Space-based surface UV monitoring for Europe using SCIAMACHY and MSG

M. van Weele[1a], R.J. van der A[a], J. van Geffen[b], and R. Roebeling[a]
[a] Royal Netherlands Meteorological Institute (KNMI), PO Box 201, 3730 AE De Bilt, The Netherlands
[b] Belgium Institute for Space Aeronomy (BIRA-IASB), Ringlaan 3, 1180 Brussels, Belgium

ABSTRACT

In order to characterize the solar UV radiation reaching the Earth's surface it is monitored from space by means of (i) the clear-sky UV index at local solar noon, which is most relevant for operational UV forecasting, and (ii) the daily UV dose including cloud shielding effects, which is most relevant for long-term UV monitoring and assessments of health risks and biological UV effects. Optimal space-based surface UV monitoring combines information from platforms in different orbits. Space-based total ozone column products from polar orbiting platforms can be used adequately for UV monitoring because the diurnal variability in the total ozone column is limited. However, cloud cover and cloud optical thickness typically vary significantly on time scales of minutes to hours, especially over land in relation to convective activity. Because diurnal variations in cloud amount and cloud optical thickness impact dramatically on the daily-integrated UV radiation levels transmitted to the Earth's surface, the time variations in (key) cloud parameters over the day need to be captured by observations. Sampling of the diurnal variations in clouds is most efficiently done from geostationary platforms. Here we demonstrate examples of calculations of the clear-sky UV index and the UV daily dose for erythema over Europe based on assimilated total ozone column data derived from observations by GOME aboard ERS-2 and its successor SCIAMACHY aboard ENVISAT, in combination with cloud information retrieved from MVIRI aboard Meteosat-7 and its successor SEVIRI aboard MSG (Meteosat-8). Some first validations with ground-based surface spectral UV data are presented.

Keywords: ultraviolet radiation, UV Index, UV dose, UV forecast, GOME, SCIAMACHY, Meteosat, MSG.

1. INTRODUCTION

Atmospheric ozone shields life at the Earth's surface from the most harmful components of the solar UV radiation. Thinning of the atmospheric ozone, e.g., due to ozone depletion and changes in the meteorology in the stratosphere, leads to elevated levels of UV-B radiation at the Earth's surface. A decrease in ozone of 1%, for example, will lead to an estimated increase in UV-B of about 2%. Exposure to enhanced UV incidence increases the risks of biological damage to humans, animals and other organisms.

Peak values are important for, e.g., sunburn ('erythema', or reddening of the skin, McKinley and Diffey, 1987), while other effects such as cataracts and immune suppression are likely a function of the accumulated dose. Therefore, it is important to monitor on a global scale (i) the peak levels at noontime in terms of the clear-sky UV index, and (ii) the surface UV daily dose including cloud shielding, and to do this over a prolonged period of time. For more information on biological effects of UV radiation and their dependence on ozone column values we refer to Madronich et al.(1998) and references therein. The health risk of exposure of the human skin and eyes to the Sun has been recognised already for a long time. About one decade ago it has been agreed internationally that it is most effective to keep the public alert on the risks involved in UV exposure by making available daily predictions of the UV radiation levels via public media. In several countries the UV index predictions are now part of the forecast bulletins by the meteorological services. For more information on the recommendations for dissemination information on UV radiation levels to the general public we refer to the publication (UV-Index for the Public, EC, 2000).

[1] weelevm@knmi.nl; phone +31 30 2206410; fax +31 30 2210407; P.O. Box 201, 3730 AE De Bilt, the Netherlands

Within the ESA project 'Tropospheric Emission Monitoring Internet Service' (TEMIS; http://www.temis.nl) a near-real time service has been set-up for UV index predictions and UV daily dose monitoring. Since 1995 satellite measurements of the near-real time ozone column by, first, GOME (aboard the ERS-2 satellite, 1995-2003) and, afterwards, SCIAMACHY (aboard the ENVISAT satellite, 2003-present) are assimilated in a tracer transport model in order to produce near-real time global maps of ozone at local solar noon. This in turn is converted to global maps of the clear sky UV index for local solar noon, using additional, constant, factors such as surface elevation, the per location varying solar zenith angle at local noon over the year, and the seasonal variation in the Earth-Sun distance. The daily UV dose is computed every day for the day before over Europe. For the UV dose, use is made of analysed ozone fields instead of forecasted ozone fields and in addition of diurnal cloud information from MVIRI on METEOSAT-7(1998-present) and SEVIRI on MSG/METEOSAT-8 (2004-present). The TEMIS archives and latest data and images are made available via the TEMIS website at http://www.temis.nl/uvradiation/. Here, also information is given on the GOME and SCIAMACHY instruments. Extensive information on the Meteosat data and the instrument details can be found at the EUEMETSAT website: http://www.eumetsat.int/ . For more information on the method and quality of the analysed and forecasted total ozone assimilated columns we refer to (Eskes et al., 2002; 2003). In this paper we explain the methods used, show some calculations of the clear-sky UV index and UV dose, and further focus on the required cloud products and the parameterisation of the effects of clouds on the UV daily dose. Finally we give some results of our first validation exercises.

