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Modelling UV irradiances on arbitrarily oriented surfaces: effects of sky obstructions

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Abstract

A method is presented to calculate UV irradiances on inclined surfaces that additionally takes into account the influence of sky obstructions caused by obstacles such as mountains, houses, trees, or umbrellas. Thus the method allows calculating the impact of UV radiation on biological systems, such as for instance the human skin or eye, in any natural or artificial environment. The method, a combination of radiation models, is explained and the correctness of its results is demonstrated. The effect of a natural skyline is shown for an Alpine ski area, where the UV irradiance even on a horizontal surface may increase due to reflection at snow by more than 10%. In contrast in a street canyon the irradiance on a horizontal surface is reduced down to 30% in shadow and to about 75% for a position in the sun.

1 Introduction

UV radiation is a part of the solar spectrum with high impact on biological systems. With respect to human health, there are two conflictive effects: on the one hand, UV radiation is able to cause health damages reaching from sun burn to skin cancer and on the other hand, the UV radiation is essential to produce vitamin D. For both effects the UV irradiance on the human skin is the basic source and thus this quantity has to be considered, namely under the conditions of the human environment. However, the UV quantity that usually is measured (Bais et al., 2007; Seckmeyer et al., 2007), derived from satellite (Arola et al., 2002; Verdebout, 2004) or forecasted (Staiger and Koepke, 2005) is the irradiance of the undisturbed upper hemisphere on a horizontal surface. Thus this quantity, in general given as UVI (WMO, 1994), is well known in its dependence on solar elevation and atmospheric composition, and thus as function of time and position on Earth (Bais et al., 2007). In contrast, the influence of the orientation of the skin relative to the sun has hardly been considered systematically, but rather in case studies (McKenzie et al., 1997; Parisi and Kimlin, 1999; Webb, 1999; Philipona

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et al., 2001; Koepke and Mech, 2005). The same holds for the modification of UV radiation due to objects in the human surroundings such as walls, trees, umbrellas or other obstructions of parts of the sky (Kimlin a. Parisi, 1999; Turnbull and Parisi, 2003; Grifoni et al., 2005; Gao et al., 2002; Schween and Koepke, 2005). UV irradiances measured on different positions of the body of persons moving in their environment exist (Knuschke et al., 2007) but for a limited amount of conditions, not least due to the problems with volunteers. Thus, for the purpose of determining systematically the influence of objects in the surroundings of humans on their UV radiation dose, we developed the method described in this paper that takes into account both the orientation of the skin and obstructions of the sky.

2 The model

Our method is a combination of existing models, joined together by a new program. The base of all is the radiative transfer model STAR (Ruggaber at al., 1994; Koepke et al., 2006) which yields UV radiances at each point of the sky, depending on solar elevation, atmospheric composition and ground conditions. Next, the model Radoninc (Mech and Koepke, 2004) uses such a radiance field for given atmospheric and ground conditions to calculate UV irradiances on surfaces which may be inclined with any zenith and azimuth angle, the latter relative to the sun's position. Finally, our new program Skop deals with any objects obstructing parts of the sky. It uses the Radoninc radiances to calculate the UV-brightness of an object, includes the radiances reflected from this object into the original radiance field and then again starts Radoninc, now with the modified radiance field as input, to determine the UV irradiances on arbitrarily tilted surfaces.

This approach allows one to introduce three dimensional effects into a one dimensional radiative transfer calculation.

The method is based on solar radiation with high spectral resolution, which can be integrated to the solar radiation that is relevant for a specific UV process by using a biological action spectrum. With respect to the UV effects on humans, in the following the erythemal weighting spectrum has been used (CIE1987) and the results are given as UV-index (UVI) not only for the conditions of a horizontal receiver (WMO, 1994) but for all orientations as a physical quantity to describe UV irradiances (WMO, 1997).

In the current study, we model UVI on inclined surfaces with inclination zenith angles *ZA* ranging from 0° to 180° in steps of 10°, and with inclination azimuth angles *AA* with a 10° resolution from 0° to 350°, except for the zenith angles larger than 90° where a 30° interval is applied.

2.1 STAR

STAR (System for Transfer of atmospheric Radiation) is a matrix operator radiative transfer model for the UV spectral range (Ruggaber et al., 1994; Koepke et al., 2006) which took part in several model comparison activities (Koepke et al., 1998; DeBacker et al., 2001).

