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Uncertainties in satellite-derived estimates of surface UV doses

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Abstract. Satellite-derived maps of surface UV irradiance are currently limited by their poorly assessed accuracy. Here we use an extensive data set of ground-based spectral measurements from two Alpine sites to examine the level of uncertainty expected in model results due to the time-limited nature of some satellite data. When the ozone column, cloud optical depth, and aerosol optical depth supplied to a radiative transfer model are fixed to a single noontime value, the root-mean-square difference between calculations and measurements of the erythemal daily dose is about 20%. The corresponding uncertainty in the monthly dose is less than 5%. The modeled results also show a systematic error that depends on cloud optical depth. The results suggest that satellite-derived maps of UV irradiance cannot be expected to produce accurate values of the daily dose if they rely on a single estimate of the cloud conditions but may be able to provide reasonable estimates of the monthly dose.

1. Introduction

Data from satellites are increasingly being used to provide information on the UV irradiance incident at the Earth's surface [*Soulen and Frederick*, 1999; *Herman et al.*, 1999; *Lubin et al.*, 1998; *Eck et al.*, 1995]. While ground-based spectroradiometers continue to provide by far the most accurate measurements of UV radiation, the high operational costs and assiduous long-term care required by these instruments preclude their use at any more than a handful of specialised sites. Satellite measurements, on the other hand, can readily furnish data on a global scale, in some cases with a spatial resolution of less than a kilometer. The coverage provided by satellites can potentially offer great advantages for the description of regional variations in surface UV irradiance, together with the possibility of investigating changes in the irradiance on timescales from days to years. Ozone data from the TOMS instruments, for example, are available from 1978. However, surface UV irradiance data derived from satellite measurements are subject to large uncertainties. While some uncertainty analyses are available [*Herman et al.*, 1999; *Lubin et al.*, 1998], satellite-derived maps of UV irradiance are generally limited by their poorly assessed accuracy.

While satellites give global coverage, they can only determine the downward UV irradiance at the Earth's surface by indirect means. Essentially, estimates of cloud optical depth, ozone column depth, and surface reflectance are derived from remote measurements and then used as the input parameters to a radiative transfer model. Additional or more detailed information on the atmospheric structure, such as the aerosol optical depth or surface pressure, may be supplied from similar measurements or from ground-based sources, or be set to a seasonal average.

Discrepancies between UV maps and measurements are caused by a number of factors. Considerations include uncertainty in the input parameters to the radiative transfer models (of which cloud optical depth is possibly the most important) and errors or approximations in the model algorithms. The ground-based measurements are also themselves subject to error [*Bernhard and Seckmeyer*, 1999]. Additional uncertainty is introduced by differences in resolution; whereas ground-level measurements are made at a single point, satellite instruments measure some spatial average. The relationship between point measurements and spatially av-

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eraged values must be understood if meaningful comparisons are to be made.

A rigorous validation of satellite-derived maps requires a separate assessment of each source of error and uncertainty for each type of map product and for the ground-based measurements. Once systematic errors have been corrected and uncertainties quantified, a comparison between map pixels and ground-based measurements at selected sites can be used to assess the validity of the map-generating procedure. The work presented in this paper was conducted in the framework of the MAUVE (Mapping of UV by Europe) project, in which the evaluation of UV maps against reference measurements performed with ground-based instruments was a central task.

In this paper we examine the level of uncertainty introduced into estimates of the erythemal daily dose by the time-limited nature of satellite data alone. Satellite data for a given point on the Earth's surface are often restricted to only one measurement per day. Changes in the ozone, aerosol, and, most importantly, cloud conditions through the day will then lead to errors in the calculated dose. Random errors in UV maps may be reduced by integrating the calculated irradiances over a long enough timescale (although they must be understood and quantified if the maps themselves are to be useful), but any systematic errors should be characterized and corrected. For this investigation we make use of an extensive data set of ground-based spectral measurements gathered from two Alpine sites, which are subject to very different radiation environments.

