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RADIATIVE MODELS FOR THE EVALUATION OF THE UV RADIATION AT THE GROUND

P. Koepke*
Meteorologisches Institut, Ludwig-Maximilians-Universität München, Theresienstr. 33, 80333 Munich, Germany

The variety of radiative models for solar UV radiation is discussed. For the evaluation of measured UV radiation at the ground the basic problem is the availability of actual values of the atmospheric parameters that influence the UV radiation. The largest uncertainties are due to clouds and aerosol, which are highly variable. In the case of tilted receivers, like the human skin for most orientations, and for conditions like a street canyon or tree shadow, besides the classical radiative transfer in the atmosphere additional modelling is necessary.

INTRODUCTION

Modelling solar UV radiation is a tool for the evaluation of measured UV radiation in the ground. Moreover, it is the only way to get UV radiation data for conditions where measurements are impossible or do not exist in a proper way. This includes UV in the future, in the past, at places without measurements and the conversion of satellite data into radiation at the ground. In addition, modelling is the easiest way for sensitivity studies in a wide range of applications as UV radiation for human health, radiometer design or environmental influences. Thus different radiative models for solar UV at the ground have been developed and are available.

UV RADIATION QUANTITIES

Spectral weighting

Ultraviolet radiation, i.e. radiation at wavelengths below 400 nm, has many biological and photochemical effects due to the large energy of its photons and specific absorption properties of the reacting molecules. The spectral variable emission of the Sun and the highly wavelength-dependent processes in the atmosphere result in UV radiation at the ground, which has spectral values that vary in a range of more than one million, even for fixed atmospheric conditions. Thus modelling should be made spectrally. However, since solar UV radiation is emitted simultaneously at all wavelengths, spectral integrated values are needed for all applications. The effects of UV radiation, on the other hand, are strongly wavelength dependent, described by a spectral action spectrum $s_{\mathrm{proc}}(\lambda)$ for a specific process. Thus the effective radiation for a specific process is given by spectrally integrated values E_{proc}, where the illuminating spectral radiation $E(\lambda)$ is weighted by $s_{\mathrm{proc}}(\lambda)$.

The most essential biological action spectrum is the erythemal weighting spectrum[1], which describes the sensitivity of the human skin to sunburn. It is generally used to determine the UV index (UVI)[2], a dimensionless figure to give an easily usable value for the effective solar UV irradiance.

If spectral values of UV radiation are known for specific atmospheric conditions, which needs high effort for measuring but less for modelling, every action spectrum can easily be taken into account.

Radiances, irradiances and radiation on tilted surfaces

The radiation quantity in the UV, which usually is measured and modelled, is the irradiance on a horizontally oriented surface. It is the integral over the cosine weighted radiances of the Sun and the sky from the upper hemisphere. This ‘global radiation’ is generally used in atmospheric radiation measurements, since it is independent of the solar azimuth and of photons that are directly reflected from the ground.

For many purposes, however, the UV irradiance on a tilted surface is of interest, which may strongly differ from that on the horizontal receiver[3,4]. This is especially valid for the human skin, which only has very few horizontal parts and is often vertical, like the forehead[5]. Also plants, plants in rows, buildings and mountains in general are not horizontally orientated[6]. To get UV irradiances on tilted surfaces from measurements, a very high effort is necessary[7]. The reason is that even for fixed atmospheric conditions the irradiance changes with elevation and azimuth angles of the receiver and thus many measurements must be made.

Here modelling is of great advantage, since it is possible to model the radiances of the sky and the

*Corresponding author: peter.koepke@lmu.de

Sun with high angular resolution. To get the irradiance on a surface which is tilted, the radiances from the Sun and the sky now have to be integrated over the hemisphere that is valid for the tilted surface. Thus the radiances have to be weighted with the cosine of the zenith angle to the actual surface normal. Moreover, the photons directly reflected from the ground to the receiver must be considered(8). Modelling spectral radiances, and integrating both over the wavelength and over the angles that encompass the hemisphere, enables one to determine biologically effective UV radiation for all possible conditions.