STAR calculates monochromatic radiances for any zenith and azimuth angle of the sky. These radiances depend on the solar elevation and azimuth angle, the state of the atmosphere and the ground properties. The atmosphere is described by height resolved fields of the radiative properties of aerosols, clouds and gases such as ozone and SO_2. From the radiances the angularly integrated quantities irradiance and actinic flux are calculated and the values can be spectrally integrated taking into account arbitrary action spectra.

For the purposes described here, we calculate complete hemispherical radiance fields with a 1° resolution in zenith and azimuth angle. The spectral resolution is 5 nm between 280 nm and 400 nm. Clouds are not considered in this study, but may easily be added.

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2.2 Radoninc

Radoninc (Radiation on Inclined Surfaces) (Mech and Koepke, 2004) uses spectral radiance fields to calculate the irradiances on arbitrarily oriented surfaces and additionally performs the spectrally weighted integration using action spectra. To take into account the effects of the albedo of the ground around the receiver which influences the irradiances on the tilted surface due to the photons directly reflected from the ground to this surface, a local albedo is taken that may differ from the regional albedo which is used for the calculation of the radiation coming from the sky. Under the aspect that the absorption of the UV radiation in the skin, which finally gives the relevant dose, has to be considered locally, the skin, or other biological surfaces, are divided into small areas which are assumed to be tilted, but flat. Thus in any case the radiation on the tilted surface is modelled as irradiance, taking into account the cosine weighting with respect to the local perpendicular orientation. For the erythemal weighted irradiances the results are given as UVI, also for tilted surfaces.

2.3 Skop

The newly developed program Skop (Sky Obstruction Program) organizes a sequence of Radoninc model runs by providing the appropriate input data. It creates input files for Radoninc, reads result files of STAR and Radoninc, creates modified radiance fields, and starts the final Radoninc runs. The procedure is described more detailed in the following:

a) We start with a STAR model run for the date, place, and atmospheric conditions in question. This model run yields a complete hemispheric spectrally resolved UV radiance field, using the regional albedo.

b) Next, we select the properties of the object which is obstructing parts of the sky. (Such an object may be a wall or a tree, beginning at the ground, or an umbrella or similar with an obstruction only of upper parts of the sky. Receiver in the following

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means the human skin or the measurement device whose UV exposure will be calculated, with respect to the angles assumed as a point in the middle of the radiation field.):

- size and shape of the object in terms of its angular dimensions in zenith and azimuth, as seen from the position of the receiver (Fig. 1). The object is defined by an arbitrary number of points, given by zenith/azimuth angle combinations.
- zenith and azimuth orientation of the object relative to the sun, under the assumption that the object is flat.
- spectrally resolved UV-reflectivity, -transmissivity, and -emissivity of the object.

c) The spectral irradiances impinging on this object are calculated by Radoninc using the radiance field from a).

d) The radiation emerging from the object is calculated in terms of:

- the radiances reflected at the object, calculated from the irradiances on the object (cf. c)), assuming Lambertian reflectance
- the transmitted part of the sky radiances behind the object is added if the object is transparent
- the emitted radiances are added if the object consists of a light source,

e) The radiation coming from the object is included into the original radiance field by replacing those sky radiances that are obstructed by the object by the radiances determined previously via d).

f) A second Radoninc run now yields the spectral irradiances on the inclined surfaces caused by the radiance field which has been modified by the object defined in b) and the spectrally weighted irradiances like UVI.

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It is possible to apply steps b) to e) to several objects, and to include all of them in the original radiance field at the same time. In such cases, the UV brightness of each such object is determined individually. But it has to be noted that no interactions between several objects are considered in the current version of the model. That means, there are no shadows from one object falling on the other, and there is also no reflection between such objects. We consider these effects to be of minor importance because of the usually low reflectance in the UV.

2.4 Modification factors

The main purpose of this paper is the description of the change of the UVI on tilted surfaces in a human environment compared to the UVI on a horizontal surface without any obstructions, as it is given in general as discussed in the introduction. Thus, we present modification factors that allow the use of such UVI on the horizontal surface without sky obstruction, for the determination of the desired UVI on a tilted surface under the specific obstruction conditions.