The procedure used to generate the erythemal daily doses is described in section 2. In section 3 the results of the analysis of spectral measurements from more than 2000 days are presented. The implications of these results are discussed in section 4.

2. Method

For each noontime measurement of the global erythemal irradiance, the output of a radiative transfer model is forced to equal the measured flux by adopting a suitable value for the cloud optical depth, thus mimicking a "perfect" satellite algorithm. With the cloud, ozone, and aerosol parameters held constant, the model is used to calculate an erythemal daily dose. This estimate is then compared with the measured dose for the day.

In this way a situation is created which is similar to that in which satellite-derived values of ozone column, cloud optical depth, and aerosol optical depth are only available once per day. An advantage of this method is that the results are independent of other uncertainties and assumptions used in the generation of satellite-derived maps. Provided that the model is known to reproduce the measured daily dose accurately under normal circumstances, any scatter seen in the results can be attributed entirely to the limited information available to the radiative transfer model.

The spectral data come from measurements made at two Alpine locations in southern Germany. One instrument is located at Garmisch-Partenkirchen (47.48°N, 11.07°E, 730 m altitude), a valley site with the skyline at an elevation of between 5° and 15°. The second lies at the summit of the nearby Zugspitze (47.42°N, 10.98°E, 2964 m altitude), which has an unobstructed horizon. The altitude of the Zugspitze places it above most of the boundary layer aerosols, and it often lies above the convective cloud that forms over the valley, while at other times the summit is immersed within cloud local to the mountain. Although the two sites are separated by less than 10 km horizontally, their radiation environments are therefore very different. Details of the measuring systems and their characterization can be found in the works of *Bernhard and Seckmeyer* [1999] and *Seckmeyer et al.* [1996]. These instruments have taken part in several international intercomparisons of spectroradiometers ([*Gardiner and Kirsch*, 1995; *Seckmeyer et al.*, 1998], for example). Data sets for the two instruments extend back to April 1994 and July 1995, respectively, and more than 2000 complete days of measurements were available for this analysis.

To generate estimates of the erythemal daily dose a sophisticated radiative transfer model, the BASRTM [*Gardiner and Martin*, 1997], was used. The BASRTM is based on the discrete ordinates solution to the equation of radiative transfer [*Stamnes et al.*, 1988] with adaptations to spherical geometry [*Dahlback and Stamnes*, 1991]. This model permits the efficient calculation of daily doses under well-characterized atmospheres and has been shown to give reliable values of UV irradiance under realistic atmospheric conditions [*van Weele et al.*, 2000].

The spectral measurements of UV irradiance are used to calculate values of the daily and thence weekly and monthly erythemal dose. Values of ozone column depth and aerosol optical depth are also derived from these measurements. These ozone and aerosol parameters, together with a seasonally dependent estimate of the surface albedo, are used as the input to the BASRTM.

Values for the ozone column depth and the aerosol optical depth are derived from the closest spectral measurement of the direct solar beam [*Mayer and Seckmeyer*, 1998], provided that such a measurement lies within 3 hours of the noontime spectrum. In the presence of cloud, when no reliable direct-beam measurement exists, the aerosol values are set to the seasonal average. This somewhat arbitrary assignment of the optical depth does not weaken the validity of the procedure. Under cloud the amount of radiation transmitted to the ground becomes insensitive to the aerosol component, and in any case, small errors are allowed for by altering the thickness of the cloud (see below).

When no direct solar measurements are available within 3 hours of noon, the ozone column depths are derived from the spectral global irradiance using the method described by Stamnes [*Stamnes et al.*, 1991].

This method has been shown to give excellent results for conditions where the Sun is visible and comparison with standard Dobson or Brewer measurements can be made [*Mayer and Seckmeyer*, 1998; *Dahlback*, 1996]. Under thick cloud, however, the retrieved ozone column becomes unreliable [*Mayer et al.*, 1998]. Increased scattering of radiation within the cloud extends the optical path of the photons reaching the ground, causing the UV-B photons to suffer enhanced absorption by tropospheric ozone. As a result, the Stamnes method tends to overestimate the total ozone column depth in cloudy conditions.

