous effort is required to validate the satellite derived UV with ground-based measurements.

This combined approach of satellite and ground-based observations assures long-term data-continuity and homogeneity required for UV-maps in trend and risk assessments.

3 Description of data sets

The time period of our analysis is limited by the available data of the operational OMI-product. The first data is given for 17th of august 2004; however, until 1st of October 2004 the data is too coarse. Therefore, we will use the first of October 2004 as the starting date and July 22nd 2006, the last listed data, as the end date for the analysis.[1]

The aim of this project is validation and comparison of the OMUVB product with other UV-data sets, either space-born or ground-based. In total, we are dealing with 3x2=6 distinguishable data sets:

1. OMUVB, yields 2 sets as a consequence of several values listed for the same day due to multiple overpasses. We use the data derived at the minimal Solar Zenith Angle (SZA), and constructed the average of possible multiple values listed for each day, i.e. the second set
2. AMOUR 2.0, yields 2 sets based on gridded ozone and reflection data, or overpass data
3. Ground-based UV, measured and modelled, available for 8 locations only

The pairs 1 and 2 use space-born data only, while the pair 3 uses ground-based data exclusively. All list for a particular location the wavelength-integrated erythemally weighted UV-irradiances, time-integrated over a day (J/m^2). The action spectrum of McKinlay and Diffey (1987) is used. As will be shown below, ground-based measured and ground-based modelled UV-data can be termed indistinguishable on the scale where space-born and ground-based UV-data are compared.

3.1 Operational OMI-product for UV

The operational OMI-product for UV, OMUVB, is an overpass product, given for over hundred locations spread across the world with emphasis on Europe. The OMUVB lists the aerosol index, cloud optical thickness, Lambertian Equivalent Reflectivity, surface reflectance, clear sky and cloudy sky values for the erythemally weighted daily dose and dose rate at local noon, and for spectral irradiances at 4 specific wavelengths. In this validation study, we focus on the erythemally weighted daily dose for cloudy skies, i.e. the afore mentioned wavelength integrated, erythemally weighted UV-irradiances time integrated over a day. Cloudy sky values are combined with clear sky values to infer the applied Cloud Modification Factor (CMF).

The OMUVB data is retrieved data from the Aura Validation Data Center of the NASA Goddard Space Flight Center. Direct download at

http://avdc.gsfc.nasa.gov/index.php?site=2057856112&id=56.

The data was produced at May 17th 2007, and downloaded in January 2008.

RIVM has written software to extract the day sums (J/m^2) from the data files. The software produces the average and the day sums at the smallest SZA, in the case of multiple listed values. Differences and the optimal choice here is still to be determined.

[1] Meanwhile, during the processing of the data for this project, data for a later period has been made available, see par. 3.2.3

In the report we use the following terms:

$OMUVB@SZA_{min}$:	day sum of erythemal weighted UV, listed for the smallest SZA
<OMUVB>:	average of multiple listed values for a day

Note that these two values may only differ for days with multiple listed day sums.

More background information on the OMUVB product can be read from the website at http://avdc.gsfc.nasa.gov. We quote:

'The OMUVB product contains surface UV irradiance data along with ancillary information generated using the OMI global mode measurements. In this mode each file contains the sunlit portion of a single orbit from pole-to-pole, with an approximately 2600 km wide swath composed of 60 ground pixels. The OMI measurements are used to estimate the ultraviolet (UV) radiation reaching the Earth's surface. The OMUVB product contains erythemally weighted daily dose, and erythemal dose rate at local solar noon. Additionally, the product includes spectral irradiances at 305.1, 310.1, 324.1, and 380.1 nm also corresponding to the local solar noon. These spectral irradiances assume triangular slit function with full width half maximum of 0.55 nm. The algorithm is based on use of a radiative transfer model whose input parameters are derived from the OMI measurements using the OMTO3 total ozone data product as input data. You may refer to release specific information about OMUVB for details about software versions. Surface UV irradiance data is also produced by the Sodankylä Direct Broadcast processing system. However, Direct Broadcast processing provides only local data in form of images and different data is used as an input (ozone from OMDOAO3 and radiances from Level-1B).
Algorithm Description

The OMUVB algorithm is documented in the Algorithm Theoretical Basis Document (ATBD). Contrary to ATBD, the current surface UV algorithm does not use the OMTO3 aerosol index to correct for absorbing aerosols in the free troposphere. The algorithm is similar to the TOMS UV algorithm developed by NASA. It first estimates the clear-sky surface irradiance using measured total ozone and surface albedo from the dataset described in http://promote.fmi.fi/MTW_www/MTW.html. The clear-sky value is then adjusted by a transmittance factor that accounts for the attenuation of UV radiation by clouds and aerosols. The attenuation factor is derived from the ratio of measured backscatter radiances and solar irradiances at 360 nm assuming that clouds and aerosols are non-absorbing at this wavelength. This leads to an overestimation of surface UV irradiance when UV-absorbing aerosols such as smoke or desert dust are present. Additionally, boundary layer pollution aerosols cause overestimation of surface UV irradiance in urban areas. Future version of the algorithm may correct for these effects.

Data Quality Assessment

The radiative transfer model assumes that clouds are plane parallel and homogeneous, i.e., it doesn't account for broken, multi-layer or mixed phase clouds. This error is the principal source of noise in comparing satellite measurements with ground-based instruments. The OMI surface UV irradiance represents the spatial average over the OMI footprint. OMI measurements are made once a day around 1:45 p.m. local time. No correction is made for the change in cloudiness, ozone and aerosols between local noon and satellite overpass time, or for their diurnal variability. Previous validation studies with TOMS data suggest that OMI UV irradiance estimates are on the average 0-30% larger than the ground-based reference data. The OMI surface UV data were compared with spectral ground-based measurement data of Jokioinen (60.8N,23.5E), Sodankylä (67.4N,26.6E), Toronto (43.8N,79.5W), San

Diego (32.8N,117.2W), Ushuaia (54.8S,68.3W), and Barrow (71.3N,156.7W). The validation results were presented in the AGU fall meeting in December 2005, and they imply similar results as the previous validation studies with TOMS surface UV data. The systematic bias can be attributed to absorbing aerosols from natural and anthropogenic sources. Since the soot content of the urban aerosols tend to be highly localized, these errors presumably are also localized and do not necessarily represent the error in regional estimate of surface UV made by OMI. Snow and ice further complicate estimation of the surface UV since clouds cannot be distinguished from them. Therefore, in regions with temporary snow or ice or highly heterogeneous surface albedo the OMI UV irradiance estimates have much higher uncertainty. Future version of the algorithm may use snow cover information to reduce this uncertainty.

Product Description

An OMUVB product file contains the sun-lit portion of a single Aura orbit or some 1650 measurements. Each measurement consists of a 2600 km wide OMI scan of 60 pixels. Due to optical aberrations and small asymmetry between the instrument optic axis with the spacecraft nadir, the pixels on the swath are not symmetrically aligned on the line perpendicular to the orbital plane. The latitude and longitude provided with each pixel represent the centre of each pixel on ground. The OMUVB product is written as an HDF-EOS5 swath file. Software tools that read HDF-EOS5 data files are available at http://disc.gsfc.nasa.gov/Aura/tools.shtml. The data are ordered in time. The information provided in these files includes latitude, longitude, solar zenith angle, and a large number of ancillary parameters that provide information to assess data quality. The most important of these parameters is the OMUVBQuality field, that describes the quality of the data and can be used for filtering of the data. For a complete list of the parameters, please read the OMUVB format specification document.'

3.2 UV-MAPS by RIVM, using AMOUR 2.0

3.2.1 MAP-mode

RIVM uses the AMOUR 2.0 program to calculate UV-maps based on gridded data. The clear sky UV use gridded ozone fields, CMF-maps are inferred from the gridded reflections fields to produce cloudy sky UV-maps. In principal, the CMFs are given by 1 minus the reflection including a ground-albedo correction. The ground-albedo is derived from climatological ground-albedo maps; for each month, a different map is used. An extraction program delivers time series of day UV-sums for the same locations as supported by OMUVB.

The Level 3 OMI-ozone and OMI-reflection data fields are downloaded through direct ftp from:

ftp://toms.gsfc.nasa.gov/pub/omi/data/ozone/

and

ftp://toms.gsfc.nasa.gov/pub/omi/data/reflectivity/

File transfer started at November 8th 2005, and continued automatically thereafter. In this report we use the V8 version of the 1.0x1.25 degrees gridded ozone and reflection data.

Within the AMOUR 2.0 program, some choices can be made on the resolution of the output grid and internal time and space resolution. Time series for the day sum at the required locations are extracted from the maps.

3.2.2 Overpass mode

A different approach is the AMOUR 2.0 overpass mode, $AMOUR_{ovp}$, i.e. using the same algorithm as the AMOUR 2.0, but now with the use of the overpass data sets. NASA's Total Ozone Mapping Spectrometer data server delivers overpass data for over 450 prefixed locations. The ozone data has 4-significant figures instead of the 3 for the gridded ozone values. Gridded values may be build-up from several spatial interpolated overpasses, while the overpass data lists all measured values on subsequent lines. Computer programs were written to retain the ozone and radiative cloud fraction values listed at the smallest SZA, where after the AMOUR 2.0 algorithm is applied to produce the day sums of UV as function of time.

Level2 overpass data is downloaded from the Aura Validation Data Center (AVDC) of the NASA Goddard Space Flight Center at

http://avdc.gsfc.nasa.gov/phpgdv2/avdc_tablefile.php?id=28

File transfer took place in June 2008

Version 'EOS Aura OMI OMTO3 v8.5, Collection 3' is used, note that this the most recent calibration, AMOUR map-mode makes use of the previous calibration, see par. 3.2.3.

Overpass mode is more suitable for tests on the performance of new developed algorithms or implementations of local measured ancillary data, as only data for one site is calculated.

3.2.3 OMI V8 versus the new Collection 3 data

On the 1st of February 2008, a new version (V8.5) of the ozone data has been released replacing the older version; data online on 16th of February. Unfortunately, this happened to be right in the middle of our validation study. Consequently, the MAP and the overpass mode of AMOUR 2.0 use data sets based on different calibrations. The new processed ozone data appear to have a calibration yielding 2% lower values compared to the V8-version for the Bilthoven location, and are given on a 1.0x1.0 degrees grid.

Reflection data, as gridded and overpass, is no longer supported, and has been taken over by a new quantity called the 'radiative cloud fraction' (RCF). The RCF should yield the net cloud effect. However, at this stage it is not directly clear how this should be implemented. Figure 3.1 and 3.2 clearly bring forward the different behaviour between the old reflection data, shown for EP-TOMS period in the left panels and the new OMI RCF-data shown on the right.

Within the scope of the OMI-validation project we could only perform some preliminary tests showing that best results are obtained when this new quantity is interpreted as pyranometer data 'shifted to shorter wavelength'. The latter should be read as a less curved (more linear) relationships between CMFs of different wavelength regions. A CMF represents the effect of clouds on the modelled or actual clear sky value. A CMF=1 means no clouds, and a small value is the result of heavy overcast skies. CMFs in the UV differ from CMFs in the visible range for the same cloud layer, due to multiple scattering effects of the radiation, and therefore identifications of the applied wavelength range should be made.

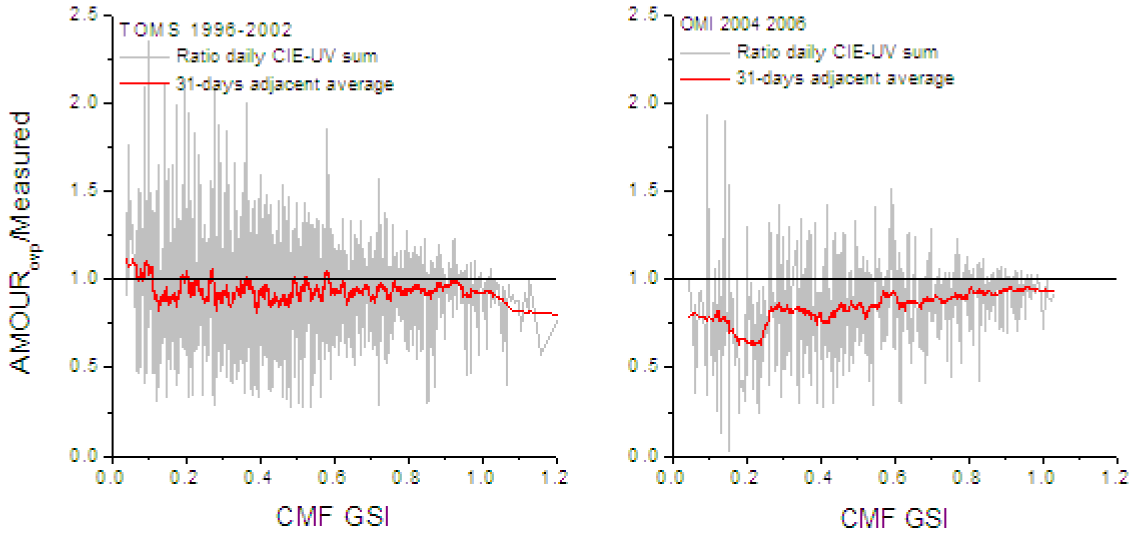

Figure 3.1 Direct implementation of the CMF as derived from TOMS (left) and OMI (right).

