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Comparison of Models Used for UV Index Calculations

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ABSTRACT

Eighteen radiative transfer models in use for calculation of UV index are compared with respect to their results for more than 100 cloud-free atmospheres, which describe present, possible future and extreme conditions. The comparison includes six multiple-scattering spectral models, eight fast spectral models and four empirical models. Averages of the results of the six participating multiple-scattering spectral models are taken as a basis for assessment. The agreement among the multiple-scattering models is within ±0.5 UV index values for more than 80% of chosen atmospheric parameters. The fast spectral models have very different agreement, between ±1 and up to 12 UV index values. The results of the empirical models agree reasonably well with the reference models but only for the atmospheres for which they have been developed. The data to describe the atmospheric conditions, which are used for the comparison, together with the individual results of all participating models and model descriptions are available on the Internet: http://www.meteo.physik.uni-muenchen.de/strahlung/cost/.

INTRODUCTION

To inform the public of risks of overexposure to UV radiation, predicted values of UV index (1) are a useful tool. The UV index describes the erythemally weighted (2) skin-damaging solar UV radiation on a horizontal surface at the bottom of the atmosphere. Any forecast of UV index is based on the use of radiative transfer models in connection with predicted values of the relevant atmospheric parameters. Because different models are in use or proposed for this purpose, a cross calibration is required. Results of a comparison organized in the action "UVB forecast" in the European Cooperation in the field of Scientific and Technical research (COST) are given in this paper. The comparison is restricted to clear sky UV index, because this is a relevant quantity with respect to informing the public and because clouds and the methods to consider clouds are so variable that they must be discussed in a separate paper. Because the goal of the comparison was to test the usefulness of the models for UV index calculations, absolute deviations in UV index were compared instead of percentage deviations that would be more relevant to estimate the quality of the models. Besides deviations in the results, the comparison also showed deviations in the possibilities to run the models and in the calculation expenses that also are essential for an operational use of a model for UV index forecast. However, these points depend strongly on the computer facilities and thus computation times given here are only rough estimates.

MODELS USED FOR COMPARISON

The radiative transfer models used to calculate UV index are described briefly in the following. Detailed information on the models and the version that is used for the comparison is available on the Internet at the address given and directly by the users of the models. Each model is identified by a number. The models are classified into three groups with different complexity and thus different quality in

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the results, different resources required to run the models and different calculation time. The groups include multiple-scattering spectral models (models 1–6), fast spectral models (models 7–14) and empirical models that directly give spectrally integrated values (models 15–18).

Group 1: Multiple-scattering spectral models. The models in this group take into account multiple scattering, and multiple streams with different zenith angles are integrated to obtain irradiance. One UV index value requires a calculation time on the order of 10–100 s.

1. DISORT, discrete ordinate radiative transfer (3) used by the Belgian Institute for Space Aeronomy, Brussels. It is run with solar irradiance (4,5), aerosol with an Angstrom wavelength dependency of 1.0 and Elterman profile (6) and a U.S. Standard (7) ozone and temperature profile.

2. GOMETRAN (8), based on the finite-difference method, is developed and used by the Institute of Environmental Physics, University of Bremen. Solar and aerosol properties are taken from LOWTRAN7 (9) and ozone profiles from the MPI Mainz 2D model. Ozone absorption cross sections measured with the GOME flight model spectrometer (10) were used. Calculations were done with a pseudospherical approximation of the atmosphere and with a maximum of nine streams for fluxes.

3. SBDART, Santa Barbara DISORT, used by the Finnish Meteorological Institute Helsinki, is based on a discrete ordinate radiative transfer module (3) and a low atmospheric transmission model with solar data from LOWTRAN7 (9). Aerosol single scattering albedo is about 0.999 and not changed.

4. STAR, system for transfer of atmospheric radiation (11), is developed and used by the Meteorological Institute of the University Munich. It is based on matrix operator theory. The spectrum is supported at 19 wavelengths, solar irradiance (12) shifted to air wavelengths is used with ozone absorption cross sections (10) and spectral aerosol properties on the basis of different aerosol types (13).

5. UVSPEC (14), used by the Institute of Meteorology and Water Management Legionowo, is based on the discrete ordinate algorithm DISORT (3). Solar data are taken from WMO (15) and aerosol models from Shettle (16).