For the purposes of this study, however, any errors introduced by the retrieval of ozone column depth from the global measurement are, in fact, unimportant, even when the ozone column is overestimated by 20% or more. The largest errors in the ozone column are seen only under thick cloud. When the model irradiance is forced to agree with the noontime measurement, an overestimate in the ozone column depth results in an underestimate in the cloud optical depth. The resulting error in the daily dose is then a second-order effect and, in fact, the change in ozone column has little influence on the final result. For example, model calculations for Garmisch-Partenkirchen on a hypothetical day in midsummer show that the same noontime erythemal flux is obtained with an ozone column of 400 Dobson units (DU) and cloud optical depth (at 320 nm) of 20 as for a column depth of 300 DU and cloud optical depth of 34.5. Even for this extreme example, the daily doses for these two cases differ by less than 1%. The correspondence will not, of course, be maintained for other wavelength bands or weighting functions.

3. Results

A comparison of model calculations with measurements from Garmisch-Partenkirchen (GAP) is shown in Figure 1. Here the ratio of model to measurement for the erythemal daily dose is plotted as a function of the modeled fraction of the clear-sky (i.e., cloudless) dose, with a logarithmic scale on the y axis. The dashed line is theoretically the minimum value of the ratio, obtained when the measured dose is equal to the estimated clear-sky dose. Changes in ozone column or aerosol optical depth through the day, unusual cloud conditions, or poor agreement between model and measurement may allow some points to appear below this line.

Large deviations from the measured values of daily erythemal dose can be seen in Figure 1. The scatter tends to be greater on the more cloudy days (smaller values in the ratio of modeled dose to clear-sky estimate). For days on which the skies were cloud-free at noon (when the modeled dose is equal to the clear-sky estimate) the scatter is much smaller, although the model result may still differ from the measurement by 50% or more. For these days it is clear that in principle, the model result can only be an overestimate of the measured daily dose. If the sky was clear at noon, the presence of cloud in the morning or afternoon will tend to reduce the measured dose compared with the clear-sky estimate. This introduces a marked systematic error or bias into the modeled values. Similarly, when the model shows a large amount of cloud (the model dose is now a small fraction of the clear-sky estimate), there is a tendency for the modeled daily dose to be an underestimate. Exceptionally thick cloud encountered at noon is unlikely to have been present since sunrise, nor is it likely to persist for the remainder of the day. Thus when the ratio of model to clear-sky model is small, there is a negative bias in the model-to-measurement ratio.

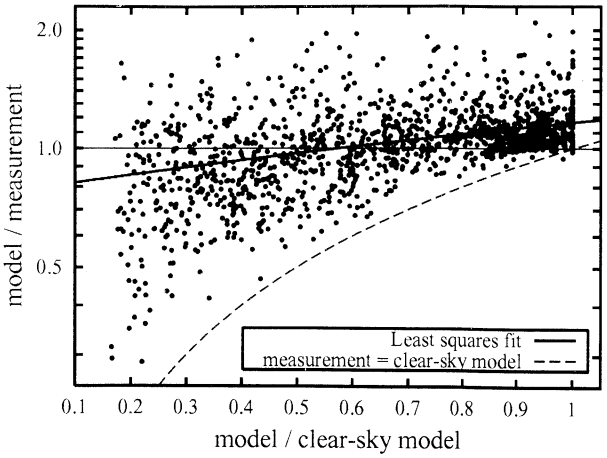

Figure 1. Ratio of model results to measured values of the daily erythemal dose at Garmisch-Partenkirchen. The model calculations are based on a single noontime measurement of the cloud optical depth, ozone column depth, and aerosol optical depth. Points to the right represent days on which there was little or no cloud present at noon. Points to the left represent days with thick cloud at noon.