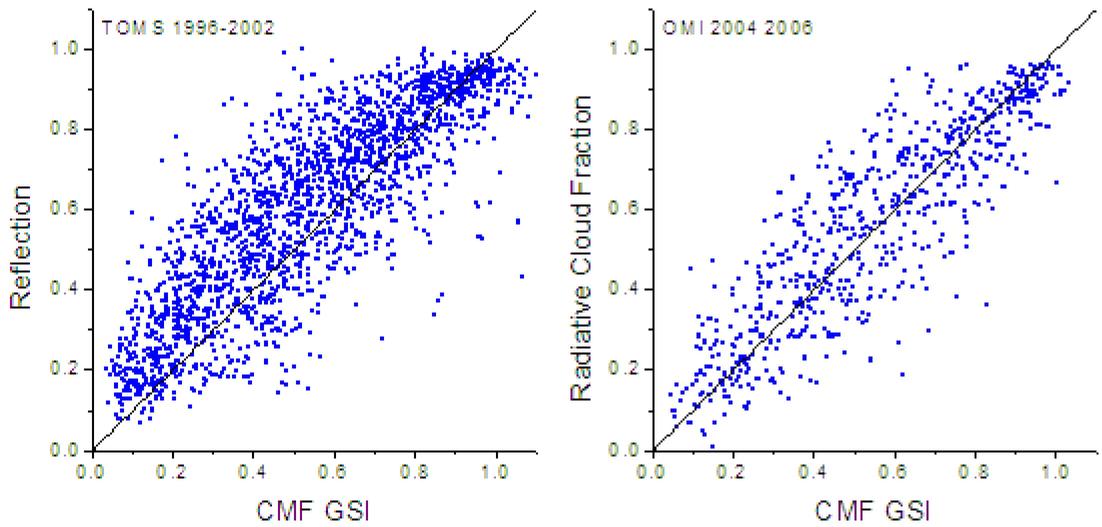

Figure 3.2 Reflection as obtained from TOMS and Radiative Cloud Fraction as derived from OMI as a function of the Cloud Modification Factor for the Global Solar Radiation. Left panel is what is expected, the linear behaviour in the right panel suggests the Radiative Cloud Fraction not to be directly applicable in the UV.

Ground-based modelling usually makes use of established relationships between CMFs for global solar irradiance (GSI) and CMFs for UV. This relationship should be concave when two far apart wavelength regions are considered, as erythemal weighted UV and global solar irradiance are. Moving towards the UVA, hence closer to the global solar irradiance region, or vice versa, using the RCF-data to infer the cloud impact on erythemal UV, this relationship should become more linear. As a starting point we use a 'Best Guess Implementation', and use the relationship coefficients as derived for the 350-360 nm interval (Den Outer et al., 2005). Establishing the true optimal relationship between the radiative cloud fraction and erythemal UV is beyond the time schedule and scope of this study.

Since July 22^{sd} 2008 'collection 3'-based OMUVB-data became available as well. Unfortunately, reprocessing takes place backwards in time. Starting in 2008 and now ending in August 2006. This is outside our time window of the other available data sets, including the OMUVB data used in this report. As far as 'readme-files' on the webpages indicate, attempts were not made yet to improve on neither aerosols nor snow cover information. Thus, we may assume that, except the apparent 2% ozone recalibration, the results found in this report will hold in general also for the 'collection 3'-OMUVB data.

3.3 Ground-based UV

The ground-based measured and modelled data sets are taken from the results of a European Integrated product: SCOUT-O3. A goal of this project was to produce UV-data records for eight UV-monitoring sites across Europe, as far back in time as possible. Ground-based UV-data and ancillary measurements where gathered and model runs where performed using 5 different UV-transfer models. Five out of eight sites delivered measured UV-sums based on spectrometer data, and 3 sites based on broadband measurements (Den Outer et al., 2007). Unfortunately, UV and ancillary data do not exist at Potsdam after the year 2003, as the effort of monitoring was transferred to the Lindenberg in 2004. We therefore added Uccle, Belgium as the eighth site and used the spectral data of IASB, and ozone and global solar radiance of KMI, both located on the same compound. Spectra were downloaded from the European UV spectral database located at FMI, Finland, (EUVDB) and analysed by the SHICrivm-spectral software tool. Overview of available ground-based data is given in Table 3.1

Table 3.1 Available ground-based data

Location	Longitude west	Latitude north	UV	Ozone	Pyranometer
Sodankylä	26.63°	67.64°	1991-2006	1978-2006	1957-2006
Jokioinen	23.50°	60.81°	1995-2006	1978-2006	1957-2006
Norrköping*	16.15°	58.58°	1983-2003	1983-2006	1983-2006
Lindenberg	14.12°	52.21°	1995-2007	1964-2007	1981-2006
Bilthoven	5.20°	52.12°	1994-2008	1973-2008	1965-2008
Potsdam	13.08°	53.36°	1995-2003	1964-2003	1937-2003
Hradec Kralove*	15.83°	50.19°	1996-2006	1964-2006	1953-2006
Thessaloniki*	22.97°	40.52°	1992-2006	1982-2006	1980-2006
Uccle	4.36°	50.80°	1993-2006	1973-2008	1951-2006

* Broadband data.

The day-to-day variation is captured by the UV-measurements, calibration of the measured and modelled results, as well as long-term stability, is ensured through a detailed intercomparison of modelled and measured data. As a result, ground-based modelled and measured data can be interchanged within the OMI UV validation project. An example is give in Figure 3.3

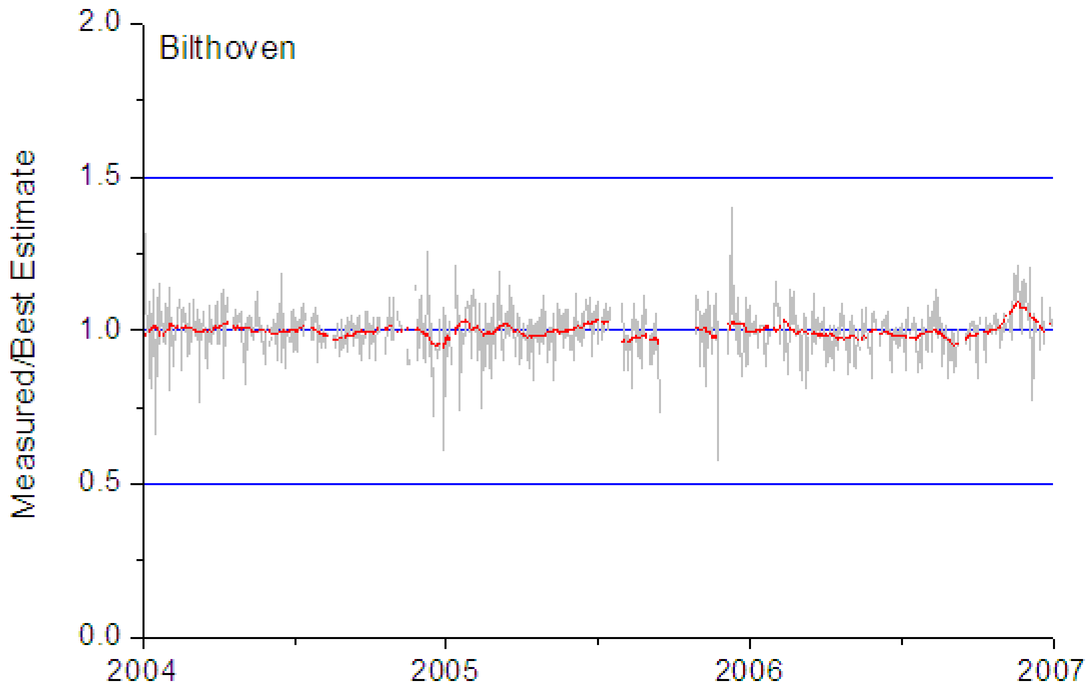

Figure 3.3 Ratios of ground-based measured and modelled day sums of effective UV as a function of time.

The averaged ratio is 1.00 ± 0.08, and averaged year sums for these 3 years are 455.9 kJ/m^2 (measured) and 450.8 kJ/m^2 (modelled). More elaborated results are given in Table 3.2 listing the average ratios of modelled divided by measured day sums for all available days, and averaged year sums. Standard deviations are of the order of 10% for the day sums, and years sums agree all within the 3%.

Table 3.2 Comparison of ground-based modelling vs. ground-based measurements

Location	Ratio	Ave Year Sums (kJ/m^2) Measured	Modelled	Years used
Sodankylä	0.99 ± 0.09	291	293	1991-2006
Jokioinen	1.01 ± 0.14	374	375	1995-2006
Norrköping	0.97 ± 0.10	395	400	1983-2003
Lindenberg	1.03 ± 0.10	522	506	1995-2006
Bilthoven	1.00 ± 0.08	441	444	1994-2006
Potsdam	1.01 ± 0.13	478	465	1995-2002
Hradec Kralove	0.96 ± 0.11	480	492	1996-2006
Thessaloniki	0.96 ± 0.09	735	749	1992-2006
Uccle	0.95 ± 0.11	412	425	2003-2006

4 Comparing with ground-based measured and modelled data sets

4.1 Introduction

In this chapter, we compare the OMUVB product with ground-based UV, measured or modelled, for the eight sites across Europe. The comparison is on daily, monthly, and yearly basis. The performance of the OMUVB product is also assessed as a function of cloudiness. The collection of ground-based UV-measurements and the ground-based modelled data at the eight sites have been performed with in the framework of the SCOUT-O3 project. Affiliations and responsible operators are listed in the Acknowledgement.

The OMUVB product lists multiple values for the day sums, as the satellite may have 2 or more overpasses per day. How to proceed from these multiple values for the same day is yet to determine. The average could be used or the value derived for the smallest SZA. The latter has been generally advised by the provider. However, if this is indeed the best choice and how results depend on this choice is still an open question. We will first address this issue in the following section.

4.2 Multiple overpasses

At Sodankylä 88% of the year multiple overpasses occur, while at Thessaloniki still 30% of the days have a double overpass. We have analysed the agreement between the OMUVB product with ground-based data for the product derived at minimum SZA and for the multiple values averaged. Only days with 2 or more overpasses where considered for this particular exercise and compared with the day sums derived from the selected eight UV-monitoring sites.

We have calculated the average and standard deviations of the ratios OMUVB divided by ground-based UV, see Table A1 and A2 in the Appendix A. The averaged ratios are closer to 1, a better agreement, for the OMUVB@SZA_{min} -values compared to the situation where the <OMUVB>-values are used. However, the standard deviations show the opposite, i.e. slightly better results are derived here for the <OMUVB>-product. The tables summarizing the results, Table A.1 and A.2, are given in the Appendix.

The end conclusion in this matter is that both choices are equally justified, or that major deviations later on cannot be attributed to the wrong choice here. As an improvement of the OMUVB-algorithm is likely to include a higher aerosol loading, and thus lower UV-estimates, the best choice could well in the end be the average values. From a physical point of view not surprisingly, where it is to be expected that more observations of the same quantity - in our case mainly the cloud field- will lead to a better estimate of the actual value.

