Assessment of four methods to estimate surface UV radiation using satellite data, by comparison with ground measurements from four stations in Europe

Antti Arola,[1] S. Kalliskota,[1] P. N. den Outer,[2] K. Edvardsen,[3] G. Hansen,[3] T. Koskela,[1] T. J. Martin,[4,5] J. Matthijsen,[2] R. Meerkoetter,[6] P. Peeters,[7] G. Seckmeyer,[8] P. C. Simon,[7] H. Slaper,[2] P. Taalas,[1] and J. Verdebout[9]

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[1] Four different satellite-UV mapping methods are assessed by comparing them against ground-based measurements. The study includes most of the variability found in geographical, meteorological and atmospheric conditions. Three of the methods did not show any significant systematic bias, except during snow cover. The mean difference (bias) in daily doses for the Rijksinstituut voor Volksgezondheid en Milieu (RIVM) and Joint Research Centre (JRC) methods was found to be less than 10% with a RMS difference of the order of 30%. The Deutsches Zentrum für Luft- und Raumfahrt (DLR) method was assessed for a few selected months, and the accuracy was similar to the RIVM and JRC methods. It was additionally used to demonstrate how spatial averaging of high-resolution cloud data improves the estimation of UV daily doses. For the Institut d'Aéronomie Spatiale de Belgique (IASB) method the differences were somewhat higher, because of their original cloud algorithm. The mean difference in daily doses for IASB was about 30% or more, depending on the station, while the RMS difference was about 60%. The cloud algorithm of IASB has been replaced recently, and as a result the accuracy of the IASB method has improved. Evidence is found that further research and development should focus on the improvement of the cloud parameterization. Estimation of daily exposures is likely to be improved if additional time-resolved cloudiness information is available for the satellite-based methods. It is also demonstrated that further development work should be carried out on the treatment of albedo of snow-covered surfaces. *INDEX TERMS:* 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling; *KEYWORDS:* satellite ultraviolet estimation, ultraviolet radiation, ultraviolet radiation measurements

1. Introduction

[2] Surface UV radiation has been traditionally measured with ground-based instruments. However, the number of instruments with sufficient accuracy will remain relatively sparse, so satellite-based UV methods offer a complementary approach to better document the geographical distribution of surface UV irradiance. These methods use satellite measurements in conjunction with radiative transfer models to estimate the surface UV exposure.

[3] The differences between ground-based measurements and satellite-derived estimates result from inaccuracies in both data and from intrinsic differences in the two approaches. The uncertainty of UV ground measurements depend on a large number of factors [*Bernhard and Seckmeyer*, 1999]. The most important are calibration by lamps and its transfer, the characteristics of the input optics and wavelength alignment problems. Furthermore the uncertainty depends on the quality control and quality assurance applied to these measurements. The accuracy of the satellite-based UV data, on the other hand, is sensitive mainly to the radiative transfer input parameters and the suitability of the radiative transfer code used. The radiative transfer in the atmosphere is a three dimensional problem that can be approximated by one dimensional radiative transfer models. However, 3-D models have not yet been widely used in the derivation of radiation at the ground due

[1]Finnish Meteorological Institute, Helsinki, Finland.
[2]National Institute of Public Health and the Environment, Bilthoven, Netherlands.
[3]Norwegian Institute for Air Research, Tromsø, Norway.
[4]Fraunhofer Institute for Atmospheric Environmental Research, Garmisch-Partenkirchen, Germany.
[5]Now at University of Graz, Graz, Austria.
[6]Institute for Atmospheric Physics, Deutsches Zentrum für Luft- und Raumfahrt, Wessling, Germany.
[7]Belgian Institute for Space Aeronomy, Brussels, Belgium.
[8]Institute for Meteorology and Climatology, University of Hannover, Hannover, Germany.
[9]Space Applications Institute, Joint Research Centre, Ispra, Italy.

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Table 1. Description of the Main Features of UV Algorithms

	DLR	IASB	JRC	RIVM
Ozone	GOME	GOME	GOME	TOMS
Clouds	AVHRR[a]	GOME[b]	MVIRI[c]	TOMS[d]
Surface albedo	no snow: 0.03 snow: 0.85	seasonal albedo	MVIRI[c]	0.02
Aerosols	fixed with total optical depth of 0.2 at 0.55 μm	none	daily visibility data from about 1000 ground stations	optical thickness 0.28 at 320 nm (1/λ dependency)
Model	matrix-operator[e]	UVspec[f]	UVspec[f]	UVtrans
Coverage	Europe	global	Europe	Europe
Spatial resolution	1 ×1 km^2	40 × 320 km^2	0.05 × 0.05 deg	1/6 × 1/6 deg

[a] Using APOLLO algorithm [*Kriebel et al.*, 1989].
[b] ICFA cloud algorithm, later radiance measurements.
[c] Visible and infrared images.
[d] Radiance measurements.
[e] *Plass et al.* [1973] and *Fischer and Grassl* [1984].
[f] *Mayer et al.* [1997] and *Kylling et al.* [1998].

to the limited computational resources and the difficulties in characterization of 3-D cloud structure in an atmospheric column.

[4] Typically the cloud information is calculated from satellite measurement done once a day, while the cloudiness may change rapidly during the course of the day. In other words, low temporal resolution of satellite data may cause differences between daily satellite- and ground-based surface UV. *Martin et al.* [2000] have shown that when model calculations of erythemal daily dose are based on a single estimate of ozone column, cloud optical depth and aerosol optical depth, the difference between the model results and ground-based measurements is typically about 20%.

[5] The spatial resolution has effect as well; the satellite field of view and related spatial averaging does not necessarily represent the area, the cloud field structures and the radiative interaction processes that affect the ground-based measurements. Also, non-perfect positioning of the satellite pixels may contribute to the total uncertainty. *Degünther and Meerkötter* [2000], for example, show how remote clouds affect local surface UV radiation. An estimation of 3-D cloud effects in relation to cloud effects resulting from the independent pixel approximation (IPA) as a function of spatial averaging is given by *Meerkötter and Degünther* [2001]. IPA approach neglects the radiative transfer of photons between pixels. The study shows that 3-D effects can exceed the 10% limits for satellite FOV below about 20 km resolution, reaching up to 100% at a high resolution of 1 km.