2. METHODS

Two of the most important satellite products that are needed for accurate space-based surface UV radiation monitoring are the daily total ozone column at noon and the diurnally varying cloud cover. For the clear-sky UV index predictions the availability of accurate total ozone column forecasts is most crucial (Eskes et al., 2002; Eskes et al., 2005a). Currently forecasts of total ozone are made for the coming eight days. Several instruments on polar-orbiting platforms monitor the total ozone column. The NASA TOMS record, recently continued with the Dutch-Finnish OMI instrument on EOS-Aura, dates back to the late 1970s (http://www.toms.gsfc.nasa.gov/ . The ESA GOME-SCIAMACHY series dates back to 1995 and is used here. This record will be continued by Eumetsat with the GOME-2 series of instruments on MetOp platforms from 2006 onwards. Present-day total ozone instruments obtain (near-) global coverage in one day. Data assimilation based on ozone tracer transport using meteorological analysis and forecast data from numerical weather prediction models such as ECMWF has been shown a powerful method to fill in data gaps and produce accurate ozone forecasts (Eskes et al., 2002; 2005). The method to calculate the clear-sky UV index from the predicted total ozone column at noontime is fully described in (Allaart et al., 2004).

For the UV dose a combination of (satellite) data sources is needed. Basically, the required information includes, apart from the total ozone column data, cloud cover and cloud optical thickness, aerosol optical thickness and aerosol optical properties (absorption; scattering), UV surface reflection data and the incoming solar irradiance (Madronich et al., 1998; Herman et al., 1999; Martin et al., 2000; Verdebout, 2000; McKenzie et al., 2001). Most important are the total ozone column and the time-varying cloud cover (Martin et al., 2000). Improvements will come from the inclusion of observations of cloud optical depth, aerosol optical depth, aerosol absorption optical depth and surface albedo in the algorithm. In addition a continuous validation program is needed for the calculated surface UV doses with the aid of a surface UV network, augmented with a validation program for the various underlying satellite products, including at least ground-based observations of ozone column, cloud cover, cloud optical thickness and aerosol optical thickness.

For UV risk assessments is it required to establish climatological maps of the incoming UV radiation levels at the Earth's surface. The climatological data should contain averages, variability in space and time, trends and extremes. Climatologies and long time-series based on measurements at single stations are extremely useful, but interpolation in space between stations is very difficult and it introduces large uncertainties. The size, representativity and homogeneity of the ground networks will limit direct contributions of ground-based surface UV monitoring to spatially-resolved climatologies. In order to develop representative climatological maps of the UV dose global space-based monitoring is required on a time scale of decade or more and it can only be obtained by calculations that are based on combinations of satellite measurements. Again, it is emphasized that the role of ground networks is indispensable for space-based long-term monitoring, because the calculations based on satellite measurements as well as each of the underlying satellite products need adequate and continuous ground validation for quality assurance and quality control.

Cloud cover and cloud optical depth typically vary on time scales of minutes to hours. Therefore, the usefulness of cloud information from polar-orbiting platforms to calculate the UV daily dose is typically limited. Nevertheless, for practical reasons cloud information from instruments that measure over a certain location only once a day has been applied in several existing satellite UV estimates (Eck et al., 1998; Herman et al., 1999; Meerkoetter et al., 1997). The question is how representative measurements at a certain local overpass time of a polar-orbiting platform are for the integrated cloud shielding during the day. Clearly, this will depend on the meteorological situation and it will be a better assumption at one location than another. However, typical examples of diurnal cycles in cloudiness that frequently occur include over land the increase in convective activity during the day and over sea and in coastal zones the break-up of stratus and stratocumulus clouds during the day, both as a result of the diurnal cycle in solar radiation. Nevertheless, relations have been sought and found between the dose rate at a certain time (e.g. noontime) and the daily dose. Weatherhead et al.(2005) presents relationships with acceptable statistical uncertainty as a function of latitude and month, albeit only for ideal conditions, i.e., when cloud cover and cloud transmission remain constant over the day. Martin et al. (2000) concluded that satellite-derived maps of UV daily dose cannot be expected to produce accurate values if they rely on a single estimate of the cloud conditions, but these methods may be able to provide reasonable estimates of the monthly dose (<5%).