4.3 Direct comparison of OMUVB with ground-based data.

4.3.1 Day sums

In Figure 4.1 we plot the ratios of day sums, OMUVB divided by ground-based, as a function of time. OMUVB@SZA_{min} is shown only. For the Norrköping site the modelled values are used. Grey lines are the ratios of day sums and the red lines the 31-days adjacent averages. Generally, OMUVB overestimates the actual UV-levels as determined by ground-based measurements. The pattern of Norrköping and Jokioinen is caused by snow coverage in wintertime, which apparently is not fully taken into account. Results are summarized in Table 3.3 and Table 4.4 (summer-half year only) where also results of <OMUVB>, AMOUR 2.0 and $AMOUR_{ovp}$ are gathered. Numbers shown are based on concurrent days of the OMUVB and AMOUR 2.0 data sets.

In Figure 4.2 we plot the ratios of Figure 4.1 as a function of CMF for the global solar irradiation. In this way the behaviour of the OMUVB-algorithm as a function of cloudiness becomes visible. Apparent from Figure 4.2 is that the current OMUVB algorithm makes an additional overestimation for overcast days by 20 to 50% for CMF smaller than 0.4, leading to overestimated year sums by 3 to 10% accordingly. The precise figures hold for the Bilthoven location where we could analyse a modelled data set for the years 1964 to 2006. About a third of the days at Bilthoven have a CMF below 0.4 for the GSI, with a mean of 0.25. The same days have a mean CMF of 0.4 in the UV and a 13% contribution to the yearly UV-sum (note that days with the CMF-UV below 0.4 yield a different subset with a larger contribution,18%, to the yearly UV-sum). Fortunately, these larger overestimations are of less importance, but nevertheless should not be disregarded as long-term development of the UV-burden typically changes of the order of 5 to 10% over a 10-years period. Moreover, if cloudiness is not correctly taken into account, the performance of an UV-algorithm becomes weather dependent.

Why this extra overestimation is not observed for the Norrköping site is unclear. The argument that this is due to the modelling of the ground-based data does not hold as a direct comparison of modelled to measured data prior to the OMI-period shows a CMF independent behaviour.

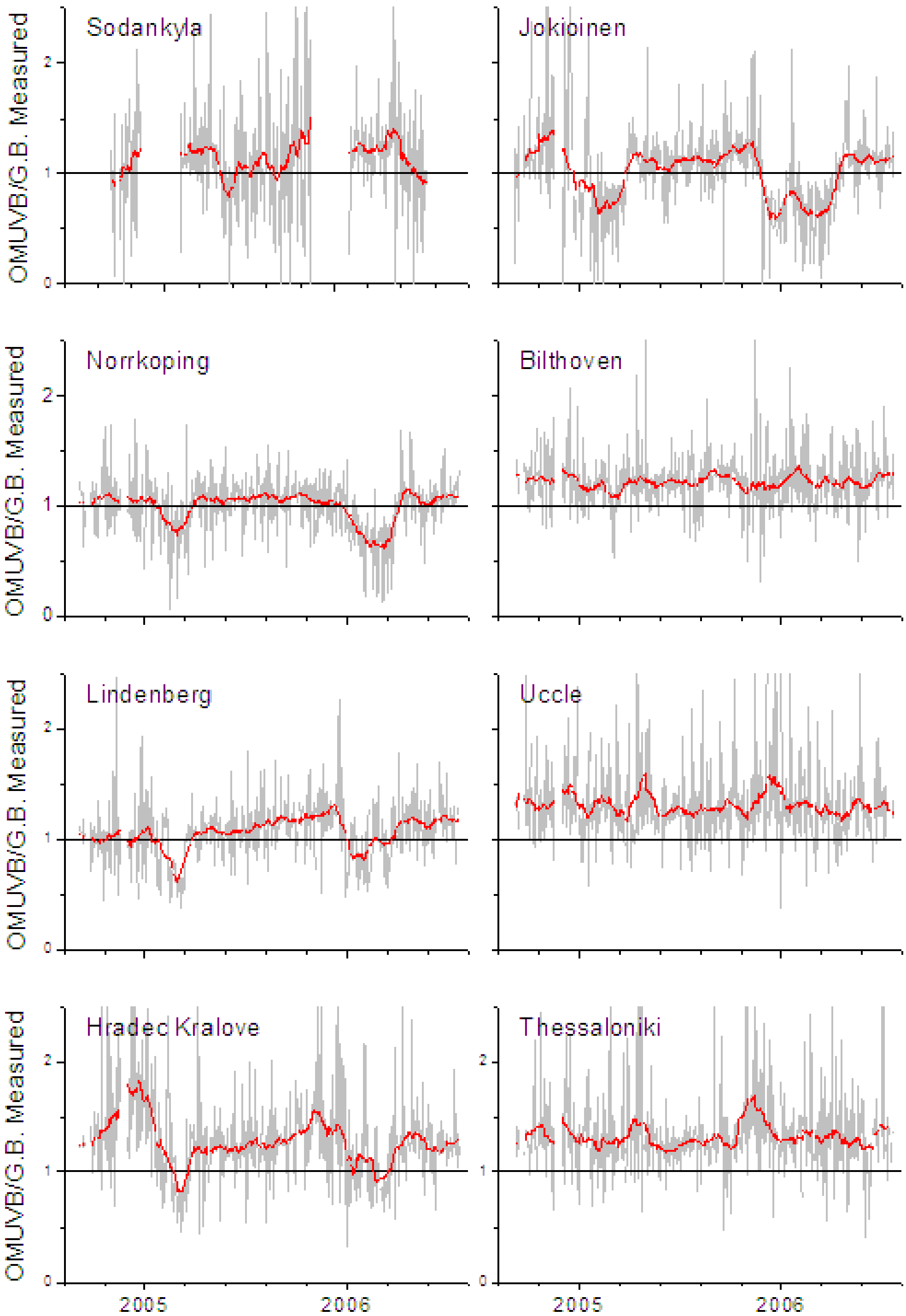

Figure 4.1 Direct comparison of OMUVB@SZA$_{min}$ day UV-sum vs. ground-bases UV-measurements; grey lines. Red lines show 31-days running means of ratios. For Norrköping ground-based modelled data is used.

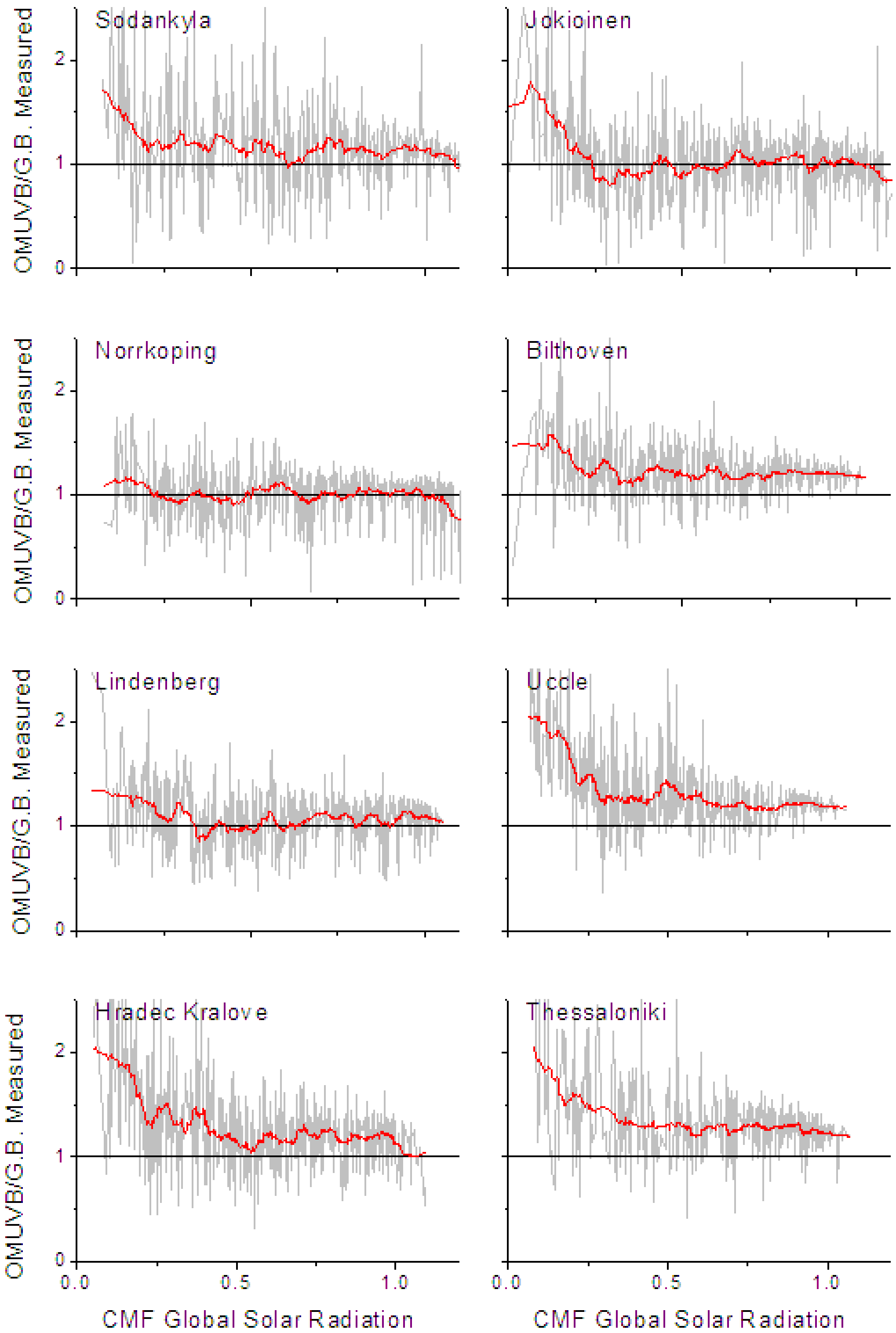

Figure 4.2 Same data as in Figure 4.1 but now as a function of the Cloud Modification Factor (CMF); 1: clear sky, CMF small: heavy overcast. Grey lines: day values. red lines show 31-days running means of ratios.

Knowing that the OMUVB algorithm has a tendency to underestimate the cloud impact on UV, it is interesting to see if the different use of the OMUVB data leads to an obvious difference in the allocated cloud impact on the UV-sums. For every day, OMUVB lists also a clear sky value of the UV-sum. Hence, we can construct CMFs for OMUVB-data at the minimal SZA and average the clear sky values to infer the CMF for the <OMUVB> -product. A third option, i.e. averaging the CMFs was not considered. Thus we make a comparison of OMUVB derived UV-CMFs with measured CMFs. The latter implies measured day sums divided by the ground-based modelled clear sky estimates. In Figure 4.3 we show correlation graphs for all year data (top) and additionally for the summer-half years (bottom), CMFs derived from OMUVB@SZA_{min} are shown in the left panels, and those for <OMUVB> in the right. Results are summarized in Table 4.1 and 4.2.