To gauge the reliability of the model calculations, the clear-sky model (i.e., with the cloud optical depth set to zero) is also compared with the measurements. The data are plotted in Figure 2 as a function of the fraction of the day for which the Sun was visible. (This fraction is unity if the Sun remains unobscured for all spectral measurements from sunrise to sunset.) For the Sun to be visible does not necessarily imply a cloudless sky, but this parameter is easier to obtain reliably from the existing data. If the Sun remains visible for most of the day, the sky is likely to be largely free of cloud. Figure 2 shows that as the clear-sky situation is approached, the model and measurement come to agree to within 10%. Similar results are seen in the data for the Zugspitze, where there is also agreement to within 10% for the clear-sky days. The remaining scatter and any offset are the result of changes in the ozone column and the aerosol optical and cloud optical depths through the day, combined with errors in

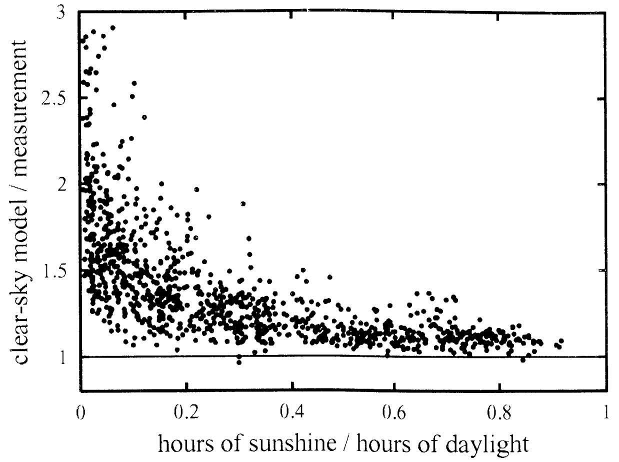

Figure 2. Ratio of clear-sky model results to measured values of the daily erythemal dose at Garmisch-Partenkirchen. The model calculations are based on a single noontime measurement of the ozone column depth and aerosol optical depth.

both the model and the measurements. Previous comparisons of the UVSPEC radiative transfer model with data from Garmisch-Partenkirchen show a similar level of agreement [*Mayer et al.*, 1997].

Data for the Zugspitze site are shown in Figure 3. There are fewer data points (about 700 compared with nearly 1500 in Figure 1), but a large amount of scatter about the line of equality can still be seen. The tendency for the model to give an underestimate when provided with a large cloud optical depth is more pronounced.

Some statistical parameters for the GAP and Zugspitze data shown in Figures 1 and 3 are presented in the left-hand side of Tables 1 and 2. Although the measurement sites are separated by more than 2000 m in altitude, which has a large impact on both the mean values of the daily erythemal dose and the frequency distribution of the data points, the scatter about the mean is similar at the two stations. Even with the large amount of scatter and a systematic component in the ratio of model to measurement, the mean values of modeled and measured doses are within a few percent of each other for both sites.

Under conditions of broken cloud or apparently homogeneous cloud layers, a ground-based measurement series made at a single point may show large changes in cloud optical depth, while the cloud optical depth returned from satellite measurements will be some spatial average of the local conditions. The average of a number of measurements may therefore be more representative. The time period chosen for this averaging should be large enough to capture the small-scale variations in cloud cover but not so long that any diurnal change becomes apparent. In other words, the scene seen by the satellite should remain constant over the averaging period. Convective cloud develops on a timescale of 10 to 15 min, and even a 3 m s^{-1} wind will move a cloud field more than 10 km over 1 hour. We therefore also tabulate the data for cases where the spectral measurements have been averaged over a period of a little over 1 hour about the midday spectrum. (Sixty-five minutes are allowed in order to include eight spectra in the sum; a spectral scan typically takes around 8 min to complete.) This averaging has a significant effect on the scatter for the daily doses, as expected, reducing the overall standard deviation from 24% to 19% for the case of GAP and from 23% to 17% for the Zugspitze. The frequency of extreme situations (large or small values of cloud optical depth) is reduced, and the magnitude of the systematic error is reduced slightly. The ratio of the total of modeled and measured daily doses is little changed, however.