[6] In addition to these resolution dependent issues, part of the differences between ground-based and satellite-based UV data is due to the accuracy of the input data themselves, such as total ozone amount, cloud optical depth, cloud coverage, and surface albedo, for example.

[7] The objective of our study was not only to assess the size of the differences between satellite-based and ground-based UV data, but also to look for the possible reasons for these differences. Previous validation papers have typically compared one satellite-based method to the ground-based measurements [e.g., *Herman et al.*, 1999; *Kalliskota et al.*, 2000; *Wang et al.*, 2000; *McKenzie et al.*, 2001], while in our study, four methods are included, allowing one to compare not only the satellite-based and ground-based data, but also the methods with each other.

2. Data and Methods

2.1. Satellite-Based Data

[8] Four methods, which derive surface UV radiation from satellite data, are included in the comparisons. The acronyms of the methods stand for their home institutes: Deutsches Zentrum für Luft- and Raumfahrt (DLR) in Germany, Institut d'Aéronomie Spatiale de Belgique (IASB) in Belgium, JRC (Joint Research Centre) in Italy and Rijksinstituut voor Volksgezondheid en Milieu (RIVM) in Netherlands. The methods differ by their spatial and temporal resolution and also by the input data used. Table 1 summarizes the methods. Spatial resolution of each method is restricted by the cloud product they use, so the resolution of DLR and IASB for example, differ drastically.

[9] IASB method [*Peeters et al.*, 1998] uses earth-shine, ozone and cloud measurements from GOME. GOME provides an estimation of the cloud coverage of the observed pixel using the Initial Cloud Fitting Algorithm (ICFA). Cloud top pressure and pixel cloud coverage are estimated by comparing computed and measured radiances around the oxygen A-band (761 nm) and is a standard level 2 product. When a cloudy scene is detected, the final surface flux is a linear combination of the clear sky estimated flux and fully cloudy scene flux. However, since ICFA does not give any information concerning the cloud optical or physical thickness, it is assumed that fully cloudy scene has a water cloud layer of optical thickness of 25 and physical depth of 1 km.

[10] JRC method [*Verdebout*, 2000] uses fully coupled radiative transfer calculations in the form of a lookup table giving the surface UV irradiance as a function of the influencing parameters. These are estimated from various satellite data (e.g., TOMS or GOME for ozone, MVIRI/ Meteosat for clouds and albedo) and other sources (visibility observations for the aerosols, altitude from a DEM).

[11] The RIVM method for producing UV radiation maps uses a two-stream UV transfer model UVtrans, which is used to calculate lookup tables for a variety of biological action spectra in relation to solar height and ozone column. In this study the method of *Eck et al.* [1995] is used to

estimate cloud effects from the overpass TOMS-reflection measurements. This method has been validated by comparing with ground-based analysis of cloud effects [*Slaper et al.*, 2001; *Matthijsen et al.*, 2000]. The UVtrans model provides cloudless sky estimates and is used with a standard atmosphere. The two-stream model has been used in a model intercomparison and the biologically weighted UV irradiance was within 3% of the benchmark value for high sun (SZA < 35 degrees) and within 7% for low sun (SZA 65–70 degrees) [*van Weele et al.*, 2000]. Using ground-based input data the two-stream model results have been shown to compare well with ground-based UV measurements at Bilthoven [*den Outer et al.*, 2000]. A full description of the RIVM-methodology for UV mapping is described by *Slaper et al.* [2001].

[12] The DLR method [*Meerkötter et al.*, 1997] is based on the independent pixel approximation and uses a lookup table (LUT) relating wavelength integrated UV irradiances that account for different action spectra to a broad range of the main UV affecting parameters as total ozone, solar zenith angle, cloud optical depth, surface elevation, and surface albedo. The LUT has been generated with a 1-D radiative transfer model based on the matrix-operator-theory. For the aerosol optical depth a constant climatological value has been assumed that decreases with increasing surface elevation above MSL. Satellite data provide the input for total ozone (e.g., TOMS, GOME) and cloud optical depth (NOAA/AVHRR). The cloud optical depths are derived from the "AVHRR Processing Scheme Over Clouds, Land and Ocean" (APOLLO) [*Kriebel et al.*, 1989] giving several cloud products in a high spatial resolution of about 1 km × 1 km at overpass time. Source for the altitude data is the GTOPO30 digital elevation model.

[13] If their accuracy has been assessed, these type of methods can provide information for several applications, such as long term evaluations of the changes in the UV doses at different timescales and surface UV climatology studies.

2.2. Ground-Based Data

[14] Following stations were included in the comparisons: Jokioinen, Finland (60.81°N, 23.50°E), Garmisch-Partenkirchen, Germany (47.48°N, 11.07°E), Brussels, Belgium (50.80°N, 4.36°E), Bilthoven, Netherlands (52.11°N, 5.19°E), Tromsø, Norway (69.66°N, 18.97°E), Ny-Ålesund, Norway (79.9°N, 11.7°E). Results of Jokioinen, Garmisch-Partenkirchen, Brussels and Bilthoven are shown in this paper.

[15] The Finnish instrument at the Observatory of Jokioinen, situated 107 m above sea level, is a double monochromator scanning spectroradiometer (Brewer Mk-III 107). The site is characterized by a relatively flat terrain which gives a satisfactory horizon consisting of trees to the South at the elevation of 8° and to the West at 10–12°. The surface coverage in the surrounding area is half agricultural fields and half medium sized subarctic forest with mixed species.

[16] The instrument measured at predefined values of the solar zenith angle, and each scan in this data set took about 8 min. The corrections were made for stray light, dark current, dead time of the photo multiplier tube and for temperature dependence. The wavelength setting was calibrated prior to each sky scan. Irradiance calibrations were carried out once a month and stability checks once a week. No correction for the directional dependence (mainly cosine error) has yet been applied to the data. It is estimated that the cosine correction would increase the measured irradiance by about 7–11%.