Representative high frequency observations of clouds can be obtained from instruments on a geostationary platform such as MVIRI on Meteosat-7 in the case of Europe and Africa (Verdebout, 2000). Spatially much better resolved cloud cover information is now available from MSG (now called: Meteosat-8). Cloud masks are produced operationally within the framework of the Eumetsat Nowcasting Satellite Application Facility (NWCSAF): http://www.meteorologie.eu.org/safnwc/ . Furthermore, quantitative cloud information is also becoming available from MSG, e.g., within the Eumetsat Climate Monitoring Satellite Application Facility (CMSAF): http://www.dwd.de/en/FundE/Klima/KLIS/int/CM-SAF/index.htm . The most important improvements of MSG compared to Meteosat-7 are the higher spectral, spatial and temporal resolution. Due to these improvements cloud properties, such as cloud optical thickness, can be retrieved with much higher accuracy up to latitude 65 °N. The cloud optical thickness product from MSG is a very important step for an improved parameterisation of UV cloud transmission. In the current algorithms it is assumed, arbitrarily, that overcast clouds transmit 50% of the UV radiation, which will be largely in error for both thin and thick overcast clouds.

3. RESULTS AND DISCUSSION

At present, total ozone columns are operationally retrieved at KNMI from the SCIAMACHY nadir observations using the TOSOMI scientific algorithm (Eskes et al., 2005b). The algorithm is run in near-real time, which implies that the ozone column data is made available within a few hours after observation by SCIAMACHY. In combination with the latest ECMWF meteorological forecasts, data assimilation by a tracer transport model provides every day an accurate forecast of the global ozone fields for eight days ahead (Eskes et al., 2002). The forecast ozone fields are used to provide accurate forecasts of the clear sky UV index eight days ahead using the algorithm described in Allaart et al (2004).

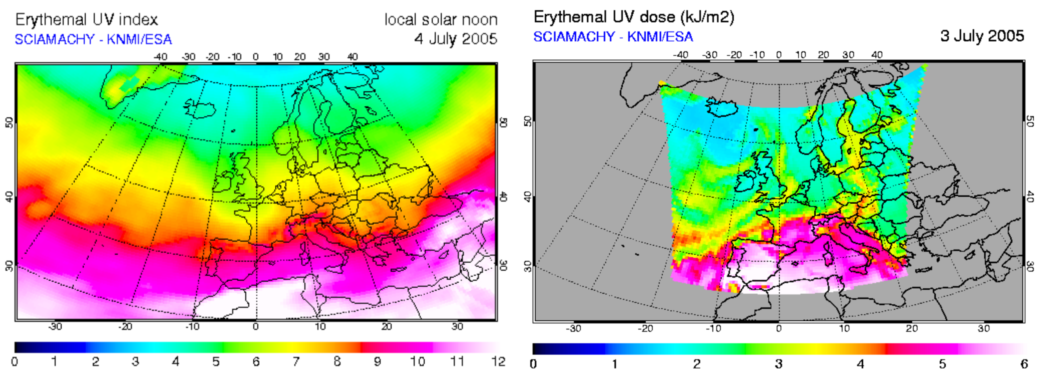

Figure 1 Clear sky UV Index over Europe predicted on 3 July 2005 for 4 July 2005 (left) and the analysis of the (erythemal) UV daily dose (in kJ/m^2) over Europe calculated on 4 July 2005 for 3 July 2005. The spatial coverage of the UV dose domain is limited by the domain of the operational Meteosat-7 cloud mask product at KNMI. Surface elevation effects are taken into account in both algorithms.