UV RADIATIVE TRANSFER MODELS

General aspects

For modelling of the UV radiation at the ground, the radiative transfer equation (RTE) has to be solved, which cannot be done analytically. Different models have been developed for this purpose, with different quality(9,10) and, as a consequence, with different computational effort.

Simple models, which give the erythemal weighted irradiance as a function of solar elevation and ozone content directly via parametrisation, are fast but rather uncertain. However, they are no longer needed to be used because of the dramatic increase of computer performance.

One-dimensional models

State-of-the-art are one-dimensional spectral multiple scattering models (e.g. DISORT, SBDART, STAR, UVspec), which model the radiation field for one atmosphere in the order of seconds or less. They divide the atmosphere into thin layers with fixed properties and change these properties only vertically (one dimension)(11–14). Different mathematical methods are used to solve the RTE (discrete ordinate, matrix operator) and combined with algorithms that determine the values of spectral extinction and absorption coefficients for each layer, which are the quantities used in the RTE. The quantities have to be determined on the basis of the amount and the properties of the variable atmospheric constituents. These models calculate the radiation spectrally and thus can consider any biological weighting. Since the models calculate radiances, their results can be used to determine the irradiances, e.g. the UVI, on horizontal and also on tilted surfaces.

For the human environment it is of interest to consider artificial or natural shadow(15,16). This can be modelled using the radiance fields and take into account sky obstructions. A model by Hess and Koepke(17), e.g. calculates the UV brightness of a given object that obstructs the sky or the Sun—like mountains, a building, a tree or a sunscreen—and changes the radiances from the sky behind the object to the radiances that are reflected at the object. With the new radiance field again the irradiance on any tilted receiver can be modelled.

Three-dimensional models

The UV models with highest quality are three-dimensional, which mean that they allow one to consider different optical properties not only vertically, but also horizontally(13).Thus these models can calculate UV radiation fields, e.g. for conditions with scattered clouds or with variable surface albedo, and also with sky obstructions. However, such models even nowadays need long computation times. Moreover, for actual conditions it is nearly impossible to get precise information for a cloud field in all three dimensions, which should be used as input parameters. Thus three-dimensional models are very good for sensitivity studies, but not for routine modelling and the evaluation of the UV radiation at the ground.

ATMOSPHERIC PARAMETERS

General aspects

Ultraviolet radiation at the ground, as it is solar radiation that has passed the atmosphere, depends on the irradiance of the extraterrestrial Sun, the Earth–Sun distance, the solar elevation, which is responsible for the photons' pathlength through the atmosphere, and on the scattering and absorption processes due to the atmospheric parameters, which are strongly wavelength dependent. If all these parameters are known for an actual case, all radiation quantities can be modelled with high quality, since the radiative transfer codes have very low uncertainties with respect to the mathematical procedure.

The parameter with the strongest influence, the highest variability, is the solar elevation. It changes the radiation from values negligible during night up to the high values at noon and is also responsible for the variability of UV irradiance as function of the geographical latitude and the day in the year. However, solar elevation is perfectly known from the position on Earth and time and thus can be taken into account for modelling with correct values. The same holds for the Earth–Sun distance and, besides minor temporal variations, for the spectral extraterrestrial solar irradiance.

The atmospheric and ground properties, however, are more or less variable and often for an actual case not all information that is needed for precise modelling is available(18,19). A review of the UV effects of all atmospheric and surface parameters can be found in Koepke *et al.*[20]; in the following only a short description is given.

Ozone and aerosol

Ozone strongly absorbs the UV, especially at the short wavelengths, which are dominating in the erythemal weighted UV, i.e. in the UVI. Thus the reduction in the ozone layer thickness during the last decades has often been directly connected to an increase in the UV radiation.

Aerosol particles interact with solar radiation by absorption and scattering, generally increasing with decreasing wavelength. The effect depends on the total aerosol amount, but is variable with the aerosol type, due to variable mixing of aerosol components. They have different size distributions and complex refractive indices and thus variable scattering functions and single scattering albedo. Due to the high variability of the aerosol properties, often in actual cases the complete aerosol information is not available.