6. UVSPEC, used by Fraunhofer Institute Garmisch-Partenkirchen, is a modified version (17) of model 5, with correction for the spherical shape of the earth, solar irradiance (12) shifted to air wavelengths, aerosol as background volcanic conditions (6) with an Angstrom wavelength dependency of 1.3.

Group 2: Fast spectral models. This group covers a wide range of very different spectral models, from analytical functions up to model 10, TUV, which is capable of handling multiple scattering with more than two streams and that, however, run with two streams in its operational use for UV index calculations and is thus connected to the fast spectral models. The models in this group need a calculation time for one UV index value on the order of 0.1–10 s.

7. Diffey's model (18), used by the Institute of Medical Physics and Biostatistics Vienna, fits simple functions to measurements (19) at Davos at 1590 m above sea level for 16 wavelengths between 297.5 and 380 nm. Input parameters are zenith angle of the sun and ozone content. The model is used for sea level and with an increase of 16% per 1000 m elevation above sea level.

8. GREEN's model (20), used by the Danish Meteorological Institute Copenhagen, is a simplified parameterization scheme with analytical functions based on the results of more precise radiative transfer calculations (21,22). Aerosol single scattering albedo cannot be chosen; solar irradiance is taken from VanHoosier *et al.* (4).

9. GREEN's model (23), used by the Finnish Meteorological Institute Helsinki, is similar to model 8 but takes the original analytical specifications of extraterrestrial irradiance and ozone. Midlatitude ozone and aerosol distributions are assumed. Different aerosol absorption is not provided.

10. TUV, the tropospheric ultraviolet and visible radiative transfer code (24), in the version used by the Laboratory of Atmospheric Physics at the University of Thessaloniki, utilized a two-stream delta-scaled approximation to solve the radiative transfer equation. Model atmospheres used as input are taken from U.S. Standard (7).

11. SMARTS2, the simple model for the atmospheric radiative transfer of sunshine (25), used by the Department of Astronomy and Meteorology at the University of Barcelona, is a spectral solar irradiance model based on simple transmittance parameterization of relevant atmospheric parameters. Solar irradiance (25), profiles midlatitude summer (7) and aerosol with Angstrom wavelength dependency of 0.955 were used.

12. SMARTS2, used by the Finnish Meteorological Institute Helsinki, is similar to model 11, but with solar irradiance from SUSIM (4), U.S. Standard Atmosphere (7) and aerosol type Haze L (20).

13. SPCTRAL2 (26), used by the Department of Astronomy and Meteorology at the University of Barcelona, is a simple model for calculation of spectral solar irradiance in an improved version, with a resolution of 5 nm in the spectral range below 350 nm and of 10 nm above. Solar irradiance revised after Neckel and Labs (5) and aerosol with an Angstrom wavelength dependency of 1.0274.

14. SPCTRAL2 (26), also used by the Department of Astronomy and Meteorology at the University of Barcelona, is the same as model 13 but with solar irradiance and absorption coefficients from Gueymard (25).

Group 3: Empirical models. These models are direct parameterizations of measured UV index data, using analytical functions. Thus their calculation time for one UV index value is only on the order of milliseconds.

15. Canadian empirical model (27) for forecasting UV radiation, used by the Meteorological Institute of the University Munich, is an empirical relation that was fitted by choosing five coefficients to clear-sky UV irradiances measured at Toronto for summer conditions. Input parameters are zenith angle of the sun and ozone content.

16. Canadian empirical model, modified for cloud-free summer days for the territory of the Czech Republic (28) and used by the Czech Hydrometeorological Institute at Hradec Kralove. Input parameters are zenith angle of the sun and ozone content.

17. Swiss empirical model (29), developed and used by the Institute for Atmospheric Science ETH Zurich, is based on clear sky global UV-biometer measurements at Davos (1610 m above sea level), with an altitude adjustment using measurements at Davos and Payerne (490 m above sea level). Input parameters are zenith angle of the sun, ozone content, altitude and the condition of snow or no snow.

18. Canadian empirical model improved with respect to ozone content for less than 320 DU (W. R. Burrows, personal communication) is used by the Meteorological Institute at the University Munich.