Figure 1 (left) shows an example of the clear-sky UV index for Europe. Values over northern Africa, the Middle-East and Turkey reach more than 12 for this day, while the predicted UV index is in the order of 5 to 6 over the British Isles and Scandinavia. Figure 1 (right) shows an example of the daily UV dose. Values reach over 6 kJ/m^2 over northern Africa and Southern Spain, while the daily UV dose was around 2 kJ/m^2 over northern Europe for this day.
Note that the UV products are calculated on a regular grid of 0.5 × 0.5 degrees. The solar zenith angle is computed from the latitude of the centre of the grid cell. The Allaart et al. (2004) algorithm does not account for variations in aerosol load. Implicitly it contains a "zero-order" aerosol correction based on an average aerosol load. As soon as reliable space-based aerosol products will become available in near-real time, an improved aerosol correction as has been developed by Badosa and van Weele (2002) will be applied. McKenzie et al.(2003) studied the possible effect of the ozone profile (for given total ozone column) on the estimation of the UV dose from satellite sensors. They found that the effects can be significant in the UV-B region, but the sign of the effect depends on the solar zenith angle. Consequently, the effect on the daily dose is suppressed to only a percent of two, which is small compared to other effects. Therefore, the use of total ozone column data typically suffices for estimation of the daily UV dose.

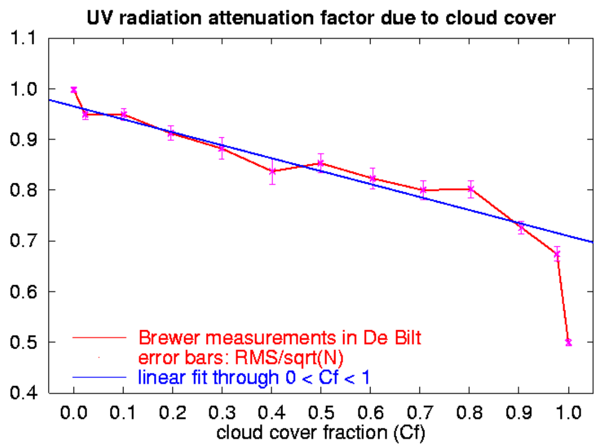

Figure 2 The assumed reduction in surface UV for a given amount of cloudiness (straight line) as derived from ground-based observations of spectral surface UV radiation and standard cloud observations at KNMI in De Bilt, The Netherlands (line with ticks).

The daily UV dose is calculated by integration of the UV index between sunrise and sunset, including a factor for the attenuation by clouds based on hourly cloud cover data from Meteosat-7. Figure 2 shows the assumed reduction in surface UV for a given amount of cloudiness as derived from ground-based observations of spectral surface UV radiation and standard cloud observations at KNMI in De Bilt, The Netherlands. Validation has shown that the approximation works reasonable except for overcast situations where large variations occur in the attenuation factor, depending on the cloud optical thickness.
Basically, the use of parameterisations such as presented in Figure 2 can be avoided on theoretical grounds, e.g. by application of full 3-D radiative transfer modelling for a given 3-D cloud field. However, it should be realised that this would be a very time consuming set of calculations. Further, in practice, the uncertainty in the 3-D input cloud field would be much too large to justify such an approach. Nevertheless, the quality of the parameterization of UV transmission as a function of cloud cover can certainly be verified by a set of 3-D radiative transfer modelling calculations for various typical 3-D cloud fields. In fact, different (statistical) relations may exist between cloud cover and incident surface UV radiation at different locations. At present, the increase in spatial and temporal resolution information on cloud cover and more complete cloud information (including cloud optical thickness) as derived from SEVIRI on MSG is most useful to improve upon the current calculations of the daily UV dose.
High resolution cloud masks are produced operationally within the framework of the Eumetsat Nowcasting Satellite Application Facility. The time resolution is 15 minutes instead of one hour. Further, within the framework of the Eumetsat Climate Satellite Application Facility (CM-SAF) quantitative cloud products are being derived from MSG data, including cloud optical thickness (Roebeling et al. 2003; Feijt et al. 2004). This data is most important to improve upon situations with overcast cloud cover. Currently, the crude assumption is made that, if overcast clouds are present, UV cloud transmission is 50%.

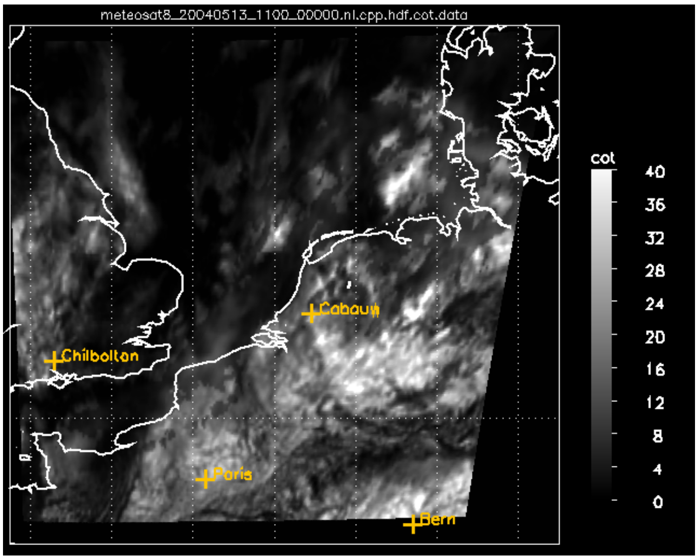

Figure 3. Cloud Optical Thickness (COT) over part of N-W Europe. Example for 13 May 2004, 11 UTC based on MSG.