Ground albedo and altitude

The albedo of the ground influences the UV irradiance on a horizontal surface via atmospheric backscattering of reflected photons. However most surface types have a low albedo in the UV and only snow reflects strongly. Thus in the case of snow or regional snow cover adequate values must be taken into account. Here again, a problem arises for modelling, since the regional snow properties, which influence the UVI, often only can be estimated.

The altitude of the ground has influence on the UV radiation due to the reduced amount of air molecules and ozone above the receiver and thus reduced protection against the extraterrestrial Sun. This 'background altitude effect'[21] can be modelled easily. However with increasing altitude often also the ground changes from meadow to stones or snow and also the amount and type of aerosol may vary.

Clouds

Cloud properties are highly variable, in all aspects like height, geometrical and optical thickness, microphysics, and distribution. Stratus cloud types can be modelled as layers even in a one-dimensional model. For conditions with scattered clouds, however, additional considerations are necessary.

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Actual atmospheric parameters

The different atmospheric parameters have variable influence in the UV, due to the unequal strength of their effects and variable amount and properties[20]. Moreover, in an actual case, as it is the case of the evaluation of UV measurements, the accuracy and availability of the atmospheric values are limited[18,19].

Ozone data are available from satellite measurements. In general, the percentage uncertainty of the ozone layer thickness results in the same uncertainty of the UVI. The actual barometric pressure as a function of the known altitude of a measuring site can easily be taken into account; the meteorological variations of the pressure has negligible effect.

For an increase of the surface albedo of 10 % the UVI for cloudless conditions increases in the order of 5 %[22]. As mentioned, the albedo effect is essential only in the case of snow. Nevertheless, here different effects have to be taken into account: the regional albedo, which influences the global irradiance from the sky via backscattering, and the local albedo, which directly contributes to the irradiance on a tilted surface. The local albedo can be described by typical values for snow, as it is given in the literature with values up to 80 %. For the regional snow albedo, however, the effects of trees, streets and other areas free of snow and the snow conditions have to be taken into account. This can be done, e.g. via a combination of the snow age and the snow height[22].

Highly variable in amount and properties are the aerosol particles. Also the amount of information on actual aerosol is very different, starting with climatic means as an assumption, over visibility, measured aerosol optical depth in the visible or in the UV, up to additional knowledge of the single scattering albedo. Thus the uncertainty of the UV irradiance due to uncertain aerosol properties may occur up to 30 %[23].

The largest uncertainty in actual UV results from the clouds, because typically not even their optical depth is known. The microphysical properties, in contrast, are less essential. Highly variable is the cloud effect for scattered clouds. Here the cloud amount is important, but even more the position of clouds relative to the Sun. In case of the direction of the Sun is obstructed, which means shadow, the UV irradiance is strongly reduced. In cases with the Sun being free and clouds in its vicinity, reflected radiation may even increase the total irradiance to values that are higher than those for the same atmospheric conditions without clouds[24].

Clouds in one-dimensional models

To model the effect of clouds with a one-dimensional model, often the cloud effects are taken into account by cloud modification factors (CMF). These are the ratio of the irradiance under cloudy conditions against the irradiance for a hypothetical atmosphere with the same conditions, but without clouds. The latter can easily be modelled, and the resulting cloud-free irradiance shifted to the irradiance for cloudy conditions by multiplication with the CMF.

Such CMFs are available for different descriptions of the clouds, like cloud amount or cloud amount for different cloud layers[25]. By far the most suitable way to get actual CMFs is to use a measured effect of the clouds in the visible spectral range (CMF_{VIS}) and transmit this cloud effect to the UV[25,26]. CMF_{VIS} can be derived from solar global radiation measurements, which are often available. This method takes into account all effects of the actual cloudiness, like optical thickness, amount and position of the clouds. The transformation of the CMF_{VIS} to the CMF_{UV} depends on the solar elevation[26].

CONCLUSION

Different radiative models for the evaluation of the UV radiation at the ground are available. The quality of the mathematical procedure to solve the RTE in general is high. Thus the uncertainties of modelled UV radiation predominantly results from the accuracy and availability of the data to describe the actual atmospheric, surface and environmental properties.

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