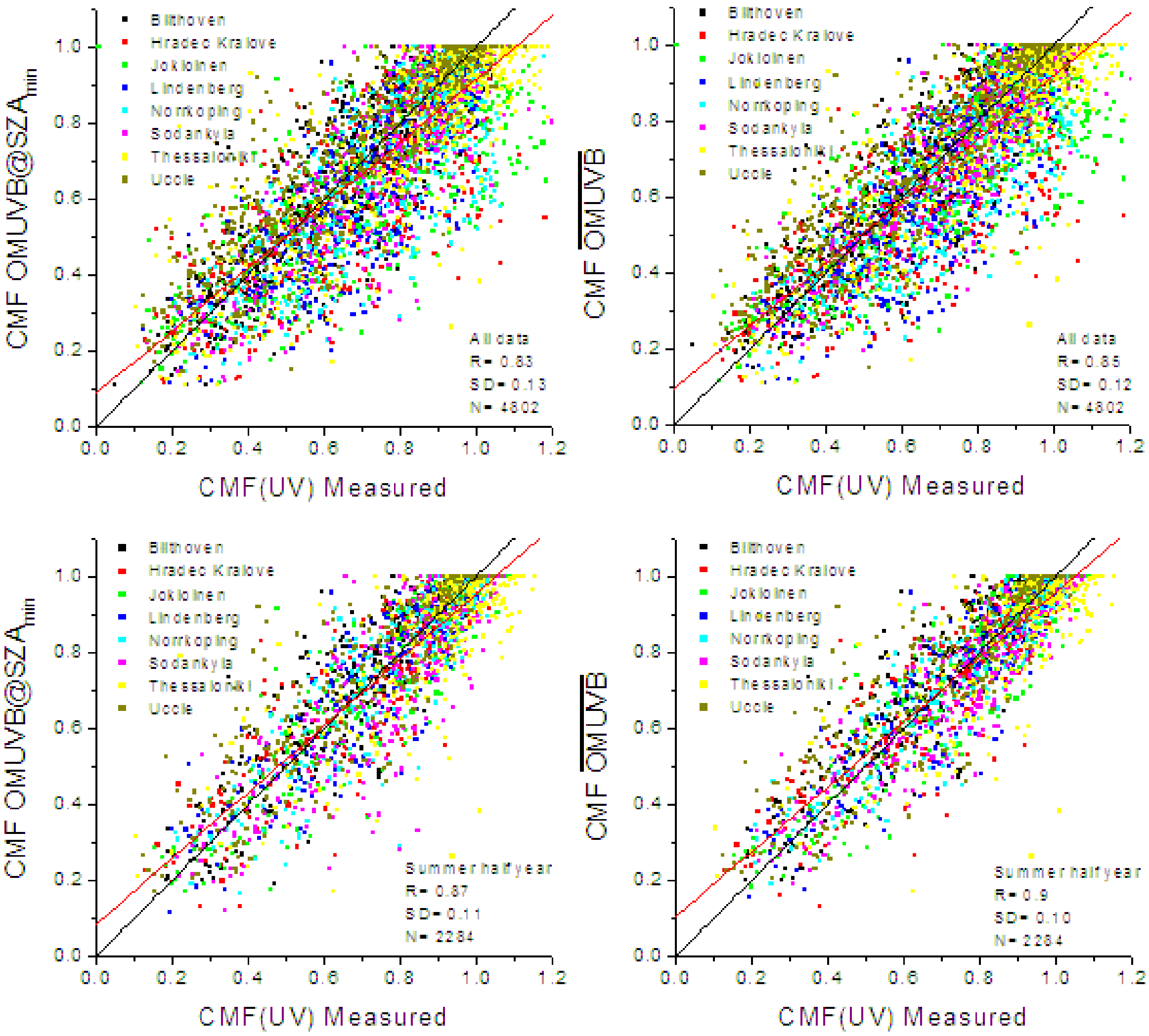

Figure 4.3 CMFs derived from ground-based measurements and modelling correlated with OMUVB used CMFs. Black lines denote a 1-1-relationschip; red lines are the fitted straight lines. Top two panels show all data, bottom two show the summer-half year only.

Table 4.1 Correlations of CMFs as used by OMI vs. ground-based derived CMFs

Site	N	OMUVB@SZA$_{min}$			<OMUVB>		
		R	Y0	Slope	R	Y0	Slope
Sodankylä	470	0.86	0.02 ± 0.02	0.91 ± 0.02	0.91	0.05 ± 0.02	0.89 ± 0.02
Jokioinen	611	0.79	0.12 ± 0.02	0.74 ± 0.02	0.81	0.13 ± 0.02	0.74 ± 0.02
Norrköping	622	0.83	0.01 ± 0.02	0.89 ± 0.02	0.86	0.02 ± 0.02	0.89 ± 0.02
Bilthoven	622	0.90	0.07 ± 0.01	0.92 ± 0.02	0.90	0.08 ± 0.01	0.90 ± 0.02
Lindenberg	620	0.86	-0.03 ± 0.02	0.97 ± 0.02	0.86	-0.03 ± 0.02	0.97 ± 0.02
Uccle	621	0.88	0.15 ± 0.01	0.82 ± 0.02	0.89	0.15 ± 0.01	0.82 ± 0.02
Hradec Kralove	619	0.78	0.09 ± 0.02	0.79 ± 0.03	0.78	0.09 ± 0.02	0.79 ± 0.03
Thessaloniki	617	0.84	0.10 ± 0.02	0.81 ± 0.02	0.84	0.11 ± 0.02	0.80 ± 0.02
All data	4082	0.83	0.088±0.006	0.827±0.008	0.85	0.096±0.005	0.853±0.009

Table 4.2 Same as Table 4.1 but using data of the summer-half year only

Site	N	OMUVB@SZA$_{min}$			<OMUVB>		
		R	Y0	Slope	R	Y0	Slope
Sodankylä	288	0.85	0.00 ± 0.03	0.93 ± 0.03	0.91	0.03 ± 0.02	0.91 ± 0.02
Jokioinen	287	0.91	0.02 ± 0.02	0.95 ± 0.03	0.92	0.05 ± 0.02	0.92 ± 0.02
Norrköping	286	0.89	0.05 ± 0.02	0.91 ± 0.03	0.92	0.06 ± 0.02	0.90 ± 0.02
Bilthoven	287	0.91	0.05 ± 0.02	0.97 ± 0.03	0.91	0.08 ± 0.02	0.94 ± 0.02
Lindenberg	285	0.90	0.06 ± 0.02	0.91 ± 0.03	0.90	0.07 ± 0.02	0.90 ± 0.03
Uccle	285	0.87	0.15 ± 0.02	0.82 ± 0.03	0.88	0.16 ± 0.02	0.82 ± 0.03
Hradec Kralove	284	0.89	0.07 ± 0.02	0.90 ± 0.03	0.89	0.09 ± 0.02	0.87 ± 0.03
Thessaloniki	282	0.76	0.16 ± 0.03	0.75 ± 0.04	0.76	0.19 ± 0.03	0.73 ± 0.04
All data	2284	0.87	0.084±0.008	0.871±0.010	0.89	0.105±0.007	0.853±0.009

In Table 4.1 and 4.2 we list the derived correlations for the CMF ground-based measured versus OMUVB-used. Although the values are quit similar, again the entangled ranking of the performance of OMUVB@SZA$_{min}$ and <OMUVB> emerges. This holds especially for the northern sites. The correlation, R, is slightly higher for the <OMUVB>, while the slopes of the linear fits are closer to 1 for OMUVB@SZA$_{min}$.

4.3.2 AMOUR 2.0 compared with ground-based measurements

In this paragraph we include results from RIVM's mapping approach, i.e. using the AMOUR 2.0 program. Time series labelled AMOUR are extracted from UV-maps where the older V8 version data for ozone and reflection data sets have been used. Overpass results are labelled AMOUR$_{ovp}$ and these results are based on the newer 'collection 3' ozone overpass data and accompanying the new released

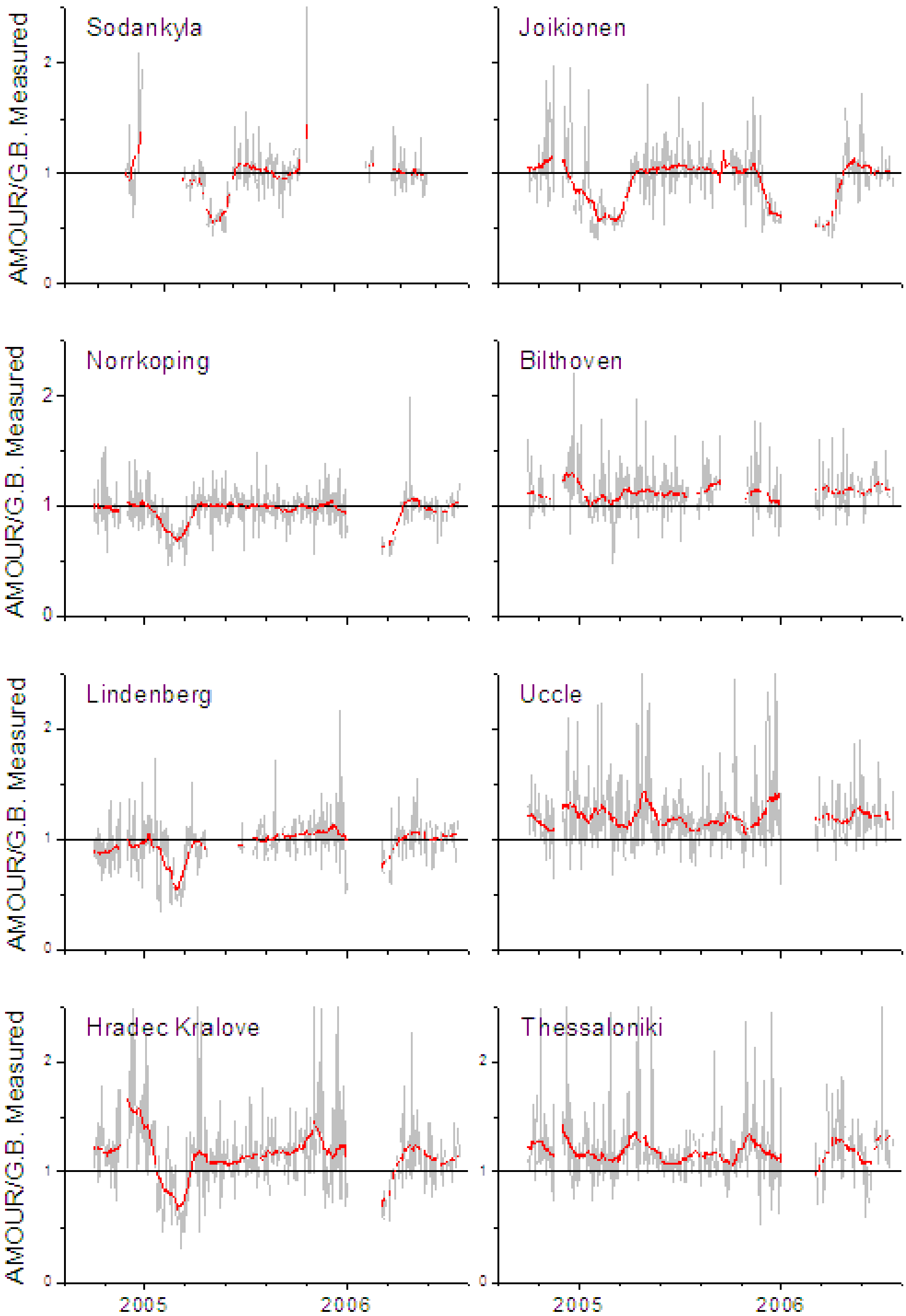

Figure 4.4 Direct comparison of AMOUR UV day sum vs. ground-based UV-measurements; grey lines. Red lines show 31-days running means of ratios. For Norrköping ground-based modelled data is used.