The change of the UVI on a tilted surface for conditions without sky obstructions has been given as the Tilt Modification Factor (Mech and Koepke, 2004), TMF, taking into account the zenith angle *ZA* of the tilted surface and its azimuth angle *AA* against sun's azimuth with $\mathrm{UVI_{hor}}$ the UVI on the horizontal surface

$$\mathrm{TMF}(ZA, AA)=\mathrm{UVI}(ZA, AA)/\mathrm{UVI_{hor}} \tag{1}$$

Here no sky obstructions have been taken into account, neither for the tilted nor for the horizontally oriented surface. Now, in this paper, we introduce effects of sky obstructions by the so called Sky Obstruction and Tilt Modification Factor, SOTMF,

$$\mathrm{SOTMF}(ZA, AA)=\mathrm{UVI_{so}}(ZA, AA)/\mathrm{UVI_{hor}} \tag{2}$$

Here $\mathrm{UVI_{so}}(ZA,AA)$, UVI with the lower index so for sky obstruction, is given for the specific conditions with sky obstruction for a receiver surface oriented towards *ZA*

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and *AA*. UVIhor here also, as always, is the UVI for conditions without sky obstruction on the horizontal surface. Thus for conditions without sky obstruction applies SOTMF(*ZA*,*AA*)=TMF(*ZA*,*AA*).

If the receiver surface is not tilted, but oriented horizontally, this is given by *ZA*=0 and *AA*=0 (The latter is of no relevance, but given to fulfil the nomenclature) and SOTMF(0,0) is called $\mathrm{SOTMF_{hor}}$. This describes the modification of the UVI on a horizontal receiver due to sky obstruction:

$$\mathrm{SOTMF_{hor}}=\mathrm{UVI_{so}}(0,0)/\mathrm{UVI_{hor}} \quad (3)$$

If a quantitiy is presented without azimuth angle, e.g. UVI(*ZA*) or SOTMF(*ZA*), it describes the average over all azimuth angles.

2.5 Model verification and validation

In order to verify the model results, i.e. to check that the model works consistently and correctly, a number of consistency tests have been performed. One of the results is shown in Fig. 2. We assume as obstruction a vertical wall with a UV reflectivity of 10%, in a cloud free environment with 330 DU ozone, mean aerosol turbidity, local and regional albedo 3%. The receiver is a vertically oriented surface that rotates around its vertical axis, positioned directly in front of the wall. The $\mathrm{UVI_{so}}$(90,*AA*) on this vertical receiver surface is calculated with a resolution of 10° in azimuth. The position of the sun is in the south (azimuth=0°), the solar elevation angle is 41°.

Figure 2 shows SOTMF(90,*AA*) as function of *AA* modelled for 4 different walls, each oriented towards one of the four cardinal directions. Additionally shown is SOTMF(90,*AA*) for conditions without any wall, no sky obstruction, i.e. TMF(90,*AA*). If the receiver surface is oriented exactly in the same direction as the wall, the radiation falling on the surface is not influenced by the wall at all, and thus SOTMF=TMF. If the receiver is looking exactly towards the wall, it only gets radiation reflected from the wall, which is 10% of the radiation impinging on the wall, because of the wall's Lambertian reflectivity of 10%. In the East and West wall cases, the highest UVI occur slightly

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beside the direct South direction, as the receiver is turned away from the wall, which is dark because it doesn't get radiation from the direct beam.

The validation of the model, which assures that the model is well suited to reproduce atmospheric and environmental conditions, has been achieved by comparing appropriate model calculations with UVI measurements using broad-band erythemal weighting radiometers.

One example of the comparisons is given in Fig. 3. Here we show measured and modelled $SOTMF_{hor}$ for receivers in different distance to a south-west oriented vertical wall on the roof of the Meteorological Institute in Munich. This wall has a geometric extent of 2.2 m above the instrument and a width of 8 m. Its UV reflectivity in the broad bright parts was measured to be about 15%. The measurement took place on 13 April 2007 between 09:02 and 09:27 GMT (Greenwich Mean Time). The UVI measuring device was first situated 1.07 m in front of the wall, and then subsequently moved away from the wall to measure in distances of 2.07 m, 4.07 m and 7.77 m. Then, it was placed exactly in front of the wall (at a distance of 0.07 m), and then a second series of measurements with distances of 1.07, 2.07, 4.07 and 7.77 m started. At the same time, measurements on top of this wall took place, which represent undisturbed conditions without sky line obstruction.

Figure 3 shows that modelled and measured $SOTMF_{hor}$ differ only by a few percent. This is in the order of the measurement quality. The small systematic decrease of the measured UVI with increasing distance can be explained from the relevant albedo of the wall which changes a bit with the distance, since the wall has dark brown stripes which contribution to the reflected radiation decreases with reduced distance of the receiver to the wall

3 Results

To demonstrate the model's different possibilities we show two examples. The first describes the effect of the sky line in a natural environment, and the second that in an

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urban street canyon.