ATMOSPHERIC DATA USED FOR COMPARISON

To make the comparison cogently, calculations are made for a wide range of present, possible future and extreme atmospheres as they occur at midlatitudes and during summer conditions. The complete list of 106 atmosphere and solar zenith angle combinations is available on the Internet. The atmospheres are assumed to be cloud free, as mentioned above, with the exception of subvisible cirrus in some cases. All internal parameters (*e.g.* spectral extraterrestrial solar irradiance, temperature-dependent absorption properties of ozone and other gases, spectral radiative properties of aerosols, height profiles) were taken as usual by each modeler. This means that all atmospheric parameters not mentioned below were used in a way decided by the contributors. The data, from which the atmospheres were compiled, are given in the following solar zenith angle: 15°, 30°, 60°, 80°; total ozone content: 150, 190, 285, 380 DU; ground level: sea level and 2000 m; aerosol particles: described by aerosol optical depth (aod) in combination with a certain single scattering albedo (ssa), both given at 340 nm with the following combinations (aod, ssa): (0.1, 1.0), (0.2, 1.0), (0.3, 0.98), (0.6, 0.92), (1.5, 0.88), additionally subvisible cirrus with aod = 0.1 between 8 and 10 km; surface albedo: 0.03, 0.5, 0.8, independent of wavelength, an assumption that is close to reality in the relevant spectral region.

RESULTS

The comparison was blind, with no chance for adjustment. For easier comparison, for each atmosphere a reference UV index is calculated as the arithmetic mean of the results of the multiple-scattering spectral models 1–6. These reference

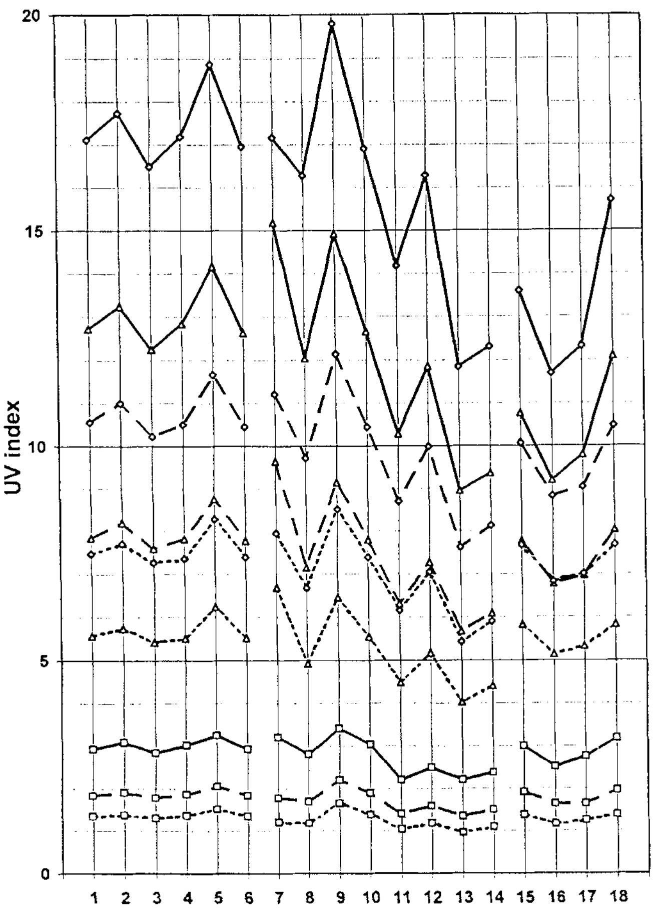

Figure 1. Ultraviolet index calculated with models 1–18 (see text for details) for solar zenith angles: 15° (◇), 30° (△) and 60° (□) and for total ozone: 190 DU (———), 285 DU (– – –) and 380 DU (········). Other parameters: surface at sea level, albedo: 0.03, aerosol with optical depth 0.6 and single scattering albedo 0.92 at 340 nm.