Figure 3 shows the cloud optical thickness as derived from MSG/SEVIRI observations over part of North-western Europe. Some smaller areas with thick clouds (COT > 20) are surrounded by areas with medium thick clouds (5 < COT < 20) and thin clouds (COT < 5). Figure 4 shows on the left the frequency distribution of the cloud optical thickness for the domain shown in Figure 3 and, on the right, the cumulative frequency distribution. In this case it can be concluded that for about 70% of the pixels there are either no clouds or clouds with an optical thickness smaller than 10. For the selection of pixels with overcast cloud cover the current algorithm would overestimate the UV dose because it assumes 50% cloud transmission, roughly corresponding to cloud optical thickness of 10. Analysis of longer time series for the area over North-western Europe showed for the cloud optical thicknesses day-to-day variations of the median between 2 and 20 (Roebeling et al. 2005). Figure 4 also shows that the retrievals of cloud optical depth correlate well with retrievals based on AVHRR on NOAA-17.

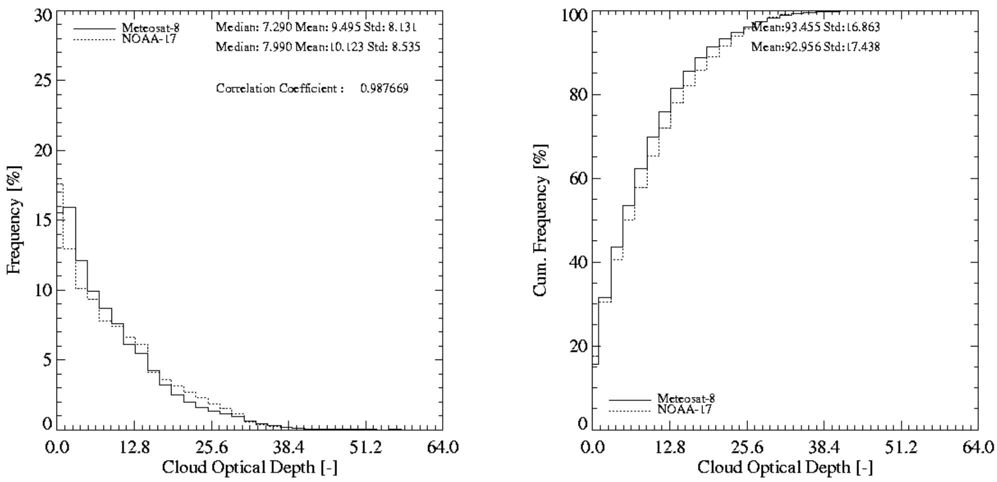

Figure 4. Frequency distribution (left) and cumulative frequency distribution (right) of the Cloud Optical Thickness (COT) as derived from MSG for 13 May 2004, 11 UTC over the domain shown in Figure 3. The dotted lines represent similar retrievals of COT based on NOAA-17 AVHRR data.

The dependence of UV cloud transmission (T_{UV}), on cloud optical thickness (τ_c) can be written as $T_{UV} \approx (1 + 0.1\tau_c)^{-1}$, in first ($\delta$-Eddington) approximation (van Weele and Duynkerke, 1993). Here, it is assumed that there is no cloud absorption, and that the dependence of cloud transmission on the angle of the incident solar beam can be neglected in first order. The latter assumption is quite reasonable in the UV spectral range because a significant part of the UV radiation that is incident at cloud top is diffuse radiation due to Rayleigh scattering out of the solar beam above cloud top. To give some idea on the UV cloud transmission to cloud optical thickness relationship: roughly 50% cloud transmission is found for a typical cloud optical thickness of 10 (stratus, fair weather cumulus, stratocumulus); ~70% cloud transmission or more for thin clouds with an optical thickness of 4 or less; cloud transmissions are as low as 25% and 10% for thick clouds (thick stratus or cumulus, nimbostratus 'thunderstorm clouds') with cloud optical thicknesses of 30 and 90, respectively. Clearly, the current assumption of 50% cloud transmission for overcast situations can easily lead to several tens of percent error in the daily UV dose in cases that cloud optical thickness is very different from a value of about 10. The relationship also shows that cloud transmission is more sensitive to relative errors for thin ($\tau_c < 5$) and medium thick clouds ($5 < \tau_c < 20$) than for errors in thick clouds ($\tau_c > 20$). Current uncertainties in cloud optical thickness can reach 50-100% for a single location and time. Therefore, for practical applications, such as the derivation of the daily UV dose, it will be already a significant improvement to be able to distinguish between thin, medium thick and thick clouds and to assign a more realistic cloud transmission to different overcast situations.