3.1 Effect of mountain sky line

The glacier on mount Zugspitze in Germany is situated at an altitude of 2600 m, about 300 m below the summit. Thus the sky line is up to an elevation of more than 30°. In this area stands the observatory Schneefernerhaus (UFS), where the Meteorological Institute performs long-term UV radiation measurements on horizontal surfaces. The measurement platform has a similar skyline as parts of the glacier, i.e. a certain part of the sky is always obstructed by the mountains. So it is of interest to determine the impact of this sky line on the UVI, especially in cases when the mountains are covered by snow. For this purpose, the angular course of the sky line has been determined from panorama photographs. These data have been included in our model. The sky line is composed by 72 rectangles, each with a width of 5° in azimuth *AA*, with different height (*ZA*) and a slope of 45 ° in zenith in each case. It is shown in Fig. 4 with the violet colour. In this figure the outer angle describes the azimuth *AA*, where 0° is south, and the distance to the center the zenith angle *ZA*, with 0° in the center and 90° at the border. The circles show *ZA*=30° and 60°.

The colours in Fig. 4 represent the situation as modelled for solar zenith angle 25.4° and solar azimuth 336° (south at 0°/360°), as valid for 21 June at 12:00 GMT. A rainbow colour scale, reaching from violet (low values) to red (high values) is used to show UV radiances at 315 nm, non-linearly distributed between 0.024 and 0.412 ($W\,m^{-2}\,sr^{-1}\,nm^{-1}$). It is clearly to be seen that the mountains are dark (violet to blue), but are brightest (blue) in the region opposite the sun's position, since the radiation here impinges nearly perpendicularly on the surface. In other mountain regions the angle of incidence is larger, resulting in lower reflected UV brightness.

In Fig. 5, the calculated diurnal variation of the $SOTMF_{hor}$ is shown for 21 June for three assumptions of the mountain albedo. Albedos of 5% and 18% are assumed for summer conditions. The 18% value has been measured to be the albedo of rocks around Schneefernerhaus (Bucars, 2006), and 5% is a value taken from literature

(Blumthaler and Ambach, 1988). Secondly, an albedo of 80% has been chosen to model snow conditions (Grenfell and Warren, 1994). Of course, it is not very likely to have a snow cover on 21 June, even not on mount Zugspitze, but this calculation is intended to show the sensitivity of the UVI on the albedo of the obstructing parts of the horizon for a wide range of solar zenith angles. The regional albedo in all cases is assumed to be 3%, indicating no snow in the surrounding wide area below the mountain. In case of the two lower albedo values, the $SOTMF_{hor}$ is a bit less than 1, i.e. the sky line reduces the UVI. This reduction is less than 5% between 07:00 a.m. and 04:00 p.m., when the absolute UVI is larger than 2, and thus within the range of the measurement uncertainties. But it is of course a systematic deviation. In case of snow cover, the mountains are brighter than the parts of the sky that they obstruct, and thus the UVI becomes up to 10% larger than without the sky obstruction. Therefore, the UVI measurements at Schneefernerhaus are not significantly disturbed by the sky line in summer, but may be up to 10% too high during winter. This is valid for a horizontally oriented receiver. For the skin of people on the glacier (tilted surfaces) the effect of snow can be much larger, up to 70% (Philipona et al., 2001; Koepke and Mech, 2005).

3.2 Street canyon

A large number of people spend most of their time in cities. Even if they leave the house, their gain of UV radiation is always reduced compared to an open environment, because the buildings obstruct parts of the sky considerably.

As an example of a typical urban street canyon, Türkenstraße in Munich is used. The angular extent of the houses has been estimated from a series of photographs (Fig. 6). The width of the street is 18 m and the typical height of the 5 store houses is also about 18 m. The resulting sky line, as used in the subsequent model calculations, varies with $ZA=90^{\circ}$ as a maximum for the azimuths where the street meets the horizon and minimum of ZA of 32° for the position perpendicular to the observer. The street is oriented by about 15° in SE-NW direction, as indicated in Fig. 6.

The modelled variations of UVI(ZA), UVI_{so}(ZA) and SOTMF(ZA) are shown in

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Fig. 7a, b, c as function of time for a cloud free summer day (21 June), under the assumption that people are moving, i.e. the values are averaged over the orientation azimuth angles of the receiver surfaces. The values are given for fixed hours only, linearly connected to guide the eye.

Figure 7a shows UVI(*ZA*), i.e. under the assumption of no obstructions, and the typical daily course can be seen with increasing irradiance with decreasing solar zenith angle and a maximum at local noon at about 11:15 GMT. The UVI(*ZA*) decrease with increasing slope of the receiver, *ZA*, because due to this effect the contribution of sun and sky is reduced and replaced by lower radiances reflected at the ground.