[17] No quantitative uncertainty budget is available for the Brewer 107. The quality of the data, however, can be estimated by frequent visits to international intercomparisons. These were CAMSSUM-1995 [*Gardiner and Kirsch*, 1997], NOGIC-1996 [*Koskela et al.*, 1997], SUSPEN-1997 [*Bais et al.*, 2001] and NOGIC-2000 (T. Thorseth et al., manuscript in preparation, 2002). The instrument's irradiance typically differed by −5 to +6% from the reference of each campaign depending, among other things, whether its data and the reference were based on cosine corrected or uncorrected data. In the SUSPEN campaign, which is the most relevant for this study, the instrument regularly produced irradiances 2 to 5% lower than the objectively selected reference. The latter only was based on data corrected for cosine error.

[18] The station at Garmisch-Partenkirchen is equipped with a spectroradiometer using a Bentham DTM300 double monochromator [*Seckmeyer et al.*, 1996]. The instrument is temperature stabilized and the dark current is electronically corrected by the use of a chooper and a lock-in amplifier. Corrections are made for wavelength misalignment, non-linearities and cosine errors and frequent calibrations on a weekly basis. The uncertainty of the measurements is estimated to be about 7% for the Garmisch instrument [*Bernhard and Seckmeyer*, 1999], The instruments of Garmisch have been participated in numerous intercomparisons [e.g., *Bais et al.*, 2001; *Seckmeyer et al.*, 1995]. It is situated 730 m above sea level in alpine environment.

[19] The UV monitoring system at RIVM in Bilthoven, The Netherlands, consists of a DILOR-XY double monochromator spectroradiometer, which is housed inside a temperature stabilized container, and two temperature stabilized broadband Robertson Berger meters (SL501) providing approximated erythemally weighted UV doses [*Reinen et al.*, 1993, 1994]. The spectra cover 285–380 nm and are taken routinely each 12 min from sunrise to sunset. Spectral irradiances are corrected for the cosine errors, and for wavelength errors using the SHICRIVM-software tool [*Slaper et al.*, 1995; *Slaper and Koskela*, 1997]. Observed (and corrected) wavelength scale errors are typically lower than 0.1 nm. Stability checks of the spectroradiometer are performed monthly using a 200 W lamp and an absolute irradiation calibration of the spectroradiometers is scheduled once per year or when found necessary from the stability checks. The absolute irradiance calibration of the instrument is performed on top of the roof of the container with a 1000 W lamp. Routine operation is embedded in the quality system of the laboratory of radiation research at RIVM: standard operational and calibration procedures are used and instrument performance and checks are logged. Measured solar spectra produced by the spectroradiometer were within 2–3% from reference values during two international intercomparisons on spectroradiometers in March 1999 in Garmisch Partenkirchen (Germany, MAUVE/CUVRA campaign) and in June 2000 in Tylösand, (Sweden, NOGIC 2000). Using the recorded stability checks the spectra of the SUSPEN intercomparison

Table 2. Statistics of the Comparison Between Satellite- and Ground-Based Daily CIE Doses at Four European Stations in 1997[a]

	IASB			JRC			RIVM		
	CIE	UVB	UVA	CIE	UVB	UVA	CIE	UVB	UVA
				Jokioinen					
Mean	34.5	35.9	39.5	−4.6	9.9	−10.6	1.8	1.0	−2.3
RMS	61.2	66.1	69.9	36.6	44.5	35.5	30.9	33.2	29.6
Cor. coeff.	0.943	0.947	0.963	0.933	0.938	0.944	0.970	0.972	0.974
				Garmisch-Partenkirchen					
Mean	30.5	29.6	23.9	−0.9	6.5	−9.1	−2.5	−4.5	−6.1
RMS	56.0	55.0	49.9	30.9	33.2	30.5	36.9	36.1	34.5
Corr. coeff.	0.933	0.935	0.909	0.966	0.966	0.954	0.932	0.933	0.917
				Bilthoven					
Mean	40.1	36.9	34.5	−16.1	−10.3	−23.2	−0.9	−4.0	−4.2
RMS	67.7	66.0	34.5	32.0	33.1	33.1	26.0	25.6	25.8
Corr. coeff.	0.956	0.958	0.946	0.976	0.976	0.972	0.968	0.969	0.957
				Brussels					
Mean	52.2	46.9	49.0	−6.2	−3.0	−9.4	11.6	5.6	12.0
RMS	90.7	90.1	85.5	30.7	33.2	29.6	33.3	31.4	32.7
Corr. coeff.	0.957	0.958	0.935	0.971	0.971	0.962	0.961	0.962	0.951

[a] Differences are calculated as percentages, i.e., (satellite-ground)/ground.

campaign in 1996 were recalibrated and also within 3% of the reference spectra [e.g., *Bais et al.*, 2001].

[20] The station at Brussels has modified Jobin-Yvon HD-10 instrument, which is double monochromator and is measuring between 280 and 550 nm with a step of 0.5 nm. Dark current is automatically removed. This instrument also has participated in several intercomparisons [e.g., *Bais et al.*, 2001]. It is situated in residential area of the suburban Brussels, 105 m above the sea level. Absolute calibrations are performed every two to three months and the relative stability is verified frequently (every two to three weeks).

3. Results and Discussion

3.1. Comparison of Daily and Monthly Doses

3.1.1. Data of the Year 1997

[21] Satellite-derived daily and monthly doses of erythemal (CIE87) [*McKinlay and Diffey*, 1987], UVB (280–315 nm) and UVA (315–400 nm) from the year 1997 were compared to the ground-based measurements. Table 2 shows the error statistics of the daily dose data at four European stations for each method. DLR is not included, since it is a very high resolution model and provided data for selected periods only. The behavior of each method is generally very similar from station to station. If the error statistics are compared to some earlier validation studies, [i.e., *Kalliskota et al.*, 2000], who compared NASA's UV algorithm against NSF ground-based data in Palmer, Ushuaia and San Diego, deviations to ground-based measurements are smaller for JRC and RIVM methods. *Kalliskota et al.* [2000] compared CIE-weighted daily doses estimated by TOMS UV algorithm against ground-based NSF measurements (not cosine corrected) and found mean percent differences (bias) of −13%, −35% and 25% for Ushuaia, Palmer and San Diego, respectively.