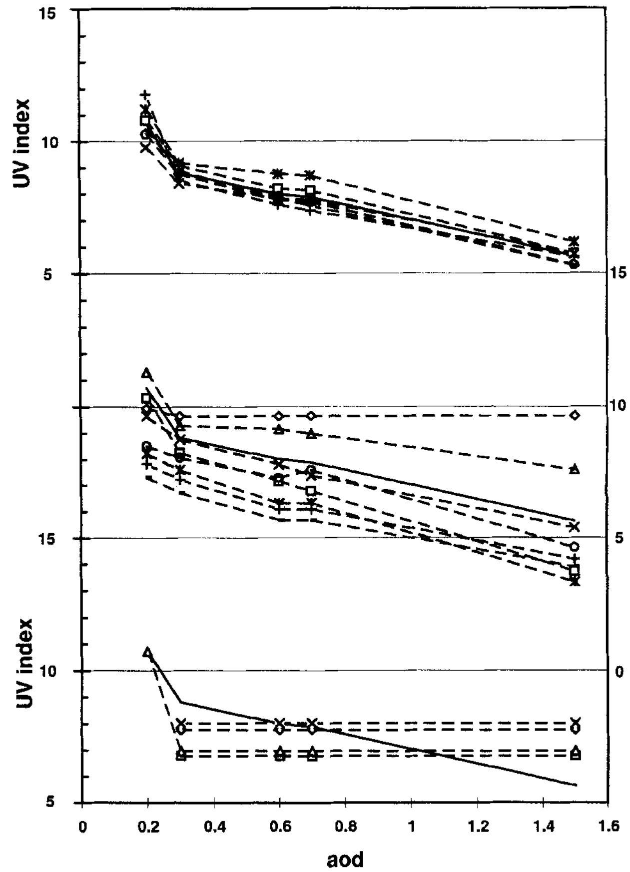

Figure 2. Ultraviolet index as function of aerosol load for solar zenith angle 30°, total ozone content 285 DU and albedo 0.03. The aod values indicate aerosol optical depth at 340 nm and are relevant also for the single scattering albedo, which is varied simultaneously (see text). For aod 0.3, 0.6 and 1.5, the other atmospheric properties are taken with values that are valid at sea level. For aod 0.2 all atmospheric parameter values are appropriate for a surface at 2000 m above sea level. Results of the three model groups are separated by 10 UV index values against each other. In each group values of reference UV index (arithmetic mean of results of models 1–6) are given as solid lines. Upper part, left axis, multiple-scattering models with symbols: 1, –; 2, □; 3, +; 4, ×; 5, ★; 6, ○; middle part, right axis, fast spectral models with symbols: 7, ◇; 8, □; 9, △; 10, ×; 11, ★; 12, ○; 13, –; 14, +; lower part, left axis, empirical models with symbols: 15, ◇; 16, □; 17, △; 18, ×.

values cannot be taken to be the truth, which is not really known. But, because the results of the multiple-scattering models are close together, these average values provide good expediency to compare all models. It will be shown later that model 5, in the version taken for the comparison, gives relatively high values compared to the other multiple-scattering models. Nevertheless, its results are taken into the averages, because it seems not to be justifiable to take one model out just because it does not agree with the others.

As an example of the results, Fig. 1 shows the UV index modeled for a wide range of ozone content and solar zenith angles. The results are given for each of the models described in the previous section with the three groups of model types separated. The results for each set of atmospheric conditions are connected by a line, which is given however only to guide the eye. All models clearly show the increase of UV index with decreasing ozone content and solar zenith angle. However, the consistency of the results is different. Relatively close together are, as expected, the results for the multiple-scattering spectral models. The remaining deviations result from the different calculation schemes and from different descriptions of spectral aerosol properties, of height profiles and of other internal parameters. The results of the fast spectral models are highly variable. The reasons are the very different ways of calculation and the different values that are used for the internal parameters. The empirical models do not consider different aerosol conditions, thus their agreement with the other results is somewhat arbitrary.