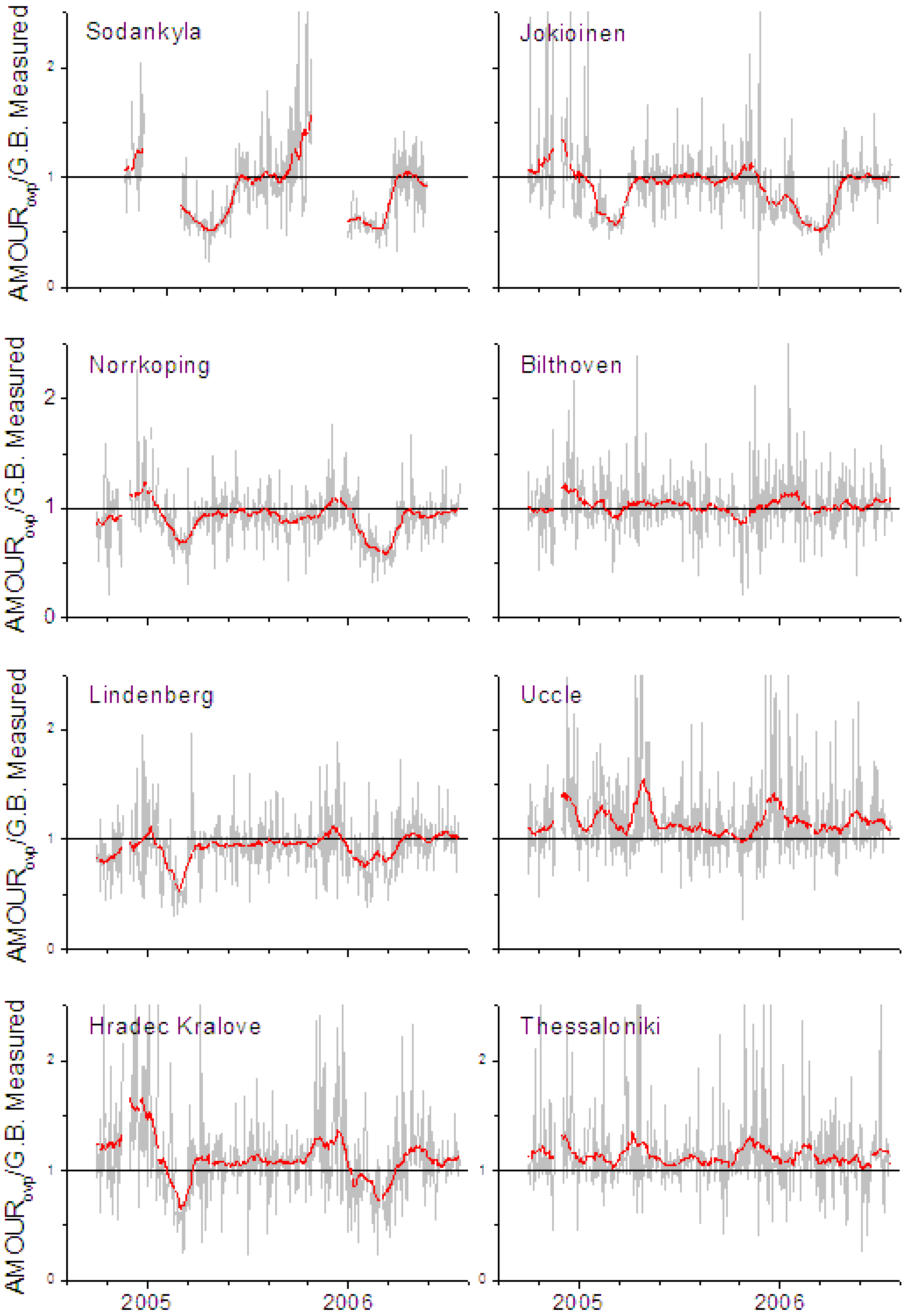

Figure 4.5 AMOURovp compared with ground-based measured data; grey lines. Red lines show 31-days running means of ratios. For Norrköping ground-based modelled data is used.

cloud effect proxy ‘radiative cloud fraction’. The $AMOUR_{ovp}$-results should be regarded as preliminary results only.

Figure 4.4 shows day sums derived by AMOUR divided by the ground-based measured ones as a function of time. Again for Norrköping ground-based modelled data is used. In Figure 4.5 we show the same but for the overpass data. The overall level of the curves is closer to agreement for both AMOUR modes compared to the results by OMUVB as we use a standard higher aerosol loading. Clearly, we also lack the local ground-albedo information emerging as large underestimations in wintertime for the northern sites, where erroneously snow cover - meaning a high reflection - is interpreted as cloud cover.

Tables 4.3 and 4.4 (summer-half year) give an overview of the agreement between the four space-born based datasets ($OMUVB@SZA_{min}$, <OMUVB>, AMOUR and $AMOUR_{ovp}$) and the ground-based measured data. The tables list the average and standard deviations of the ratios space-born day sum divided by ground-based measured, where the results are ordered with respect to the degree of latitude. A split in the agreement emerges, with the transition between Lindenberg and Bilthoven. The values for Lindenberg and up north exceed less the measured values, compared to values for Bilthoven and down south. A discussion on this result is deferred to the end of this section. Retaining the summer-half year data only yields much better results for the standard deviations for all algorithms, Sodankylä only slightly because almost the same data set is addressed due to the absence of sunlight during mid winter.

Table 4.3 Average ratios space-born vs. ground-based, year around concurrent days

Location, Latitude north	Num	$OMUVB@SZA_{min}$	<OMUVB>	AMOUR	$AMOUR_{ovp}$
Sodankylä, 67.37°	293	1.12 ± 0.27	1.15 ± 0.22	0.98 ± 0.26	0.93 ± 0.36
Jokioinen, 60.81°	465	1.05 ± 0.31	1.07 ± 0.29	0.93 ± 0.28	0.92 ± 0.35
Norrköping, 58.58°	533	1.05 ± 0.21	1.06 ± 0.20	0.96 ± 0.17	0.91 ± 0.23
Lindenberg, 52.22°	449	1.08 ± 0.27	1.08 ± 0.26	0.96 ± 0.22	0.93 ± 0.24
Bilthoven, 52.12°	438	1.21 ± 0.23	1.23 ± 0.22	1.13 ± 0.19	1.04 ± 0.24
Uccle, 50.80°	521	1.32 ± 0.34	1.33 ± 0.34	1.20 ± 0.27	1.16 ± 0.37
Hradec Kralove, 50.19°	531	1.30 ± 0.39	1.30 ± 0.36	1.14 ± 0.33	1.11 ± 0.38
Thessaloniki, 40.63°	500	1.32 ± 0.34	1.33 ± 0.34	1.18 ± 0.27	1.14 ± 0.30

Table 4.4 Average ratios space-born vs. ground-based, summer half-year concurrent days

Location, Latitude north	Num	$OMUVB@SZA_{min}$	<OMUVB>	AMOUR	$AMOUR_{ovp}$
Sodankylä, 67.37°	201	1.09 ± 0.23	1.12 ± 0.18	0.89 ± 0.23	0.92 ± 0.24
Jokioinen, 60.81°	226	1.12 ± 0.17	1.13 ± 0.16	1.03 ± 0.18	0.98 ±0.18
Norrköping, 58.58°	267	1.09 ± 0.17	1.10 ± 0.15	1.00 ± 0.13	0.95 ±0.16
Lindenberg, 52.22°	185	1.11 ± 0.18	1.11 ± 0.16	1.00 ± 0.16	0.99 ± 0.17
Bilthoven, 52.12°	232	1.20 ± 0.22	1.23 ± 0.20	1.11 ± 0.16	1.03 ± 0.20
Uccle, 50.80°	255	1.24 ± 0.29	1.25 ± 0.28	1.14 ± 0.22	1.15 ± 0.39
Hradec Kralove, 50.19°	266	1.22 ± 0.23	1.24 ± 0.22	1.12 ± 0.18	1.10 ± 0.26
Thessaloniki, 40.63°	237	1.22 ± 0.31	1.23 ± 0.33	1.11 ± 0.27	1.12 ± 0.26

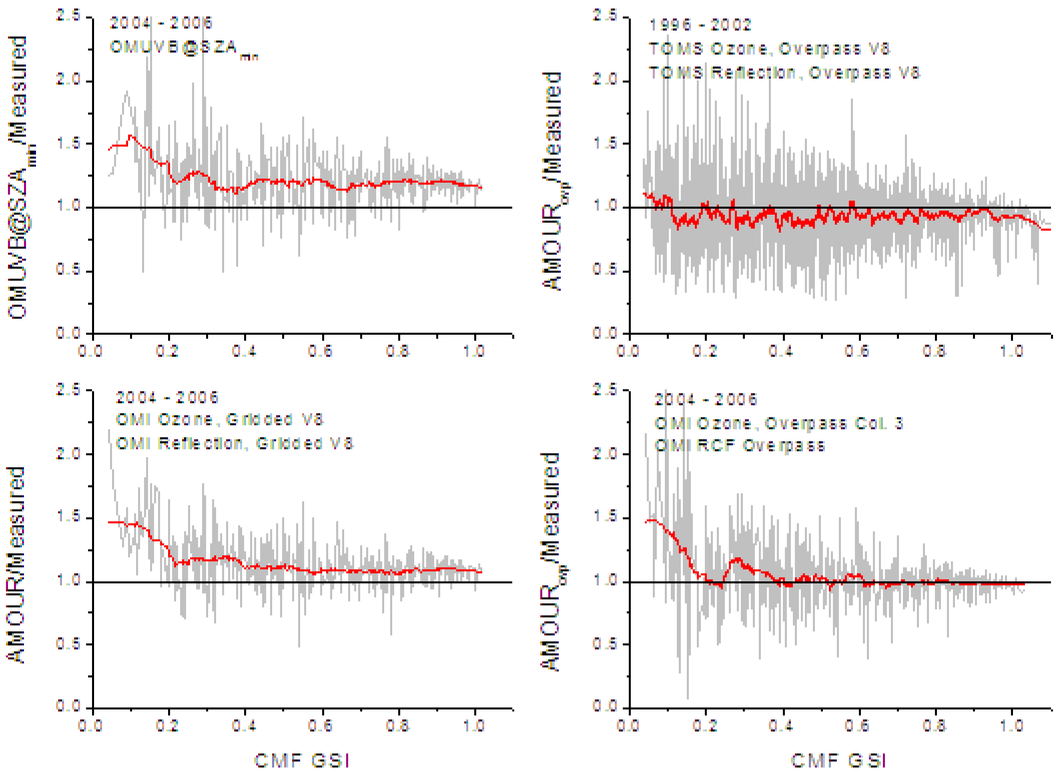

Figure 4.6 Ratios of day sums space-born vs. ground-based for various algorithm and used data sets. All graphs apply for the Bilthoven location.

Figure 4.6 gives an overview of how well cloud effects are taken into account. All graphs show again the ratios space-born day sums divided by ground-based measured as a function of the CMF for the global solar irradiance. Graphs involve data for Bilthoven only. Clearly, the OMUVB-ratios become CMF-dependent for CMFs below 0.2, left upper graph. The same, however, holds for the AMOUR result using the OMI ozone and reflection V8 data. Contrary, applying the same algorithm to the EP-TOMS V8 data set does not show this dependency. The absence of this dependency, using TOMS V8 data, is demonstrated for a wide European area (Matthijsen et al., 2000; Williams et al., 2004). Hence, the OMI-reflection data set behaves for heavy cloudiness different from its preceding produced by EP-TOMS. This means that deviations found in Figure 4.2 could well be attributed to the input data, instead of to the OMUVB-algorithm itself.

Using the radiative cloud fraction as a reflection product yields results as previously shown in Figure 3.1, while using the best guess implementation in AMOUR$_{ovp}$ yields results as shown in the right lower graph of Figure 4.6. We could state that we ‘missed’ the straight line with our best guess, since we are now above the ideal line. Hence, it should be possible to improve our best guess and determine a relationship between the new RCF-data and the CMF-UV yielding a cloudiness independent result.

Returning the Figures 4.1, 4.4 and 4.5 that show the agreement as a function time, a pattern in the red curves - the 31-days running means - can be identified in the graphs for Norrköping, Lindenberg and Hradec Kralove. It appears that an underestimation in January, February, is preceded by an overestimation in November, December for both winters. Because all algorithms show this feature, and at least $AMOUR_{ovp}$ uses a fixed, small, ground-albedo, this sequence of over-underestimation must be caused by the underlying ozone or cloud effect data. It could well be that a climatological snow cover is used in the OMI algorithm that produces the reflection data and the RCF-data.

A small positive ‘trend’ between spring 2005 and fall 2005 is clearly visible for the three sites Norrköping, Lindenberg and Hradec Kralove, see Figure 4.1 and 4.4, which seems to be corrected in the updated data sets used by $AMOUR_{ovp}$, c.f. Figure 4.5 where this so-called ‘trend’ is not visible any more.

Apparently, structures as shown in Figure 4.1, 4.4 and 4.5, reducing the overall agreement between OMI-based UV and ground-based measurements, can partly be attributed to the underlying ozone and cloud radiation fields, and not to the algorithms used by either OMUVB or AMOUR.

4.3.3 Month and year sums

Comparing month sums puts more weight on the absolute calibration and less weight to cloudy sky days, i.e. the performance of the used CMF-algorithm. Data gaps must be addressed before construction of monthly and yearly totals sums can be performed. As became clear in the SCOUT-O3 reconstruction study (Den Outer et al., 2007), only good results can be obtained when measured and modelled datasets are supplemented using the same algorithm. Otherwise differences are by a large part due to the occurrence of data gaps. The supplementation algorithm makes uses of scaled modelled values - based on ground-based ancillary data- scaled to the calibrations of the data set to be supplemented. The scaling is such that the concurrent subset of available data and modelled data sets produce the same annual totals. In Figure 4.7 we show the ratios of monthly sums; OMUVB divided by the ground-based measured.

The wintertime period emerges clearly as a large deviation from the stabile level during summer. In addition, the average monthly sums listed in Table 4.5 show a small standard deviation during the summer-half year while for the whole period much larger standard deviations are found. Again we find rather larger differences for the southern sites, 24% on average, compared to the more northern sites, 9% on average for the summer-half year.