[22] Recent study by *McKenzie et al.* [2001] revealed large differences between ground-based and TOMS-estimated daily doses. Four stations were included in their study, Toronto in Canada, Garmisch-Partenkirchen in Germany, Thessaloniki in Greece and Lauder in New Zealand. At Lauder the agreement was rather good, while at other stations the satellite-derived UV was overestimated by 15% to 30% on average.

[23] *Fioletov et al.* [2001] compared noon CIE irradiance statistics for cosine corrected Brewer data with TOMS and found significant improvement to the previous studies. For warm period (May–August) mean percent difference ranged from −1.4% for Saturna (43.78°N, 79.47°W) and Goose Bay (53.32°N, 60.38°W). The mean bias (average for 10 Canadian stations) was about 10% for all sky conditions and 5% for cloud-free conditions. The bias for cloud-free conditions was attributed to gaseous pollution (SO_2 for Toronto and Halifax) and absorbing aerosols in the boundary layer. For partial cloud conditions the bias was close to the clear-sky value, if the cloud amount was less than 8, but increases to about 20% for overcast conditions (cloud amount = 10). Similar results were reported by *Chubarova et al.* [2001], who compared broadband UVA irradiance measurements with TOMS estimates at the Moscow University site (55.7°N, 37.51°E) over long time period (1978–2000). The bias varies from year to year between 5–15% for warm periods, but increases up to 25% with snow days included. It was also shown that accounting for absorbing aerosol properties significantly improves the agreement in clear-sky conditions and eliminates the bias dependence on aerosol optical thickness.

[24] IASB produces a rather large mean error, which is due to initial GOME cloud product (ICFA). The main reason is the cloud optical thickness threshold, defined earlier, that fixes the maximum optical thickness of a pixel. While the chosen value may be adequate in some geographical area, it is clearly unsuitable in most places. Recently ICFA has been replaced by a new cloud treatment in IASB method and preliminary results have indicated a significant improvement. New approach is similar to the TOMS UV algorithm [*Krotkov et al.*, 2001] and uses the observed UV top-of-atmosphere reflectance to infer the cloud conditions. Also, one has to keep in mind that the low spatial resolution of the satellite data used by IASB is causing differences particularly at heterogeneous terrain.

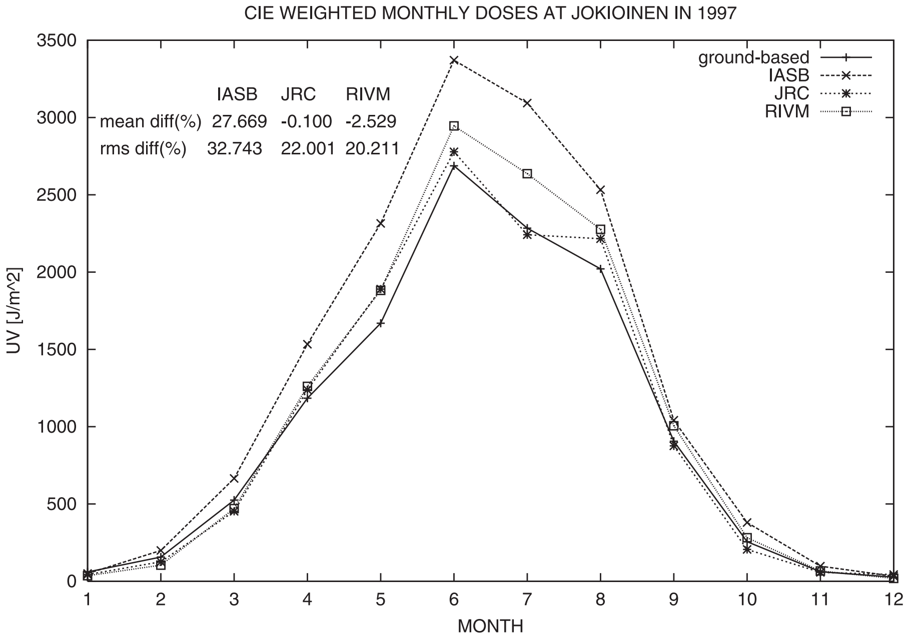

Figure 1. CIE monthly doses at Jokioinen in 1997 (J/m^2) predicted by IASB, JRC and RIVM against ground-based data.

[25] Figure 1 shows the monthly CIE doses of the same methods at Jokioinen and Figure 2 at Garmisch-Partenkirchen. When the short-time variability is averaged out in the monthly values, the mean differences and other error statistics improve. In reality there is a strong spatial and temporal variability in cloudiness, but because of the resolution constraints of the satellite measurements, this cannot be fully taken into account in the daily data of the satellite-based UV methods. It has been suggested [e.g., *Herman et al.*, 1999] that the satellite estimations should be integrated over periods of at least one week. Time integration reduces the differences between surface and satellite measurements that result from poor temporal sampling of the cloud field variation. This includes 3-D effects (especially inherent in the high spatial resolution methods) as well as effects caused by cloud cover changes in a larger spatial scale. IASB has a systematic bias caused by ICFA cloud algorithm, so it can be seen in monthly doses as well. However, reduced mean differences in monthly data suggest that there is no significant systematic