To illustrate the aerosol effect, Fig. 2 shows the UV index as a function of aerosol amount. The results are given here for a relatively low ozone value and solar zenith angle, because these conditions are essential to the public with respect to UV, but other combinations produce similar results. Figure 2 is divided into three parts for the three model groups, by shifting the results of each group by 10 UV index values against the others. To allow easier comparison, values of the reference UV index are given as solid lines in each of the three parts. The results for each model are connected by a dashed line, with different symbols. As the horizontal axis, the aod is used, but the values in each case stand for the combinations of optical depth and single scattering albedo, as given above. Aerosol optical depth values 0.3, 0.6 and 1.5 describe atmospheres valid for sea level with increasing pollution, *i.e.* increasing amount and more absorbing aerosol. The value aod = 0.2 is used for aerosol without absorption in combination with mountainous conditions (2000 m) with ozone amount and barometric pressure additionally reduced against the values used for sea level conditions. Thus, the connecting lines have a kink between 0.2 and 0.3. The additional subvisible cirrus (aod = 0.1) at mean turbidity 0.6 is given with an extra symbol (if modeled) at aod = 0.7. (For a complete parameter set of the jobs see the Internet page.)

In the upper part of Fig. 2 the good agreement between the multiple-scattering models can be seen again, but their slight deviations due to different model assumptions and internal parameters mentioned above is also visible. The deviations of the fast spectral models (middle part) are highly variable, both with respect to the absolute values and to the slope as a result of aerosol change. The results of model 7 do not alter with aerosol optical depth, because this model does not allow aerosol properties to vary. Therefore, the one result is used for all aerosol conditions, as it is common procedure. The same is valid for the empirical models, for which the coefficients in their relations are adapted to certain atmospheric conditions, under which the measurements are made. Their agreement with the reference UV index, shown in the lower part of the figure, is around an aod value of 0.6 at 340 nm for models 15 and 18 (Canadian models) and of 1.0 for model 16 (Czech modification). This is due to the local average conditions at the measuring sites. The Swiss model (17) is the only one of the empirical models that allows introduction of mountainous conditions. It agrees well for these situations but seems to be applicable for sea level only at relatively high turbidity. This, however, can be explained because the effects of molecular and aerosol scattering are combined within the parameterization coefficients, as usual in the empirical models, with the consequence that the extrapolation from high altitudes to sea level results in underestimating the UV index.

Figure 3 shows the effect of decreasing ozone on the UV index. The results again are separated by 10 UV index values for the three model types and with additionally the reference UV index as a solid line in each group for comparison. The general behavior of the results for different models and their deviations are as already discussed. For the fast spectral models, not only the absolute values but also the slopes of the curves are different, probably due to effects of neglected multiple scattering and different ozone absorption coefficients. For the empirical models, it is not the absolute values that should be compared (due to their dependence on aerosol content) but the slope. The increase in UV index with decreasing ozone is clearly lower for the empirical models 15–17 than for the reference UV index values. The cause may be that very low ozone contents occur too rarely to be used in the development of the coefficients. But because ozone content below 200 DU has now also been recorded at 50° northern geographical latitude, such values should be taken into account. This already has been done to a certain extent in the improved version of the Canadian model, which is run as model 18.