The amount of scatter seen in the model-to-measurement ratios is also considerably reduced if, rather than comparing daily doses, the ratios of monthly doses are found. Results for the ratios of monthly means for the GAP and Zugspitze data are shown in Tables 3 and 4 and are also plotted for GAP in Figure 4. Changing from a single daily measurement to the average over 1 hour does not greatly alter the ratios of monthly doses.

4. Discussion

The scatter seen in the ratios of modeled to measured doses is introduced by diurnal changes in the local atmospheric conditions relative to the situation at midday. In practice, the errors present in the modeled values are due largely to the choice of the cloud optical depth. The cloud optical depth over any short period is unlikely to be representative of the average cloud conditions for the day.

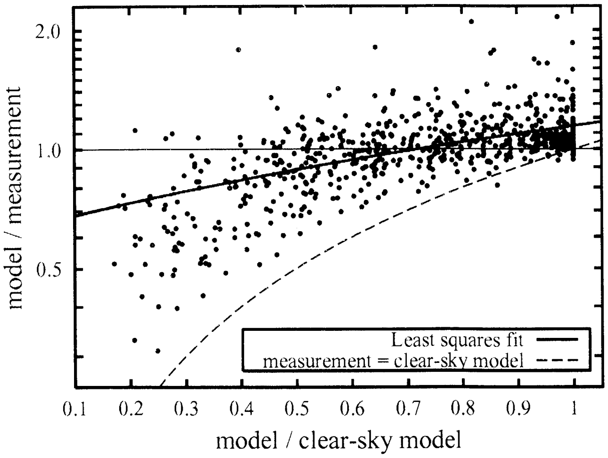

Figure 3. Ratio of model results to measured values of the daily erythemal dose at the Zugspitze. The model calculations are based on a single noontime measurement of the cloud optical depth, ozone column depth, and aerosol optical depth. Points to the right represent days on which there was little or no cloud present at noon. Points to the left represent days with thick cloud at noon.

Table 1. Erythemal Daily Dose at Garmisch-Partenkirchen

	Single Measurement					1 hour Average				
$D/D_{\max}$	n	$\overline{E}$	$\overline{\ln r}$	s.d.	%diff	n	$\overline{E}$	$\overline{\ln r}$	s.d.	%diff
0.10	0	0	0.00	0.00	0.0	0	0	0.00	0.00	0.0
0.20	73	899	-0.31	0.40	-37.0	64	721	-0.22	0.33	-26.5
0.30	136	901	-0.16	0.28	-21.4	124	870	-0.13	0.26	-18.7
0.40	148	1162	-0.14	0.24	-19.7	140	1037	-0.09	0.22	-13.7
0.50	133	1330	-0.03	0.24	-9.2	142	1262	-0.01	0.19	-4.7
0.60	138	1409	-0.01	0.23	-5.9	147	1313	0.02	0.17	-2.8
0.70	148	1197	0.08	0.16	5.4	169	1463	0.05	0.14	3.0
0.80	165	1101	0.12	0.15	12.0	196	1247	0.10	0.12	8.7
0.90	373	1879	0.08	0.11	7.9	384	1930	0.07	0.09	6.4
1.00	174	2739	0.13	0.14	12.8	122	2981	0.08	0.08	8.3
All points	1488	1524	0.01	0.24	1.6	1488	1524	0.02	0.19	1.8

Values are tabulated as a function of the modeled dose expressed as a fraction of the clear-sky value. Each bin contains data for points lying within ±0.05 of the value shown for $D/D_{\max}$; n is the number of days contained in each bin; $\overline{E} = \Sigma E_i/n$ is the mean measured daily dose (J/m^2) in that bin; $r = D/E$ is the ratio of model to measurement and $\overline{\ln r}$ is the mean of the logarithm of the ratio; s.d. is the standard deviation about that mean; %diff $= \Sigma\left[(D_i - E_i)/E_i\right]/n \times 100$ is the mean percentage difference between modeled and measured doses.