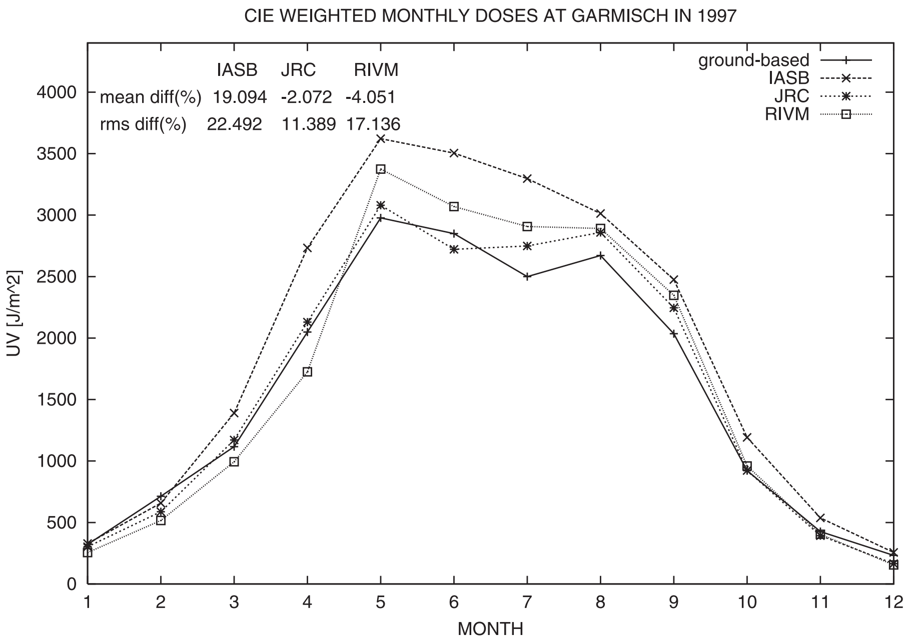

Figure 2. CIE monthly doses at Garmisch-Partenkirchen in 1997 (J/m^2) predicted by IASB, JRC and RIVM against ground-based data.

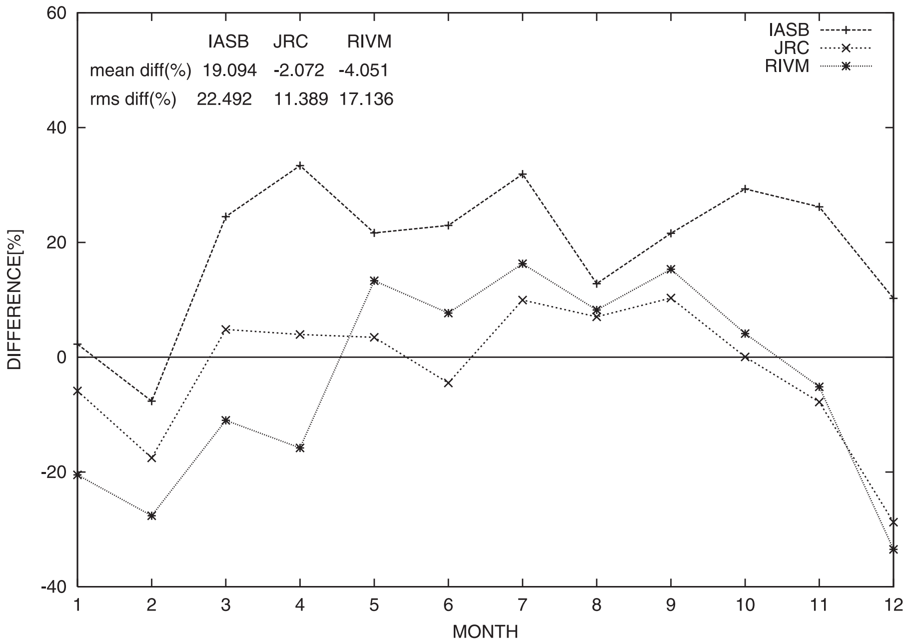

Figure 3. Differences between ground- and satellite-based monthly doses at Garmisch-Partenkirchen in 1997 (%) predicted by IASB, JRC and RIVM.

error in JRC and RIVM cloud treatments for average UV doses.

[26] Figure 3 shows the same data than Figure 2, but now the percent differences are shown. In other words, the percent difference between satellite- and ground-based data, divided by ground-based data, are plotted. JRC shows a slight, and RIVM stronger, seasonal behavior, which can be seen as a winter-time underestimation. This is explained by the snow albedo effect [*Schwander et al.*, 1999; *Degünther et al.*, 1998]. RIVM assumes constant albedo, which is a good approximation in general, but leads to significant underestimation when snow is present. JRC has a method to estimate the snow albedo from 10 day series of Meteosat signal over each pixel. There was snow in the ground during the period from the beginning of January to the end of February at Jokioinen; for instance 45 cm in February 22, which was then melted by March 9. However, during this same period, there were many days when JRC estimated albedo of a bare ground; this results from the difficulty in distinguishing snow from clouds in the Meteosat visible band. Moreover, when the snow albedo was estimated, it was relatively small, if compared to TOMS satellite estimates of snow-covered surface reflectivity around Jokioinen. So it is evident that the current approaches to estimate the albedo for snow-covered surfaces should be further developed if possible. The special problem arising from large albedo changes, such as snow, will be dealt with in another paper, based on the results from Ny-Ålesund and Tromsø, which is in preparation.

3.1.2. Selected Periods

[27] DLR calculated daily CIE doses for June 1997 that are based on cloud optical depths derived from the high-resolution AVHRR data at one satellite overpass time in the early afternoon. Figure 4 shows the comparison between ground and satellite based CIE doses. Three different time series are plotted against ground-based data. In each of them cloud optical depths are used that differ in terms of spatial averaging. Figure 4 shows the results with the following cloud optical depths: (1) no spatial averaging, i.e., the resolution is 1 km by 1 km, (2) spatial averaging over 3 by 3 pixels, and (3) over 30 by 30 pixels.