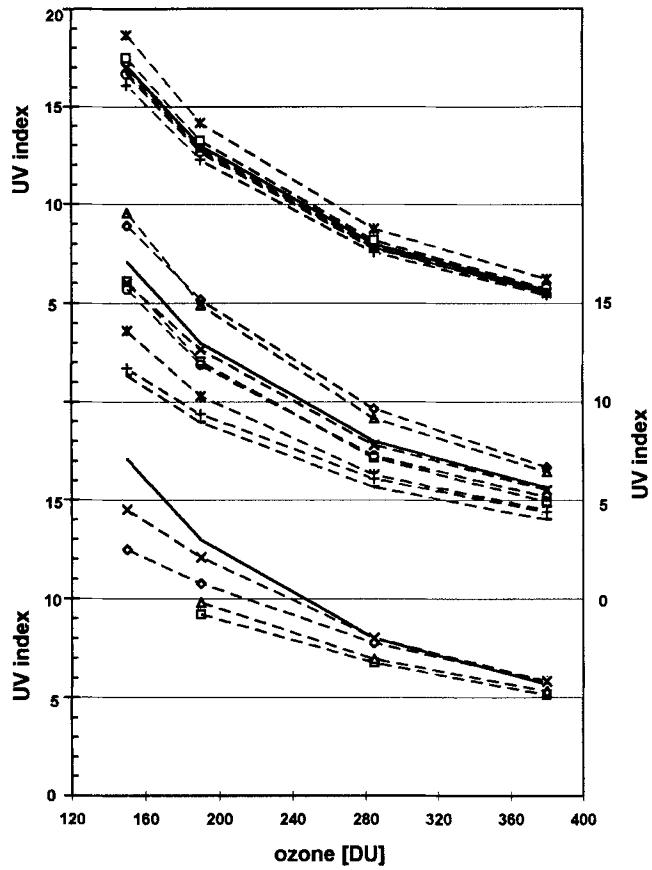

Figure 3. Ultraviolet index as a function of total ozone content for solar zenith angle 30°, aerosol with aod 0.6 and single scattering albedo 0.92 at 340 nm and albedo 0.03. Results of the three model groups are separated by 10 UV index values against each other. In each group values of the reference UV index are given as solid lines. Upper part, left axis, multiple-scattering models with symbols: 1, –; 2, □; 3, +; 4, ×; 5, ★; 6, ○; middle part, right axis, fast spectral models with symbols: 7, ◇; 8, □; 9, △; 10, ×; 11, ★; 12, ○; 13, –; 14, +; lower part, left axis, empirical models with symbols: 15, ◇; 16, □; 17, △; 18, ×.

To get a comparison of the models on a wide basis, the deviations of all the individual results against the reference UV index values are calculated. With respect to the goal of the comparison, which is the usefulness of the models for UV index forecast, absolute differences are analyzed, not relative deviations. Figure 4 shows histograms of the frequency of absolute UV differences in 1 UV index steps. Not shown are deviations for models 7 and 15–18 because they do not take into account aerosol variations. Thus, a comparison would lead to deviations that strongly depend on the atmospheric conditions taken for comparison. The results for all 106 atmospheric conditions are used as a basis for the histograms, but for some models that did not use all atmospheres the histogram is based on a reduced amount of data.

For the multiple-scattering models (upper part of the figure), the deviations against the reference UV index are dominantly around 0, with a slight shift to −1. This can be explained by the relatively high results of model 5 that shifts the reference UV index, the arithmetic mean of models 1–6, to higher values. The dominant positive deviations of model 5, up to UV index values of 3, can be seen in Fig. 4

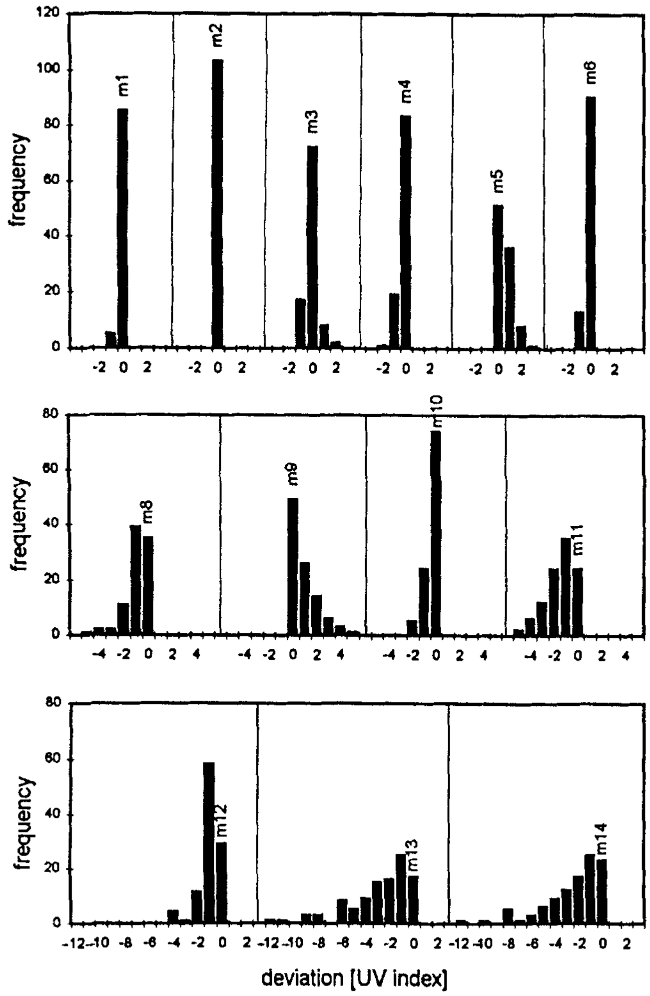

Figure 4. Histograms of absolute UV index deviations as differences between modeled and reference UV index. Model number is given in each case at value 0. Columns contain ±0.5 UV index values around the value marked.

and already in Figs. 1–3. The reason is the description of aerosol in model 5. This has been improved meanwhile, but the changes are not taken into account because a possibility of adjustment was given only for factual mistakes in the input data.