First validation studies of the daily UV dose have been performed with the surface spectral UV data contained in the European UV database EDUCE hosted by the Finnish Meteorological Institute (FMI) at http://ozone2.fmi.fi/uvdb/ . The comparisons that are shown here are for 2002 and therefore based on observations from ERS-2/GOME and Meteosat-7/MVIRI. The main difference between these products and the products based on SCIAMACHY and MSG is the improved spatial and temporal resolution of the latter two instruments. The so-called BASINT tool at the EDUCE website offers the possibility to convert UV spectra directly into an erythemal dose rate, given in $J/m^2/s$. To facilitate the comparison as a function of time of the day, the computation of the UV dose has been performed by a time-integration over 10-minute intervals. Also the TEMIS algorithm calculates the daily UV dose by integration over 10-minute intervals to fully take into account the variation in solar zenith angle over the day. Figure 5 shows two examples of validation of the 10-minute integrated UV dose for cloud free days with different aerosol load at the island of Lampedusa (35 N; 13 E), which is a very suitable location for validation of space-based UV products (Meloni et al., 2005). The results are almost identical for 14 July 2002 (right figure) with, assumingly, a kind of average aerosol load. On 28 May there is a notable difference with apparently less aerosol load. This is confirmed by measurements of the aerosol optical depth at 500 nm: 0.284 on 14 July 2002 and 0.091 on 28 May 2002 (Alcide di Sarra, private communication). The space-based calculation of the daily UV dose for 14 July 2002 is 4.86 kJ/m^2, whereas the BASINT-integrated ground-based value is 4.83 kJ/m^2. For 28 May the space-based value is 4.84 kJ/m^2 and the ground-based value is 5.31 kJ/m^2.

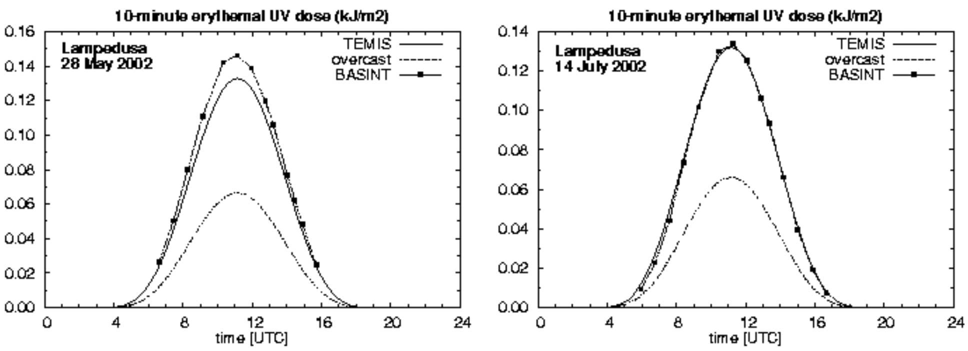

Figure 5. Validation of the 10-min erythemal UV dose at Lampedusa (35 N; 13 E) for two cloud-free days with different aerosol load: the aerosol load on 14 July 2002 is estimated higher than on 28 May 2002. The space-based calculation of the UV dose is denoted with 'TEMIS', the surface UV measurements are denoted by 'BASINT'. The lowest curve represents the space-based calculation of the UV dose if overcast conditions would have prevailed (50% cloud transmission). For the spectral UV observations at Lampedusa, courtesy: Alcide di Sarra.

Finally, a comparison has been made for an almost fully clouded day at Thessaloniki on 6 June 2002. Figure 6 shows that the space-based UV dose calculations correspond most of the day with the curve for fully overcast pixels. The BASINT integrated ground-based observations are during most of the day higher than the space-based calculations. This would imply that the clouds are actually thinner on this day than implicitly is being assumed in the algorithm that always applies 50% cloud transmission. Another possibility is of course that cloud cover at the station location was not 100% as reported by Meteosat for the entire grid cell, and that the instrument was looking through openings in the cloud field.