[28] It is interesting to note that the spatial averaging improves the results which can mainly be explained by the following two effects. First, the assumption of the independent pixel approximation cannot account for the horizontal photon transport and therefore 3-D cloud effects as for example shadow displacements or multiple scattering effects can lead to significant differences between satellite and surface UV measurements. Based on comparisons of 1-D and 3-D radiative transfer modeling results of *Meerkötter and Degünther* [2001] show that such differences reach maximum values under broken cloud conditions and for high spatial resolutions. In case of broken clouds the independent pixel approximation may lead to errors in the order of 100% when the spatial resolution is about 1 km $\times$ 1 km, the errors may be reduced to about 10% when the averaging area is increased to about 20 km $\times$ 20 km. Second, spatial smoothing inside a scene of a single cloud probe per day may give a more representative estimation of the diurnal cycle of the cloud conditions, as long as there are no orographic clouds. It is a consequence of both these effects that increasing the averaging area to 30 $\times$ 30 pixels gives a standard deviation and root-mean-square error of the DLR results similar to those of JRC and RIVM methods, although the DLR data were compared for a selected time period only.

[29] Figures 5a–5e show the distribution of the AVHRR derived cloud optical depth inside a 30 $\times$ 30 pixel area located around the measuring site at Garmisch-Partenkirchen on days 157, 158, 166, 173 and 177. As can be interpreted from the measurement data and confirmed by Figures 5b and 5c the clearest days were days 158 and 166.

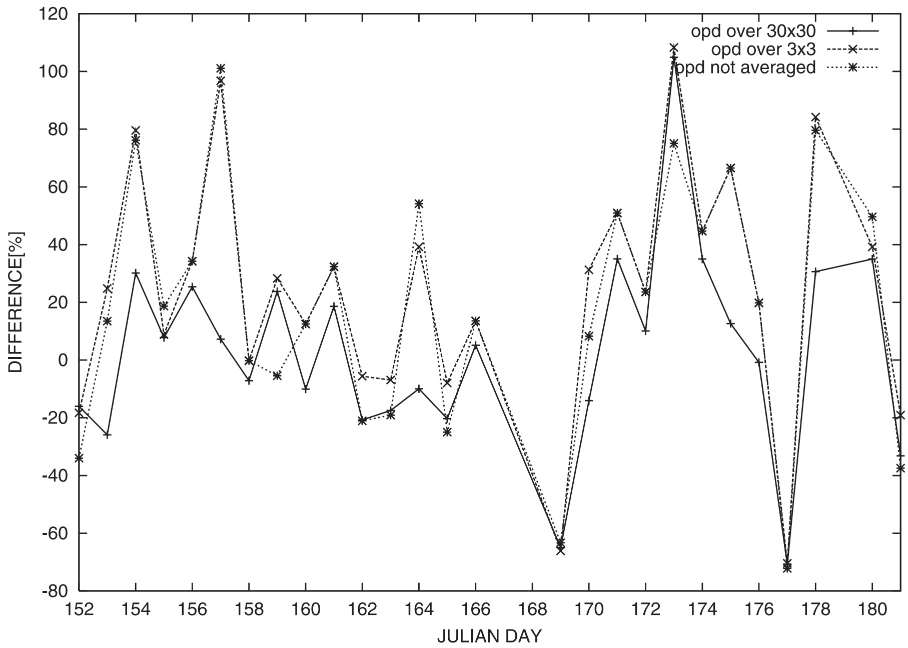

Figure 4. Differences between ground- and satellite-based daily doses at Garmisch-Partenkirchen in June 1997 (%) predicted by DLR. Opd stands for cloud optical depth, "opd over 30 × 30," for instance, means that the cloud optical depth was averaged over 30 × 30 AVHRR pixels of 1 km resolution.

It is obvious that spatial averaging cannot have a strong effect on both these days. On the other hand averaging changes the result substantially on day 157 which, as indicated in Figure 5a, is a day with broken clouds. On days 173 and 177, large-scale cloud fields fill the area around Garmisch at overpass time, with the consequence that spatial averaging has again no clear impact. However, on day 177 the cloudiness had more time variability than on day 173, therefore, using one cloud probe per day for calculating the daily dose results in a bigger difference between satellite based and ground-based measurements. Spatial averaging of cloud optical depths within a scene obtained from one cloud probe per day may therefore improve the calculation of daily doses as long as the spatial cloud distribution represents its temporal variation. However, if the cloud field varies as a function of time in a way that cannot adequately be probed by one overpass or by the specific temporal resolution of a satellite, differences between satellite and surface measurements of daily doses will still remain. It is therefore important to investigate how different typical cloud variations during a day affect the calculation of daily doses as a function of temporal sampling.

3.2. Impact of the Radiative Transfer Parameters

[30] To study whether there exists some systematic behavior in the differences between ground-based and satellite-based UV data, the errors were plotted against different UV affecting parameters, such as ozone, cloudiness and solar zenith angle. In this case these parameters are input to the methods, in other words, cloudiness and ozone are derived from the satellite measurements.

[31] None of the methods had a clear ozone dependence. Figure 6 shows the behavior of the RIVM method at Bilthoven, the ozone dependence of JRC was even smaller. Figure 7 shows the cloud transmission factor dependence. Cloud transmission factor is the ratio of cloudy to clear-sky surface irradiance. Cases with and without snow-cover are separated in this figure. Cloud transmission factor algorithm, which is based on TOMS 380 nm reflectivity, cannot distinguish between snow and clouds. It simply assigns excess reflectivity over the assumed surface reflectivity to clouds. As a result, when the assumed snow albedo is too low, too strong cloud attenuation is interpreted for snow-covered pixels. This effect is illustrated in the figure, since the points of snow-covered surface lie below the ratio of one. However, the points of snow-free conditions show cloud transmission factor dependence as well. An obvious explanation is that if there are cloud-free conditions at time of the overpass, they are not likely to remain for the entire day. On the other hand, if a very thick cloud occurred at the time of satellite measurement, it is unlikely to persist for the rest of the day. So part of the cloud transmission factor dependence could be explained by the time-resolution of the cloudiness data, while part is due to the cloud treatment itself.

[32] RIVM revealed also a slight solar zenith angle dependence, which is in accordance with the findings of the defects in snow albedo approach. In daily data, there is an underestimation in large solar zenith angles. However, this dependency was clearly reduced when only the snow-free cases were included.