Changes in ozone column or aerosol optical depth through the day also introduce uncertainties in the estimated daily dose. An examination of the ozone column depths over Garmisch-Partenkirchen derived from measurements of the direct solar beam reveals that the noontime column usually differs from the day's average by less than 5% and rarely by more than 10%. Changes in the ozone column of such magnitudes alter the erythemal daily dose received at the ground by about 6% and 12%, respectively. However, the influence of changes in the ozone column will, in practice, be much less than this since the drift occurs over the course of a day, while most of the erythemal dose is received in a few hours about noon.

The variation in aerosol optical depth is greater, but the influence of aerosols on the surface irradiance is less. Typical differences between noontime values and the day's average introduce an uncertainty of less than 5% (summer) or 3% (winter) into the model calculations. Again, these figures represent upper limits. At the Zugspitze, the effect of aerosols is negligible.

The results of the model-to-measurement comparisons presented here suggest that satellite-derived maps of UV irradiance cannot be expected to produce accurate values of the daily dose if they rely on a single estimate of the cloud conditions. Because the radiative transfer model used here is forced to reproduce the observed noontime irradiance, the results are in some sense a best-case analysis. Additional uncertainties in the input parameters to the model will, in general, act to increase the scatter or systematic error. With only one estimate of the cloud optical depth, the typical de-

Table 2. Erythemal Daily Dose at the Zugspitze

	Single Measurement					1 hour Average				
$D/D_{\max}$	n	$\overline{E}$	$\overline{\ln r}$	s.d.	%diff	n	$\overline{E}$	$\overline{\ln r}$	s.d.	%diff
0.10	0	0	0.00	0.00	0.0	0	0	0.00	0.00	0.0
0.20	17	1882	-0.53	0.31	-46.3	12	1492	-0.35	0.23	-32.0
0.30	42	2183	-0.41	0.27	-36.8	31	1950	-0.31	0.24	-29.4
0.40	45	2203	-0.25	0.24	-25.5	47	1748	-0.17	0.19	-17.3
0.50	82	1885	-0.11	0.18	-13.3	80	1973	-0.10	0.18	-12.6
0.60	81	1577	-0.03	0.16	-5.6	75	1912	-0.01	0.11	-2.1
0.70	75	1868	0.02	0.14	0.5	98	1761	0.04	0.12	3.8
0.80	90	1777	0.07	0.13	7.3	103	2023	0.05	0.12	4.6
0.90	99	2013	0.11	0.14	14.2	104	2047	0.09	0.12	11.0
1.00	190	2428	0.09	0.11	10.0	171	2399	0.06	0.06	5.8
All points	721	2033	-0.02	0.23	-1.0	721	2033	-0.00	0.17	0.2

Table 3. Erythemal Monthly Dose at Garmisch-Partenkirchen

$D/D_{\max}$	n	$\overline{E}$	$\overline{\ln r}$	s.d.	%diff
0.10	0	0	0.00	0.00	0.0
0.20	0	0	0.00	0.00	0.0
0.30	0	0	0.00	0.00	0.0
0.40	0	0	0.00	0.00	0.0
0.50	5	767	0.07	0.03	4.2
0.60	433	1592	0.01	0.04	-0.3
0.70	777	1346	0.04	0.04	2.5
0.80	243	1984	0.04	0.04	3.3
0.90	0	0	0.00	0.00	0.0
1.00	0	0	0.00	0.00	0.0
All points	1458	1523	0.03	0.04	1.8

Only 1 hour averages are shown.

viation between model and measurement can therefore be expected to be worse than 20%. However, the same algorithm may give a good estimate of a longer-term quantity, such as the monthly dose, when the influence of the diurnal variability in cloud optical depth is reduced by averaging. A similar improvement may also be seen in estimates of the daily dose if averaged values for cloudiness are used. For example, ***Lubin et al.*** [1998] find uncertainties in the daily dose of around 5% when monthly averaged ERBE cloud data are used.