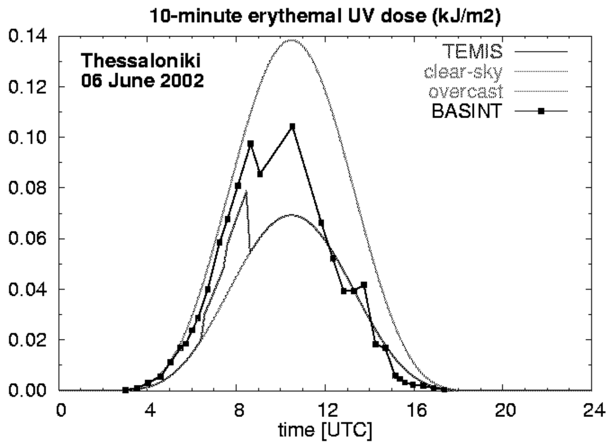

Figure 6. Validation of the 10-min erythemal UV dose at Thessaloniki (41 N; 23 E) for an almost fully clouded day on 6 June 2002. The space-based calculation of the UV dose is denoted with 'TEMIS' and overlaps with the 'overcast' curve for most of the day. The surface UV measurements denoted by 'BASINT'are significantly higher. The upper curve represents the space-based calculation of the UV dose if cloud-free conditions would have prevailed. For the spectral UV observations at Thessaloniki, courtesy: Alkis Bais.

4. CONCLUSIONS AND OUTLOOK

This paper explains methods that have been developed to obtain space-based estimates of the clear-sky UV index and the daily UV dose. It is concluded that the optimal method for space-based surface UV monitoring combines satellite products from different satellite platforms. This combined approach has been proposed first by Verdebout (2000). In recent years step-by-step the required input parameters are becoming available from (operational) satellite instruments and the data improve in resolution and quality. The first step will be to operationalise the use of the MSG (Meteosat-8) cloud mask for the TEMIS UV dose product. Next, the operational use of the MSG cloud optical thickness will be investigated. Another improvement will be to include operational space-based aerosol products in the calculations. A suitable parameterisation has already been developed based on radiative transfer modelling (Badosa and van Weele, 2002; Badosa et al., 2005). Product improvements should further derive from extensive validation studies. Up-to-date information on developments in long-term space-based UV monitoring can also be found at the ESA/EU GMES Service Element for the Atmosphere called 'PROMOTE': http://www.gse-promote.org/ . Lastly, future extensions of the satellite derived daily UV doses will include the calculation of daily UV doses that are weighted with other action spectra than the (McKinley and Diffey, 1987) erythema action spectrum, which is clearly highly desirable for UV risk assessments and does not pose conceptual problems as space-based UV data are based on forward (radiative transfer) modelling calculations using constrained input parameters.

REFERENCES

1. Allaart, M., van Weele, M., Fortuin P. and Kelder, H., UV-index as function of solar zenith angle and total ozone. Meteorological Applications, 11: 59-65, 2004.
2. Arola, A., S. Kalliskota, P.N. den Outer, K. Edvardsen, G. Hansen, T. Koskela, T.J. Martin, J. Matthijsen, R. Meerkoetter, P.Peeters, G. Seckmeyer, P.C. Simon, H. Slaper, P. Taalas, and J. Verdebout, Assessment of four methods to estimate surface UV radiation using satellite data, by comparison with ground measurements from four stations in Europe, J. Geophys. Res., 107(D16), 4310, doi:10.1029/2001JD000462, 2002.