The deviations for the fast spectral models (middle and lower part of the figure) range from narrow histograms to high underestimations of UV index up to −12. The good agreement of model 10, also slightly shifted toward −1, shows that this model is comparable to multiple-scattering models, although it is not taken into this group for the reasons mentioned above. The broad histograms of the other fast spectral models document the different numerical and internal parameter effects, including extraterrestrial sun, that shift the results.

Because the deviations are given in absolute values they are dominated by atmospheric conditions resulting in high UV index. That is, the highest deviations result from the atmospheres with snow, very low ozone and from the mountainous conditions at high solar zenith angles. In the cases of low UV index, even high percentage deviations do not result in absolute deviations outside the range ± 0.5. Thus, as an additional result, the percentage deviations of models 13 and 14 are concentrated within a small range close to −30%, nearly independent of solar zenith angle.

CONCLUSIONS

For scientific purposes and for public use, data must be of known quality and adequate for their intended use. Thus, in this paper different models are compared with respect to their quality for UV index forecast. Comparison of modeled results with observations is essential and will be done as a next step. However, in this case, additional uncertainties may arise from the quality of the description of the actual atmospheric parameters (30). Thus, for the model agreement presented here, modeled reference values are also used for comparison.

The results of all multiple-scattering models used here agree very well, with ±0.5 UV index value in more than 80% of the wide set of atmospheres taken into account. This agreement must be estimated taking into account that modeled UV indices depend not only on the numerical quality of the models but also on the internal constants used (*e.g.* solar irradiance, absorption properties of gases, properties of aerosols, vertical profiles) that were taken individually by each modeler. The fast spectral models show very different agreement, from the similar level of ±1 UV index value up to differences of more than 10 UV index values. However, the absolute deviations shown in Fig. 4 are dominated by conditions with high UV index. Thus, the results shown here should not be used to decide on the absolute quality of the models but only with respect to UV index forecast.

The empirical models give good results but only for the atmospheric conditions for which they have been developed. Moreover, they can partly be improved with respect to very low ozone values. If these models are taken for conditions with different aerosol properties, they must be carefully adjusted. It is an open question whether the possibility to take into account aerosol is really an advantage. Aerosol properties are not predicted in most cases and thus are not a parameter that can actually be varied. Nevertheless, the possibility to change aerosol properties as model input could improve results because it allows considerations of known differences between air mass types, rural and urban conditions, sea shore and country site. It must, however, be kept in mind that all improvements are only sensible for the clear sky UV index. In the case of clouds their uncertainties will dominate.

As mentioned, the question "what is the most useful model for UV index forecasts" cannot be answered on the basis of the quality of the results only. What is adequate for the intended use, must also be considered for this decision. This is at least calculation time and model effort that are of course much higher for the multiple-scattering than for the empirical models. However, the multiple-scattering models, which have the advantage of being more flexible, among others with respect to additional receiver geometries (*e.g.* ocular exposure), additional trace gases and anisotropic reflection (*e.g.* sea shore), could be improved by reduction of calculation time on the basis of reduced spectral resolution.

As a certain "electronic test-bench," the data to describe the atmospheric conditions that are used for the comparison together with the individual results of all models that participated, the model descriptions and the e-mail addresses of the contributors are available on the Internet: http://www.meteo.physik.uni-muenchen.de/strahlung/cost/.

Our comparison describes only the current state of the art, valid for the time of the comparison and the models run therein. Different contributors using the same model came out with different results. This shows that the comparison alone cannot be used to judge a model. Moreover, all models are undergoing permanent improvement, both of the models themselves and of their application. Even the results presented here already have provided reasons for improvements.

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