5. Conclusions

With access to reliable, long-term measurements, the expected uncertainty in model estimates of erythemal daily dose can be calculated in terms of the dose and cloud optical depth. When model calculations of the erythemal daily dose are made using only one value of ozone column, cloud optical depth and aerosol optical depth, the model estimate typically differs from the measured value of the daily dose by more than 20%. However, the mean of many estimates of erythemal daily dose is in good agreement with the measured mean, and the model produces a good estimate of the monthly dose.

Table 4. Erythemal Monthly Dose at the Zugspitze

$D/D_{\max}$	n	$\overline{E}$	$\overline{\ln r}$	s.d.	%diff
0.10	0	0	0.00	0.00	0.0
0.20	0	0	0.00	0.00	0.0
0.30	0	0	0.00	0.00	0.0
0.40	0	0	0.00	0.00	0.0
0.50	6	2930	0.03	0.02	2.7
0.60	173	2694	-0.02	0.04	-2.2
0.70	195	2463	-0.01	0.04	-1.0
0.80	223	1835	0.03	0.03	2.4
0.90	94	790	0.06	0.03	6.6
1.00	0	0	0.00	0.00	0.0
All points	691	2095	0.01	0.05	0.0

Only 1 hour averages are shown.

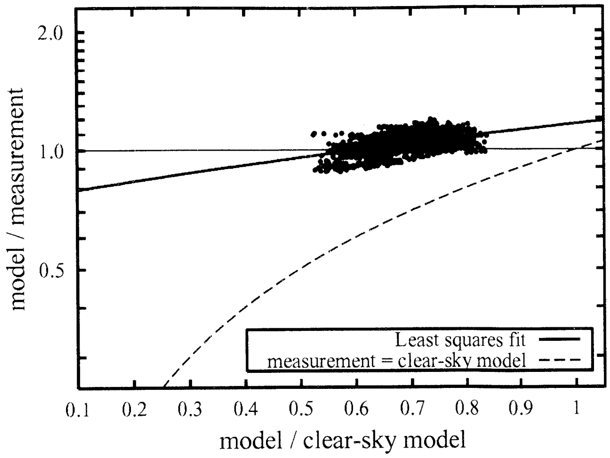

Figure 4. Ratio of model results to measured values of the monthly erythemal dose at Garmisch-Partenkirchen (running 31-day mean). The model calculations are based on the 1 hour average of the cloud optical depth, ozone column depth, and aerosol optical depth measured about noon each day.

Nevertheless, this is a best-case analysis, based on the assumption that the ozone column, cloud optical depth, and aerosol optical depth are correct at noon: any uncertainties in the satellite-derived values of the input parameters to the radiative transfer model will further increase the deviations between model results and measurement.

The results also show a systematic error that depends on the cloud optical depth. Correcting for this error may offer improvements in the accuracy of satellite maps of UV irradiance.

These results suggest that satellite-derived maps of UV irradiance cannot be expected to produce accurate values of the daily dose if they rely on a single estimate of the cloud conditions.

The high spatial and temporal variability of clouds puts severe constraints on the ability of satellites to estimate ground level irradiance. Satellite maps may be best suited to providing longer-term averages where the effects of such short-term variation are smoothed out. In this case, however, the stability of the satellite measurements must be guaranteed.

With sufficient high-resolution data and advanced model algorithms [***Meerkoetter et al.***, 1997] it may be possible to derive quantities such as the maximum daily irradiance or the dose received about noon with good accuracy. Algorithms that make use of multiple cloud measurements, such as Meteosat images [***Verdebout***, 2000], or ERBE data [***Lubin et al.***, 1998], can be applied more successfully to the calculation of daily doses, although the influence of a low spatial resolution must also be considered.

Nevertheless, the accuracy of satellite-based estimates of surface UV doses can only be verified by comparison with actual measurements. To quantify the uncertainties associated with satellite-derived maps of UV irradiance and to provide for the validation of the input parameters to the models on which the maps are based, there is a continuing need for high-accuracy spectral measurements of UV irradiance by carefully maintained ground-based instruments.

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