Table 4.5 Averaged ratios of month sums, data as in Figure 4.7

Site	Latitude north	Averaged ratios	
		All days	Summer half year
Sodankylä	67.37°	1.10 ± 0.08	1.08 ± 0.08
Jokioinen	60.81°	1.01 ± 0.15	1.10 ± 0.03
Norrköping	58.58°	1.01 ± 0.12	1.08 ± 0.03
Lindenberg	52.22°	1.05 ± 0.11	1.10 ± 0.05
Bilthoven	52.12°	1.21 ± 0.04	1.23 ± 0.03
Uccle	50.8°	1.25 ± 0.06	1.24 ± 0.05
Hradec Kralove	50.19°	1.23 ± 0.15	1.23 ± 0.05
Thessaloniki	40.63°	1.29 ± 0.05	1.27 ± 0.03

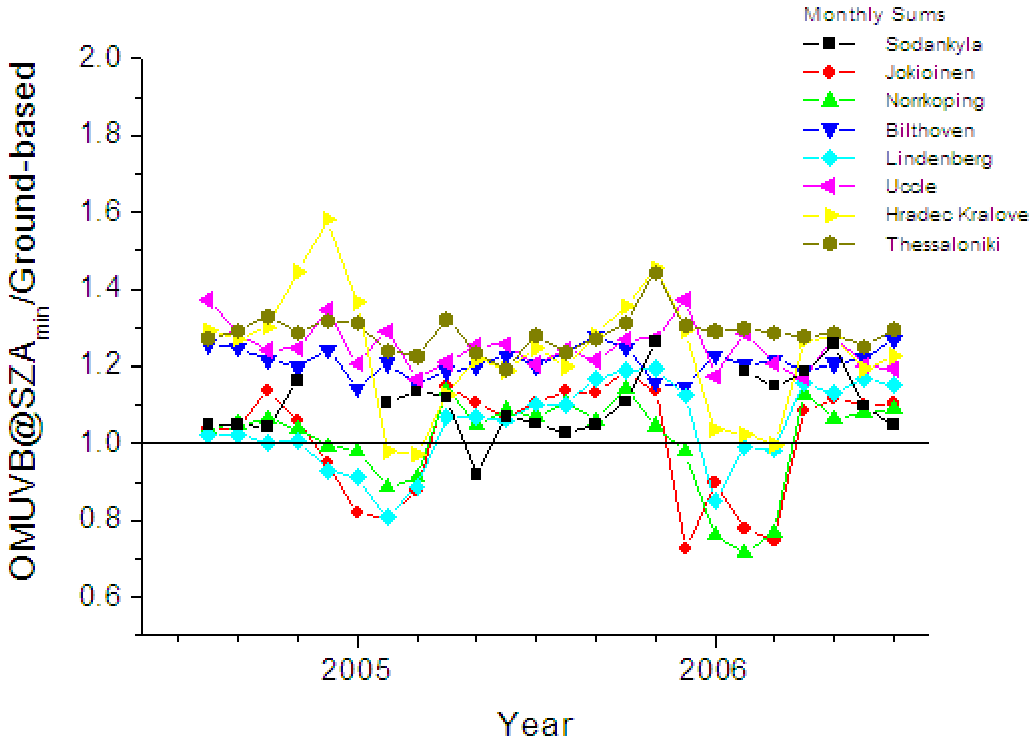

Figure 4.7 Month sums constructed from the OMUVB product divided to ground-based UV-measured. Data sets have been supplemented with scaled ground-based modelled values. Data for Norrköping are modelled values.

In Table 4.6 we list the averaged year sums derived for the considered period 2004 - 2006 for each location. Measured results and results of the three space-born methods are given. Space-born values are for the sites Lindenberg and up North 16, 17 and 5% to high using the OMUVB@SZA$_{min}$, <OMUVB> and AMOUR algorithm, respectively. For the stations Bilthoven and down South, these numbers are 23, 25 and 13 % for the same sequence.

Table 4.6 Averaged year sums for listed sites.

Site	Latitude north	Measured (kJ/m^2)	OMUVB@SZA$_{min}$ (kJ/m^2)	<OMUVB> (kJ/m^2)	AMOUR (kJ/m^2)	Num. of Days used
Sodankylä	67.37°	415.0	441.0	452.1	398.5	328
Jokioinen	60.81°	383.7	416.2	418.5	382.5	538
Norrköping	58.58°	410.5	435.7	437.5	403.0	622
Lindenberg	52.22°	436.6	479.5	480.0	427.9	534
Bilthoven	52.12°	467.7	570.6	576.8	522.8	515
Uccle	50.8°	437.4	542.2	547.0	502.7	607
Hradec Kralove	50.19°	486.1	587.3	592.9	533.8	619
Thessaloniki	40.63°	672.0	852.7	857.8	770.7	579

Thus the agreement is better for the northern sites than for the southern sites. Aerosols are likely to play a role here. Generally the total aerosol optical thickness is smaller for the northern sites than sites in central Europe. Zooming in on Bilthoven and Lindenberg, these sites are on the same latitude and have similar local surroundings, but a rather large difference in measured year sums, Bilthoven has a 7% larger year sum. This difference is significantly exceeded by the corresponding difference inferred form the satellite data, i.e. 20%. Examining local aerosol data from the SCOUT-O3 dataset Lindenberg has a mean aerosol optical depth of 0.36 at 340 nm, and 0.42 in the summer-half year and a median value of 0.25 (same for summer-half year). Bilthoven has a mean of 0.42 (0.46 in the summer-half year), and appears to have a distribution with two maxima, one around 0.25 and one around 0.55. This means that the satellite inferred difference of 20% should be reduced with 5% when local aerosols are taken into account. The remaining 8% difference in the satellite-derived sums should be still accounted for.

5 Intercomparing space-born algorithms

5.1 Operational OMUVB vs. AMOUR 2.0

For a number of available OMUVB-stations, see Table A.3 of the Appendix A, time series were extracted from the calculated UV-maps by AMOUR 2.0. In Figure 5.1 and 5.2 we plot the averaged ratios of day sums derived by OMUVB compared to those calculated by AMOUR 2.0. Figure 5.2 holds for the summer-half year. Both figures show ratios on a level of around 1.11 below 55 degree North, after which an increase is seen. All standard deviations are larger for the OMUVB@SZA_{min}-AMOUR ratios than those found for the <OMUVB>-AMOUR ratios. Tromsø, as an exception, has a rather low value and for this site also the largest relative difference between OMUVB@SZA_{min}, and < OMUVB> is found.

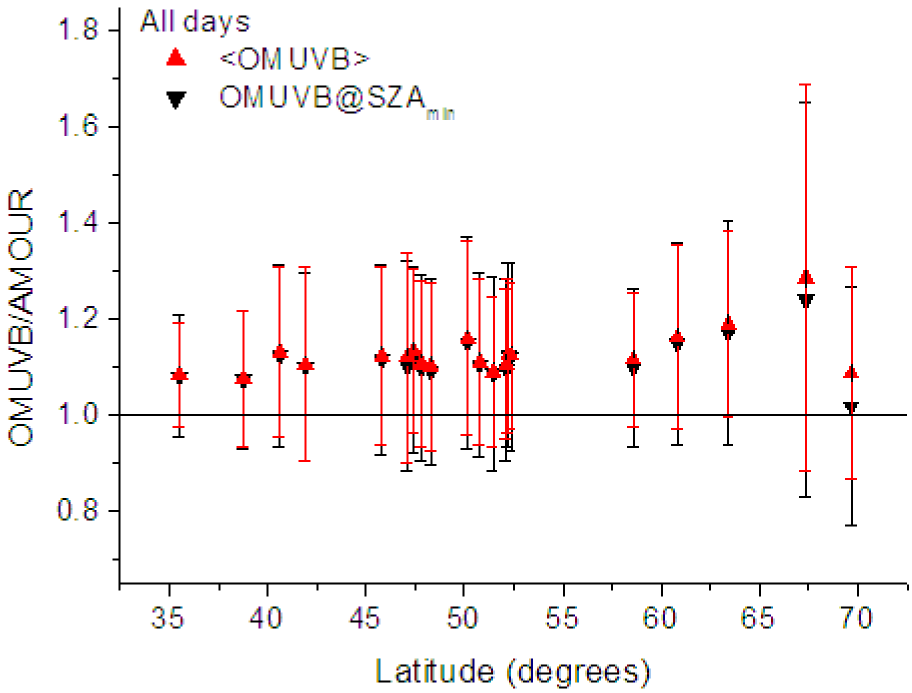

Figure 5.1 Direct comparison of day sums calculated by OMUVB and AMOUR as a function of the latitude. Error bars indicate the standard deviations

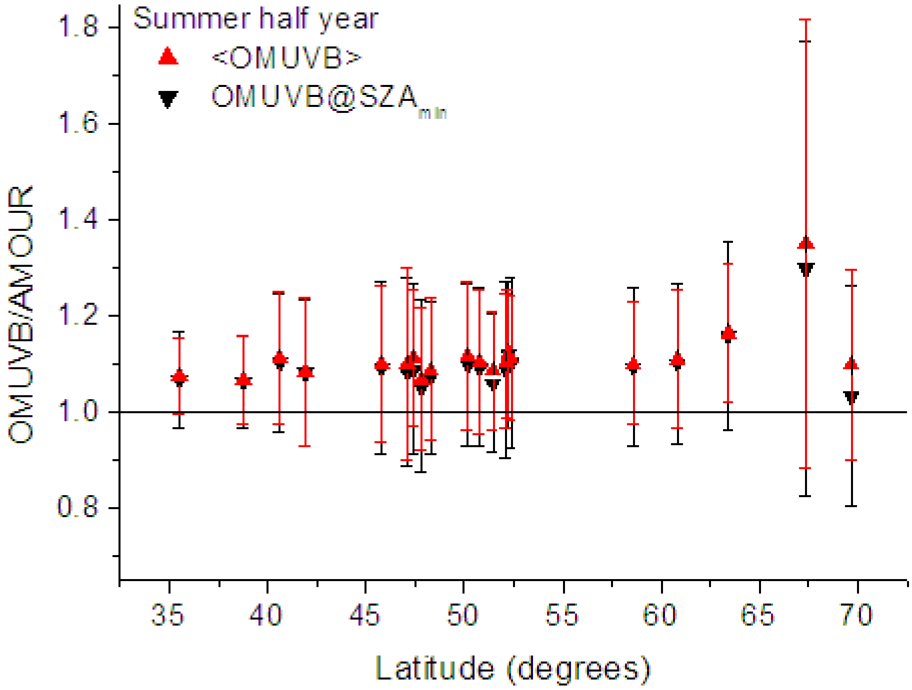

Figure 5.2 Comparison of day sums calculated by OMUVB and AMOUR as a function of the latitude. Error bars indicate the standard deviations. Only days at the summer-half year (91-273) are taken into account.

5.2 AMOUR Overpass

Here we compare for a somewhat large area the OMUVB product with $AMOUR_{ovp}$ results, the latter uses OMI overpass ozone and RCF-data to derive location specific UV by applying the same algorithm as implemented in AMOUR 2.0. We could select 33 European sites, listed in Table A.4 of Appendix A, where both OMUVB and OMI-ozone and RCF data are listed for the same overpass site.

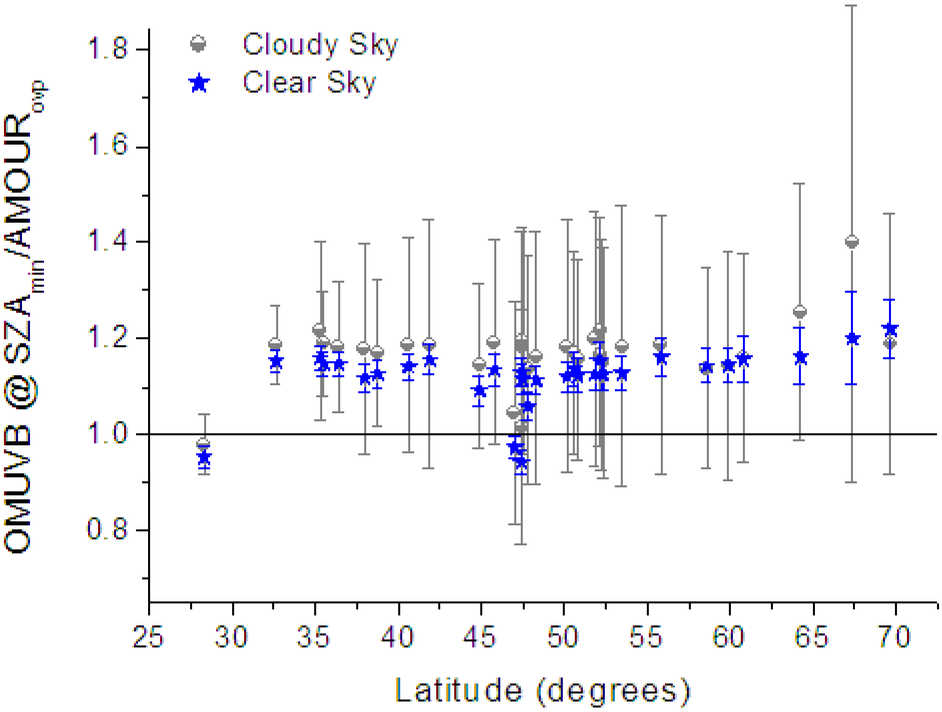

Figure 5.3 Averaged ratios of day sums derived by OMI divided by days sums derived by AMOUR 2.0 Overpass mode. The erythemal action spectrum is used. Blue stars indicate the clear sky values, while grey symbols are valid for cloudy skies. Values below 1 are for high altitude sites.