[33] RIVM has the most simple snow albedo treatment, while JRC has the most realistic one. However, we compared the snow albedo of JRC to TOMS 380 nm reflectivity measurements in clear-sky days at Jokioinen, when there was snow on the ground, and found that snow albedo of JRC method is substantially underestimated. So this is clearly an area, where further research and improvement is needed.

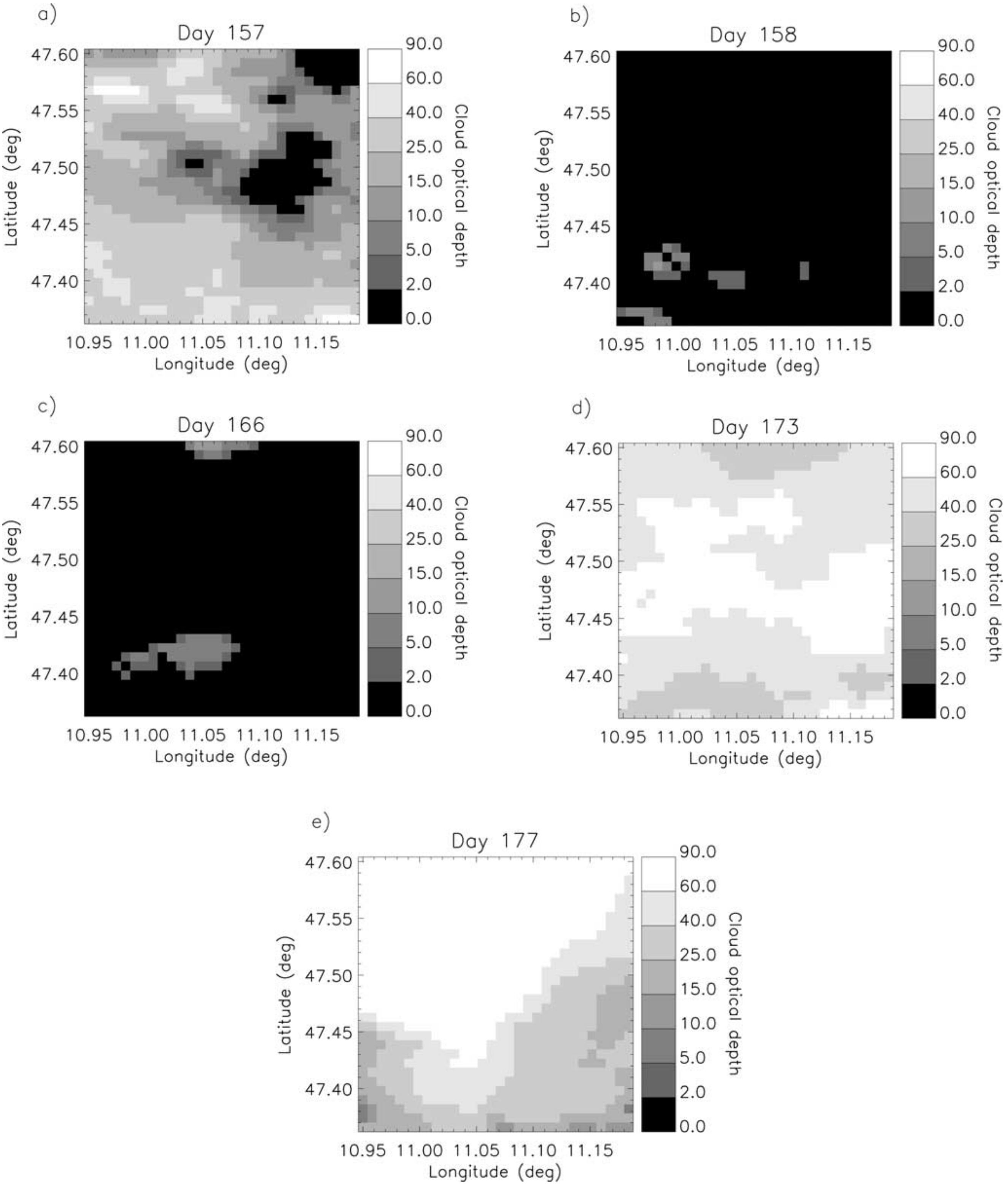

Figure 5. Cloud optical depth derived from AVHRR inside 30 × 30 km area centered at Garmisch-Partenkirchen. (a) day 157, (b) day 158, (c) day 166, (d) day 173 and (e) day 177.

[34] We also separated clear-sky days from the CIE daily dose comparisons at Jokioinen and Garmisch-Partenkirchen. Mean differences (%) of CIE daily doses for JRC and RIVM at Jokioinen were 12 and 1, respectively, while RMS differences were 14 and 24. Similarly, mean differences at Garmisch were 4 and −1, and RMS differences were 12 and 15. If these numbers are compared to the statistics shown in Table 2, it is clear that the performance of

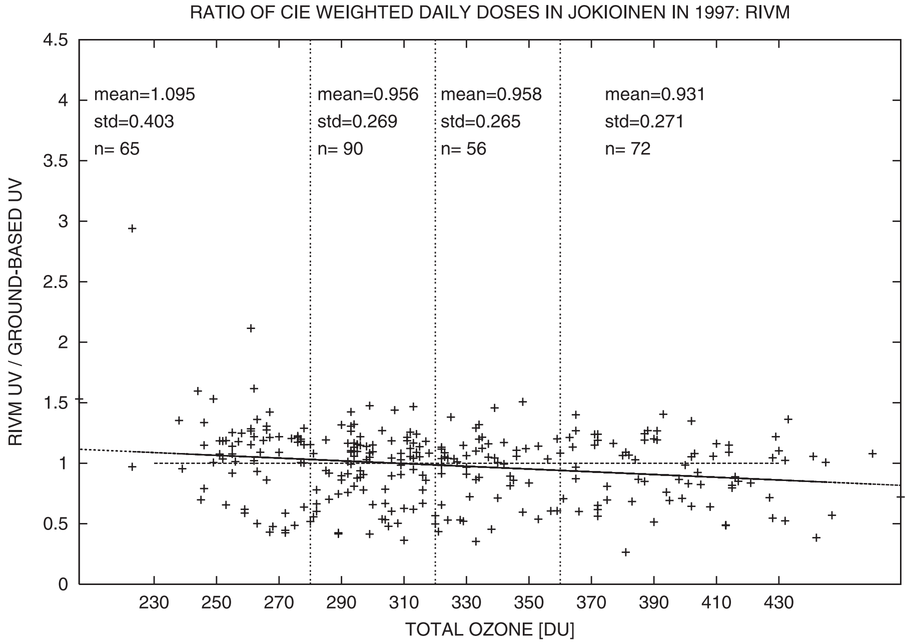

Figure 6. Ratio of satellite-based and ground-based UV data against total ozone used by RIVM.

both methods is improved, since the estimation is not complicated by the spatial and temporal variability in cloudiness.