3. Badosa, J., and van Weele, M., Effects of aerosols on UV-index, Scientific Report WR-2002-07, KNMI, De Bilt, The Netherlands, 2002.
4. Badosa, J., J.-A. Gonzalez, J. Calbo, M. van Weele, R. McKenzie, Using a parameterization of a radiative transfer model to build high-resolution maps of typical clear-sky UV index in Catalonia, Spain, J. Appl. Meteorol., 44, 789-803, 2005.
5. Eck, T.F., P.K. Bhartia, and J.B. Kerr, Satellite estimation of spectral UV-B irradiance using TOMS derived ozone and reflectivity, Geophys. Res. Lett., 22, 611-614, 1995.
6. Eskes, H.J., van Velthoven, P.F.J., and H.M. Kelder, Global ozone forecasting based on ERS-2 GOME observations, Atmos. Chem. Phys., Vol. 2, 271-278, 2002.
7. Eskes, H.J., van Velthoven, P.F.J., Valks, P.J.M., and H.M. Kelder, Assimilation of GOME total ozone satellite measurements in a three-dimensional tracer transport model, Quart.J.R.Meteorol.Soc., 129, 1663-1681, 2003.
8. Eskes, H.J., A. Segers, and P.F.J. van Velthoven, *Ozone Forecasts of the Stratospheric Polar Vortex Splitting Event in September 2002*. J. Atmos. Sci., **62** ,3, 812-821, 2005a.
9. Eskes, H.J., R. J. van der A, E. J. Brinksma, J. P. Veefkind, J. F. de Haan, and P. J. M. Valks, Retrieval and validation of ozone columns derived from measurements of SCIAMACHY on Envisat, Atmos. Chem. Phys. Discuss, 5, 4429-4475, 2005b.
10. Feijt, A.J., D. Jolivet, R. Koelemeijer, R. Dlhopolsky, and H. Deneke, Recent improvements to LWP retrievals from AVHRR, Atmos. Res., 72, 3-15, 2004.
11. Herman, J.R., N. Krotkov, E. Celarier, D. Larko, and G. Labow, Distribution of UV radiation at the surface from TOMS-measured UV-backscattered radiances, J. Geophys. Res., 104, 12059-12076, 1999.
12. Madronich, S., McKenzie, R.L., Björn, L.O. and Caldwell, M.M., Changes in biologically active ultraviolet radiation reaching the Earth's surface. Photochem. Photobiol. 46: 519, 1998.
13. Martin, T.J., B.G. Gardiner, and G. Seckmeyer, Uncertainties in satellite-derived estimates of surface UV doses, J. Geophys. Res., 105, 27005-27012, 2000.
14. McKenzie, R. G. Seckmeyer, A.F. Bais, J.B. Kerr, and S. Madronich, Satellite retrievals of erythemal UV dose compared with ground-based measurements at northern and southern midlatitudes, j. Geophys. Res., 106, 24051-24062, 2001.
15. McKenzie, R., D. Smale, G. Bodeker, and H. Claude, Ozone profile differences between Europe and New-Zealand: Effects on surface UV irradiance and its estimation from satellite sensors, J. Geophys. Res., 108, D6, 4179, doi:10.1029/2002JD002770, 2003.
16. McKinley A. and B.L. Diffey B.L., A reference action spectrum for ultraviolet induced erythema in human skin, CIE Journal, 6, 17-22, 1987.
17. Meerkoetter, R., B. Wissinger, and G. Seckmeyer, Surface UV from ERS-2/GOME and NOAA/AVHRR data: A case study, Geophys. Res. Lett., 24, 1939-1942, 1997.
18. Meerkoetter, R., J. Verdebout, L. Bugliaro, K. Edvardsen, and G. Hansen, An evaluation of cloud affected UV radiation from polar orbiting and geostationary satellites at high latitudes, 30(18), 1956, doi:10.1029/2003GL017850, 2003.
19. Meloni, D., A. di Sarra, J.R. Herman, F. Monteleone, and S. Piacentino, Comparison of ground-based and TOMS erythemal UV dose at the island of Lampedusa in the period 1998-2003: Role of tropospheric aerosols, J. Geophys. Res., 110, D01202, doi:10.1029/2004JD005283, 2005.
20. Roebeling, R.A., H. Hauschildt, D. Jolivet, E. Meijgaard, and A.J. Feijt, Retrieval and validation of MSG and AVHRR based cloud physical parameters in the CMSAF, Proceedings: published, EUMETSAT data users conference, 2003, Weimar, Germany, EUMETSAT, 183-198, 2003.
21. Roebeling, R.A., A.J. Feijt, and P. Stammes, Intercomparison of reflectances and cloud physical properties from SEVIRI on METEOSAT-8 and AVHRR on NOAA-17, manuscript in preparation, 2005.
22. UV Index for the public, COST 713 UV-B Forecasting, Office for official publications of the European Communities, EUR 19226, 2000.
23. van Weele, M., and P.G. Duynkerke, Effect of clouds on the photodissociation of NO_2: observations and modeling. J. Atmos. Chem., 16, 231-255, 1993.
24. Verdebout, J., A method to generate surface UV radiation maps over Europe using GOME, Meteosat and ancillary geophysical data, J. Geophys. Res., 105, 5049-5058, 2000.
25. Weatherhead, E.C., C.S. Long, A.J. Stevermer, and J. Enagonio, Using the erythemal ultraviolet radiation dose rate at noontime to approximate the time-integrated daily dose, Photochem. Photobiol., doi:10.1562/2003-11-18-RA-008, 2004.