We plot in Figure 5.3 the averaged ratios of day sums derived by OMI divided by day sums derived by AMOUR$_{ovp}$. At latitude 28.3 and between 45 and 50, the averaged ratios smaller than and close to 1 apply to high altitude sites. AMOUR uses an altitude corrected. i.e. UV increases with altitude, most of this correction is aerosol driven. Aerosols are presumed to be confined to the boundary layer. As OMUVB underestimated the aerosol loading, sites, - in this case mountainous, with small aerosol loading agree better. Following this reasoning Figure 5.4. and 5.5 - giving another representation of the data- show that besides the high altitude site, the whole alpine area can be deemed an area with a better agreement compared to the rest of Europe.

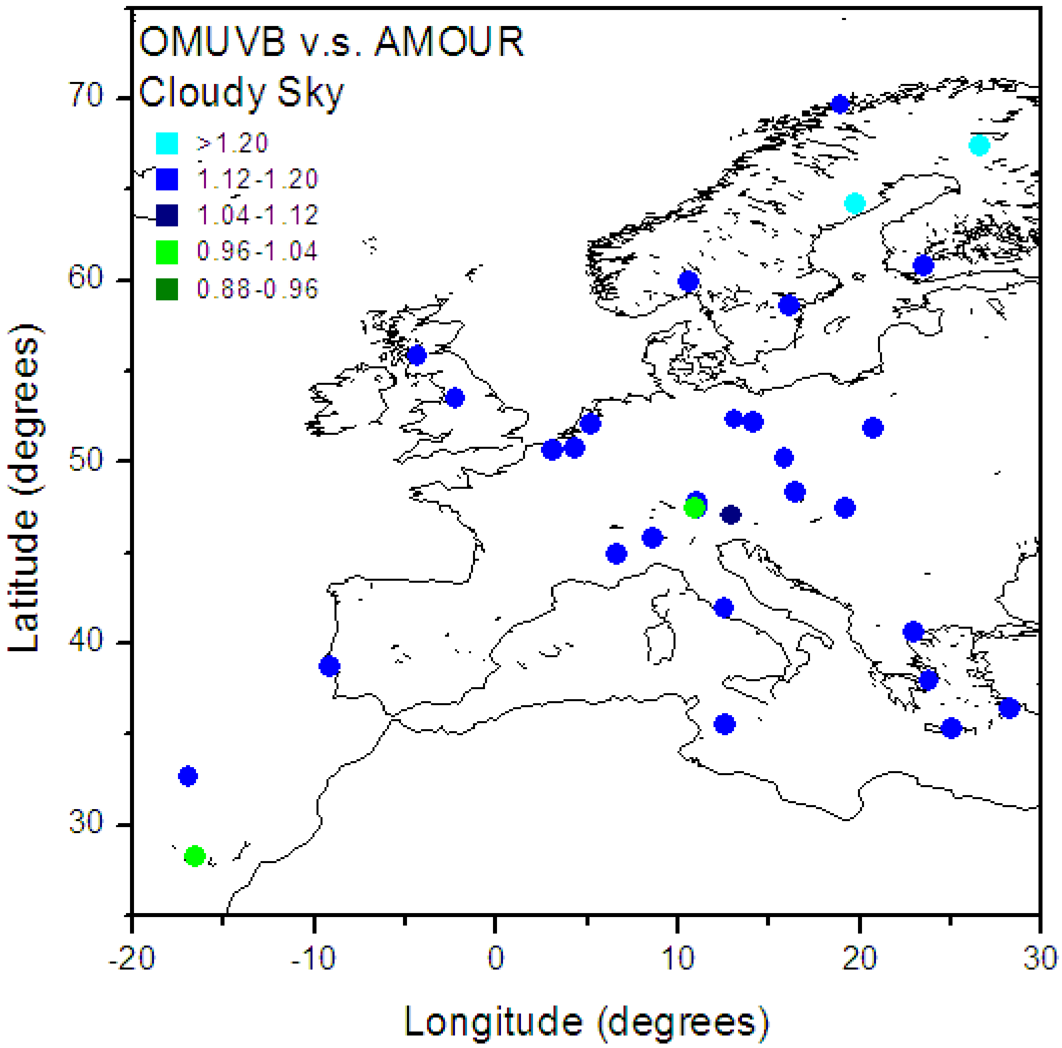

Figure 5.4 Colour scale indicate range of the averaged ratios of OMUVB@SZA$_{min}$ -derived day sums of erythemal UV divided by the AMOUR$_{ovp}$ derived ones for the shown locations. Cloud effects are included.

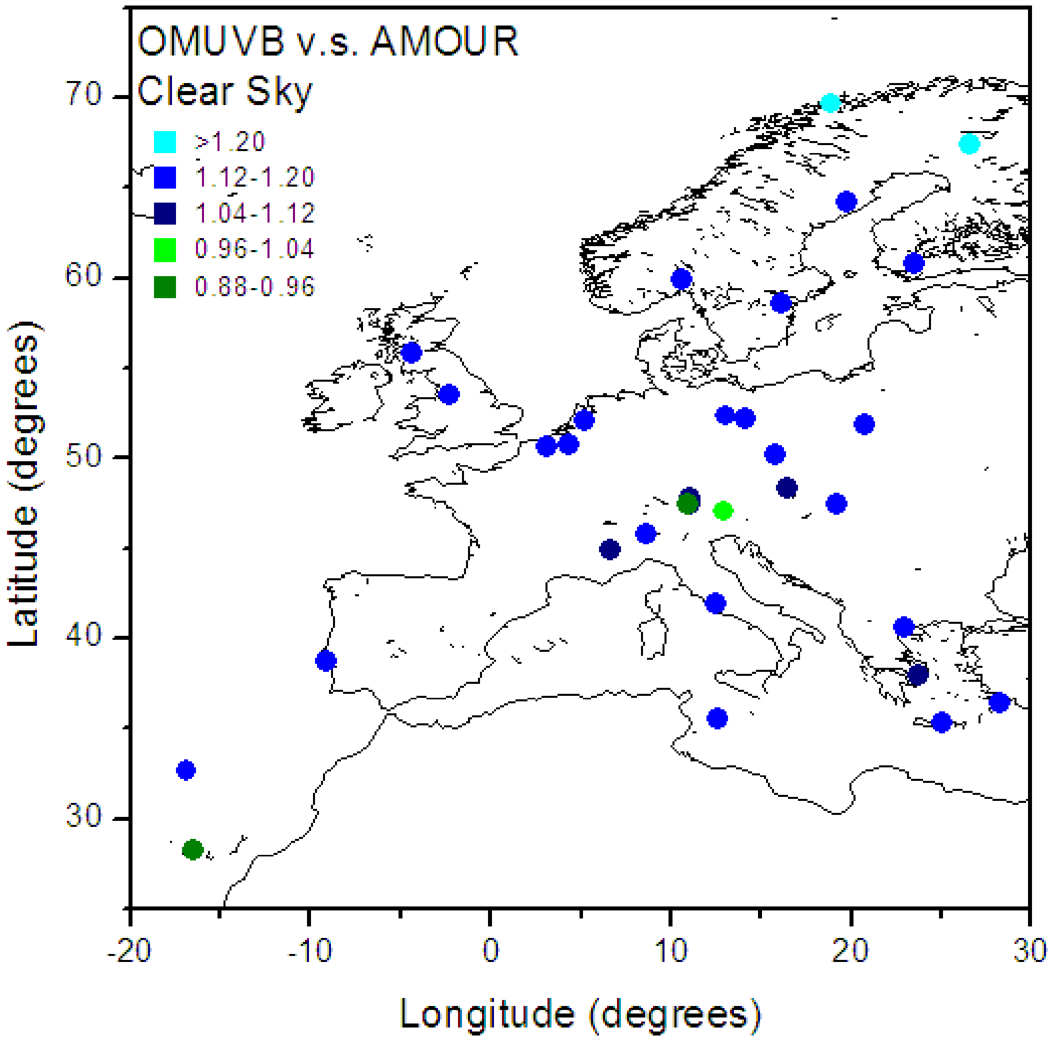

Figure 5.5 Colour scale indicate range of the averaged ratios of OMUVB@SZA_{min} -derived day sums of erythemal UV divided by the $AMOUR_{ovp}$ derived ones for the shown locations. Map is based on clear sky values, i.e. cloud effects are not taken into account

5.3 Local aerosols

It has been noticed that the major source of error in the OMUVB product is the treatment of aerosols, (Tanskanen et al., 2007) . Improvements are thus expected if local aerosol, and also ground albedo, information is used. We do have this information readily available for the eight sites that were used in the SCOUT-O3 project. Hence, we can recalculate the day sums using this additional information and find indeed a dramatic improvement of the results, as shown in Figure 5.6.

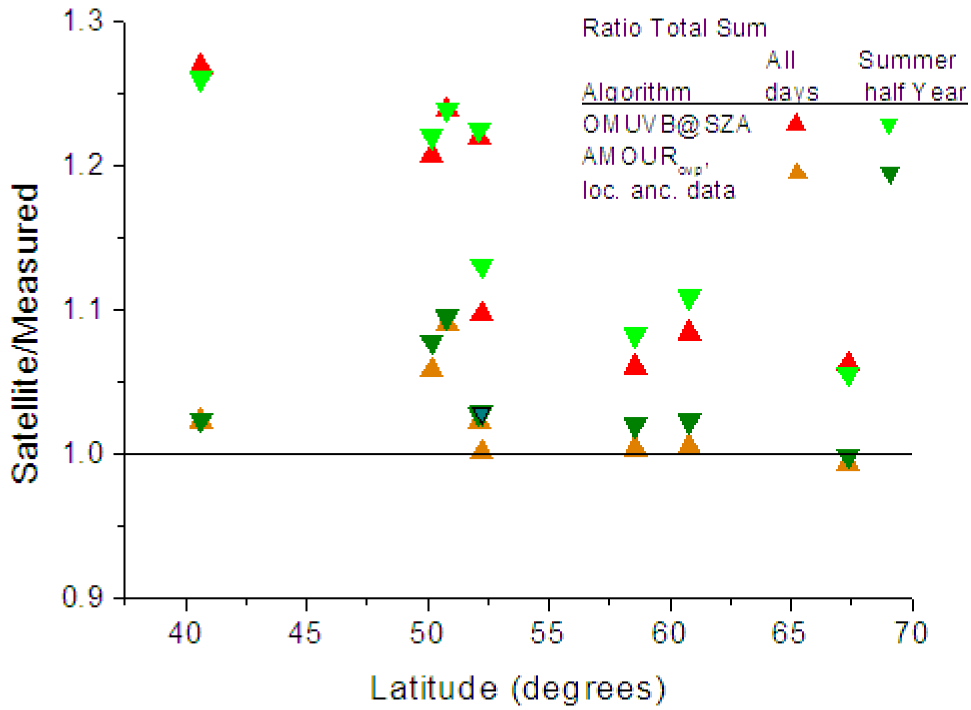

Figure 5.6 Use of local ancillary data, orange and dark green, can dramatically improve results.