[35] Of course, another important aspect is the accuracy of the model input parameters. We compared satellite-derived ozone values to the measurements (not shown). As a result, the performance of RIVM method is rather good, while IASB and JRC show an underestimation from the late spring to the autumn and overestimation from the winter to the early spring, as has been confirmed about GOME data in earlier studies [*Lambert et al.*, 1999; *Hansen et al.*, 1999]. The JRC method can use TOMS data instead of GOME, and it would be interesting to check whether this substitution can cure the results.

4. Conclusions

[36] Validation and intercomparisons of four satellite UV methods were described. The mean difference (bias) in daily doses for the RIVM and JRC methods was found to be less

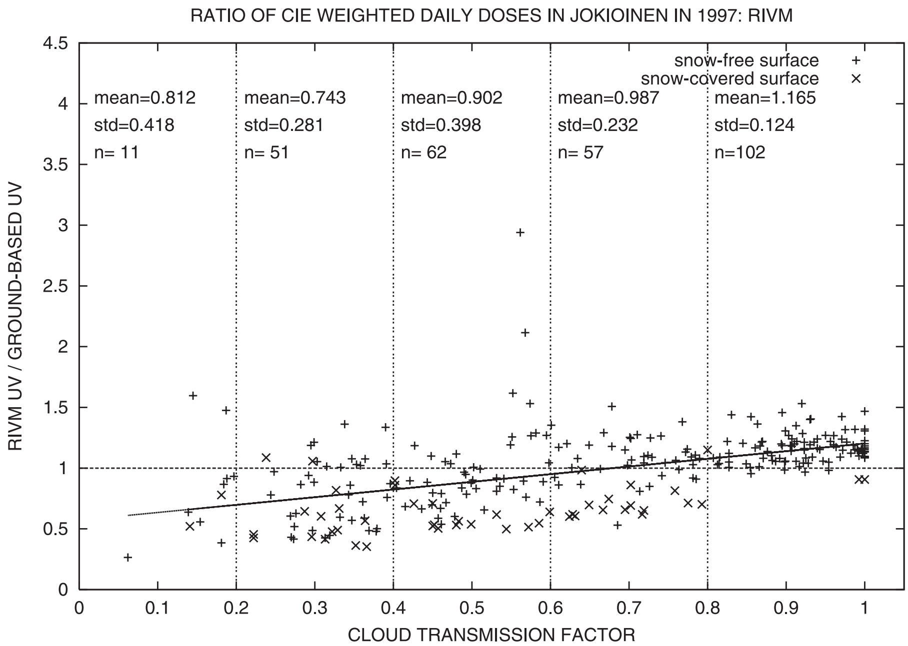

Figure 7. Ratio of satellite-based and ground-based UV data against cloud transmission factor used by RIVM. Snow-surface and snow-free cases are indicated by different symbols, plus and cross, respectively.

than 10% with a RMS difference of the order of 30%. DLR method was assessed for a few selected months and the accuracy was similar to the RIVM and JRC. For IASB method the differences were somewhat higher, due to their original cloud algorithm. Mean difference in daily doses for IASB was about 30% or more, depending on the station, while RMS difference was about 60%.

[37] Further research and development should be carried out to improve the cloud treatments. Estimation of daily UV doses is likely to be improved if additional time-resolved cloudiness information is available for the satellite-based methods. Reflectivity of a snow-covered terrain affects the surface UV radiation and the impact may be rather strong especially in spring time. It was demonstrated that further development work of satellite-based UV methods should focus also on the treatment of albedo of snow-covered surfaces.

[38] It has been shown that UV doses derived by satellite algorithms can differ significantly from ground-based measurements. Even for the algorithms showing smaller deviations, the discrepancies are not yet fully understood (e.g., spectral effects, snow effects) showing the need for further studies. It is furthermore concluded that satellite algorithms cannot be blindly used for derivation of UV doses at the ground. They should always be accompanied by ground truthing. It is therefore expected that high-quality measurements at the ground will still be absolutely needed in the coming years.

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A. Arola, S. Kalliskota, T. Koskela, and P. Taalas, Finnish Meteorological Institute, POB 503, 00101 Helsinki, Finland. (antti.arola@fmi.fi)

P. N. den Outer, J. Matthijsen, and H. Slaper, National Institute of Public Health and the Environment (RIVM), P. O. Box 1, 3720 BA Bilthoven, Netherlands.

K. Edvardsen and G. Hansen, Norwegian Institute for Air Research, N-9296 Tromsø, Norway.

T. J. Martin, Institute for Meteorology and Geophysics, Karl Franzens University of Graz, Halbärthgasse 1, 8010Graz, Austria.

R. Meerkoetter, Institute for Atmospheric Physics, DLR, Oberpfaffenhofen, D-82234 Wessling, Germany.

P. Peeters and P. C. Simon, Belgian Institute for Space Aeronomy, 3 Avenue Circulaire, B-1180 Bruxelles, Belgium.

G. Seckmeyer, Institute for Meteorology and Climatology, University of Hannover, Herrenhäuser Straße 2, 30419 Hannover, Germany.

J. Verdebout, Space Applications Institute, Joint Research Centre, I-21020 Ispra (VA), Italy.