Figure 5.6 shows results for OMUVB as such, and the so-called local ancillary data results of AMOUR$_{ovp}$, where we have incorporated the local ancillary information. We show only ratios of total sums calculated in the different ways. Although the AMOUR$_{ovp}$ results can only be regarded as preliminary, because the implementation of the new RCF-data needs optimalisation and validation, it certainly shows the high potential of the OMI products. Hence, using OMI-ozone and OMI-reflection may yield excellent results if the aerosol problem is tackled in the first place, and albedo estimates, for year around applications, in the second place.

6 Discussion and Conclusions

Ozone depletion and climate change can both have direct and indirect implications for the global and regional UV-radiation budgets received at the ground. Exposure to UV-radiation may lead to a wide variety of biological effects. Several of these effects, such as skin cancer and cataracts are related to life time exposures. An estimate of the health consequences and risks associated with ozone depletion and climate change requires knowledge on the UV-radiation received at the ground. It is therefore important to assess accurately the UV-climate and the long-term changes on a local, regional, and global scale.

Ground-based UV-monitoring stations provide the most accurate and direct way of assessing the local UV-climate. Satellite-based retrieval of ground-level UV is a cost-effective way of analysing regional and global differences, and offers a unique opportunity to couple UV-budget maps and long-term risk assessments. However, limited spatial and temporal resolution, and the fact that satellite instruments tend to degrade, requires continuous effort to validate the satellite derived UV with ground-based measurements.

Previous environmental assessment studies have thus far focused on the use of the TOMS, GOME and SCIAMACHY data. The OMI-instrument, on board the AURA satellite is the successor to the EP-TOMS instrument. In this report, we cover the results obtained when OMI-inferred UV data is intercompared, and compared with ground-based measured UV. OMI-inferred UV includes the operational OMUVB product, and AMOUR 2.0 derived results using OMI total column ozone and OMI-derived cloud effects. Eight sites across Europe were selected for the satellite-based ground-based comparison.

The main conclusions are:

- OMUVB consistently overestimates the UV-radiation received at the ground in Europe. For the eight European sites the year-integrated UV-sum is, on average, 15% overestimated, with a site-to-site variability of around 8%. For four of the more northern sites, the overestimation in the year sums is between 5-10%, and for four more southern sites, the deviation is larger: 20-27%. Similar numbers are found when considering month or day sums.

- Using the ozone and reflectivity data from the OMI-instrument, AMOUR 2.0 produces smaller overestimates of 5% on average, with a similar site-to-site variability of around 8%

- Under heavily clouded conditions, the cloud modification factors implicitly used in the OMUVB algorithm are too high. This contributes to the overall too high values of the OMUVB product.

- The overestimates by the OMUVB product are primarily due to too low aerosol loads used in the OMUVB algorithm. If local information on aerosols and ground albedo is taken into account, good agreement can be achieved

TOMS-data inferred UV shows that the influence of clouds can be well accounted for by making use of the reflectivity product, and that the agreement between satellite-based and ground-based UV is independent of the actual cloud induced attenuation. However, this statement is not fulfilled anymore when switching to OMI-data. OMI-inferred UV, using clouds and reflectivity data, shows a cloudiness dependent agreement. Hence, it could well be underlying input data that does not fully grasp the effects of clouds and not the OMUVB algorithm itself causing the additional overestimation by OMUVB under heavily clouded conditions. Recently, NASA introduced the new RCF product replacing the old reflectivity data. This new cloud product offers potential for improvements of the OMUVB algorithm, as is shown by the performance of the preliminary implementation in the $AMOUR_{ovp}$-algorithm.

Full incorporation of RCF-data in AMOUR 2.0, requires further interpretation and validation of the RCF-product, which could not be achieved in the frame of this project. Nevertheless, we would encourage having the reflectivity product available to users as well for backward compatibility.

The operational OMUVB product can, at present not be used for risk-assessments for two reasons:

1- OMUVB overestimates the ground-level UV (in Europe)
2- UV-products with other action spectra would be necessary.

It is noted that a new version of the OMUVB product is underway. Unfortunately, the data were not available at the time of the finalisation of this report in July 2008. The new version mainly deals with an ozone recalibration (personal comment A. Tanskanen), and hence we expect that our major conclusion remain: too high values due to too low aerosols amounts, and an overestimation under heavily clouded conditions.

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Ground-based UV and ancillary data
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M. Janouch, Czech Hydrometeorological Institute, CHMI, Hradec Kralove, Czech Republic
W. Josefsson, Swedish Meteorological and Hydrological Institute, SMHI, Norrköping, Sweden

Satellite data
NASA agency
EP-TOMS ozone and reflection gridded data: http://jwocky.gsfc.nasa.gov/
OMI overpass data: http://avdc.gsfc.nasa.gov/phpgdv2/avdc_tablefile.php?id=28
OMI ozone and radiative cloud fraction, griddeddata:
http://jwocky.gsfc.nasa.gov/omi/omi_data_access.html

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Appendix A

Table A.1. Averaged ratios of the OMUVB product against ground-based derived daily UV-sums. Exclusively days with two or more overpasses are used.

Location, Latitude north	% multiple overpasses	Ground-based	OMUVB@SZA$_{min}$	<OMUVB>
Sodankyla, 67.37°	88	measured	1.11 ± 0.25	1.14 ± 0.20
		modelled	1.10 ± 0.24	1.13 ± 0.18
Jokioinen, 60.81°	81	measured	1.06 ± 0.29	1.08 ± 0.26
		modelled	1.04 ± 0.22	1.06 ± 0.20
Norrköping, 58.58°	79	measured	-	-
		modelled	1.02 ± 0.21	1.04 ± 0.19
Lindenberg, 52.21°	60	measured	1.08 ± 0.26	1.08 ± 0.24
		modelled	1.08 ± 0.22	1.08 ± 0.20
Bilthoven, 52.12°	62	measured	1.24 ± 0.24	1.26 ± 0.22
		modelled	1.22 ± 0.24	1.24 ± 0.21
Uccle, 50.80°	65	measured	1.33 ± 0.34	1.35 ± 0.30
		modelled	1.25 ± 0.26	1.26 ± 0.25
Hradec Kralove, 50.12°	58	measured	1.31 ± 0.41	1.32 ± 0.35
		modelled	1.26 ± 0.32	1.26 ± 0.28
Thessaloniki, 40.52°	28	measured	1.35 ± 0.45	1.38 ± 0.21
		modelled	1.20 ± 0.27	1.27 ± 0.20

Table A.2. Averaged ratios of the OMUVB product against ground-based derived daily UV-sums. Exclusively days with two or more overpasses are used. Summer half year only

Location, Latitude north	% multiple overpasses	Ground-based	OMUVB@SZA_{min}	<OMUVB>
Sodankyla, 67.37°	94	measured	1.07 ± 0.23	1.11 ± 0.18
		modelled	1.08 ± 0.23	1.11 ± 0.17
Jokioinen, 60.81°	90	measured	1.12 ± 0.20	1.13 ± 0.19
		modelled	1.12 ± 0.18	1.13 ± 0.16
Norrköping, 58.58°	82	measured	-	-
		modelled	1.09 ± 0.17	1.09 ± 0.14
Lindenberg, 52.21°	59	measured	1.14 ± 0.18	1.15 ± 0.16
		modelled	1.11 ± 0.18	1.11 ± 0.15
Bilthoven, 52.12°	59	measured	1.21 ± 0.19	1.26 ± 0.17
		modelled	1.20 ± 0.21	1.24 ± 0.18
Uccle, 50.80°	64	measured	1.29 ± 0.30	1.30 ± 0.25
		modelled	1.24 ± 0.26	1.26 ± 0.25
Hradec Kralove, 50.12°	57	measured	1.25 ± 0.28	1.28 ± 0.25
		modelled	1.22 ± 0.22	1.26 ± 0.19
Thessaloniki, 40.52°	27	measured	1.26 ± 0.34	1.27 ± 0.16
		modelled	1.15 ± 0.18	1.19 ± 0.15

Table A.3. Sites used for comparison of OMUVB and AMOUR 2.0

Location	Latitude north	Longitude west
Tromsø	69.66°	18.93°
Sodankyla	67.37°	26.63°
Trondheim	63.43°	10.47°
Jokioinen	60.81°	23.5°
Norrköping	58.58°	16.15°
Potsdam	52.36°	13.08°
Lindenberg	52.22°	14.12°
Bilthoven	52.12°	5.19°
Reading	51.44°	-0.93°
Uccle	50.8°	4.35°
Hradec Kralove	50.19°	15.83°
Vienna	48.3°	16.43°
Hohenpeissenberg	47.8°	11.02°
Budapest	47.43°	19.23°
Graz	47.1°	15.42°
Ispra	45.81°	8.63°
Rome	41.9°	12.52°
Thessaloniki	40.63°	22.96°
Lisbon	38.77°	-9.15°
Lampedusa	35.5°	12.6°

Table A.4. Overpass locations used for comparison of OMUVB and $AMOUR_{ovp}$

Site	Latitude north	Longitude west
Athens	37.99°	23.77°
Belsk	51.83°	20.78°
Bilthoven	52.12°	5.19°
Briancion	44.9°	6.65°
Budapest	47.43°	19.23°
Funchal	32.64°	-16.89°
Garmisch	47.48°	11.07°
Glasgow	55.86°	-4.34°
Helsinki	60.32°	24.97°
Heraklion	35.31°	25.08°
Hohenpeissenberg	47.8°	11.02°
Hradec Kralove	50.19°	15.83°
Ispra	45.81°	8.63°
Izana	28.3°	-16.5°
Jokioinen	60.81°	23.5°
Lampedusa	35.5°	12.6°
Lindenberg	52.22°	14.12°
Lisbon	38.77°	-9.15°
Manchester	53.47°	-2.23°
Norrköping	58.58°	16.15°
Oslo	59.9°	10.62°
Potsdam	52.36°	13.08°
Rhodes	36.42°	28.21°
Rome	41.9°	12.52°
Sodankyla	67.37°	26.63°
Sonnblick	47.05°	12.95°
Thessaloniki	40.63°	22.96°
Tromsø	69.66°	18.93°
Uccle	50.8°	4.35°
Vienna	48.3°	16.43°
Villeneuvedascq	50.61°	3.14°
Vindeln	64.23°	19.77°
Zugspitze	47.42°	10.98°

Appendix B: List of acronyms

AMOUR	- Assessment MOdel for Uv radiation and Risks, Research model under development at the National Institute of Public Health and the Environment
AVDC	- Aura Validation Data Center
CMF	- Cloud Modification Factor
EP-TOMS	- Earth Probe - Total Ozone Mapping Spectrometer; see TOMS
ESA	- European Space Agency
EUVDB	- European UV DataBase; Initiative to collect and unify measurement data
FAO	- Food and Agriculture Organization (of the United Nations)
FMI	- Finnish Meteorological Institute
GOME	- Global Ozone Monitoring Experiment; instrument onboard the ESA ERS-2 satellite
GSI	- Global Solar Irradiation
IASB	- Institut d'Aéronomie Spatiale de Belgique
ISCCP	- International Satellite Cloud Climatology Program
KMI	- Royal Meteorological Institute, Uccle, Belgium
KNMI	- Royal Netherlands Meteorological Institute; De Bilt, The Netherlands
NASA	- National Aeronautics and Space Administration, USA
NIMBUS-7	- Seventh satellite in the NASA-NIMBUS programme
NIVR	- Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart/Netherlands Agency for Aerospace Programmes
NOAA	- National Oceanic and Atmospheric Administration; USA government Institute
NRPB	- National Radiological Protection Board, at present: HPA, Health Protection Agency
NUSP	- National User Support Programme
OMI	- Ozone Monitoring Instrument; instrument onboard the NASA EOS-Aura satellite
QA/QC	- Quality Assurance and Quality Control
RIVM	- National Institute for Public Health and the Environment
SCIAMACHY	- SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY; onboard the ESA ENVISAT satellite
SCOUT	- Stratosphere-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-O3): EU integrated project
SHICrivm	- Toolbox developed at RIVM to assess measured UV-spectra, see http://www.rivm.nl/shic
SRON	- Space Research Organization of the Netherlands
SZA	- Solar Zenith Angle
TOMS	- Total Ozone Mapping Spectrometer successive versions on board of NIMBUS 7, METEOR3 and Earth Probe satellites; source for total ozone measurements
UNEP	- United Nations Environment Programme
UV	- Ultraviolet radiation (wavelength range 100-400 nm)
WHO	- World Health Organization

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