Figure 7b shows the $UVI_{so}(ZA)$ for a receiver in the center of the street canyon, i.e. taking into account the obstruction of sky and sun due to the buildings. All values are reduced considerably against the conditions with free horizon, with a big step between 9 and 10, when the sun begins to shine into the street and the receiver comes out of shadow. The asymmetry against local noon results from the SE-NW direction of the street, with the consequence that the sun shines parallel to the street at about 12:00 GMT.

The effect of the obstructions is presented in Fig. 7c as SOTMF(*ZA*). During morning and afternoon, when the street is in shadow, SOTMF is less than 30%. But even without shadow, during the time when the sun shines into the street, the $UVI_{so}(ZA)$ is reduced to 75% or less compared to the undisturbed conditions. The effect is lowest for the surfaces looking towards the sky, i.e. for the small *ZA*. For *ZA* larger than 50° the SOTMF(*ZA*) decrease strongly with increasing *ZA*, and goes down to values of 20% for sunny and 10% for shadow conditions for vertically oriented surfaces (ZA=90°) like parts of the skin. For the conditions with shadow at the receiver position, the obstruction effect increases with decreasing solar zenith angle, because of reducing the relative contribution of the unobstructed sky near the zenith to the global irradiance. The SOTMF(*ZA*) are nearly constant as long as the sun is shining into the street. This effect results from the irradiance on the buildings, which increases when it changes from grazing near noon to more perpendicular illumination in the afternoon.

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4 Conclusions

A method has been presented which allows one to model spectral weighted UV irradiances for all applications relevant with respect to biological systems. The irradiances can be determined on arbitrarily inclined surfaces and in presence of any obstructions of parts of the sky, with and without shadow.

We are able to perform calculations for all atmospheric conditions given by solar zenith and azimuth angle, surface albedo, surface topography, and atmospheric constituents such as ozone concentration, aerosol amount and composition, and clouds. The resulting UV irradiances may be weighted by any spectral response function. Furthermore, the surfaces where the radiation is impinging on, may be tilted by any angle in zenith and azimuth directions. This feature allows to model the UV irradiance for the human skin or eye. The new feature of the method is the consideration of obstacles obstructing parts of the sky and thus reducing the diffuse UV radiation, and also the direct solar beam, i.e. shadow. These obstructions may be of any size and shape, and they may have individual reflection, transmission and emission properties. So it is possible to model as well the effects of objects forming a skyline such as walls, trees, street canyons or mountains, as effects of shadows caused by umbrellas, awnings or trees. The results can be used to modify values of UVI for undisturbed conditions and horizontal receivers as they usually are available.

The model will be compared with measurements made for a wide range of radiation environments and be used for sensitivity studies, to give modification factors valid for average conditions.

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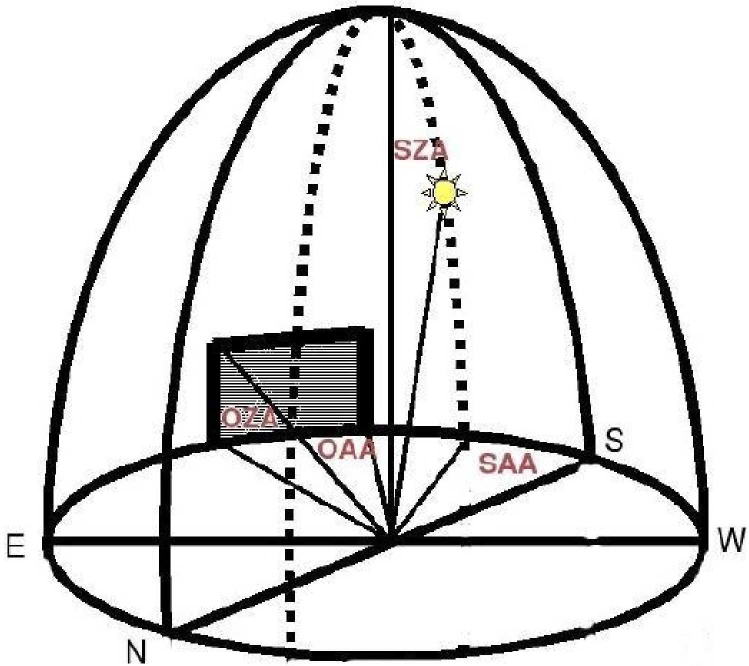

Fig. 1. Definitions of zenith and azimuth angles of sun position (*SZA* and *SAA*) and object extent (*OZA* and *OAA*). The orientation of the receiver, given with *ZA* and *AA* of its surface normal, is not shown in this figure.

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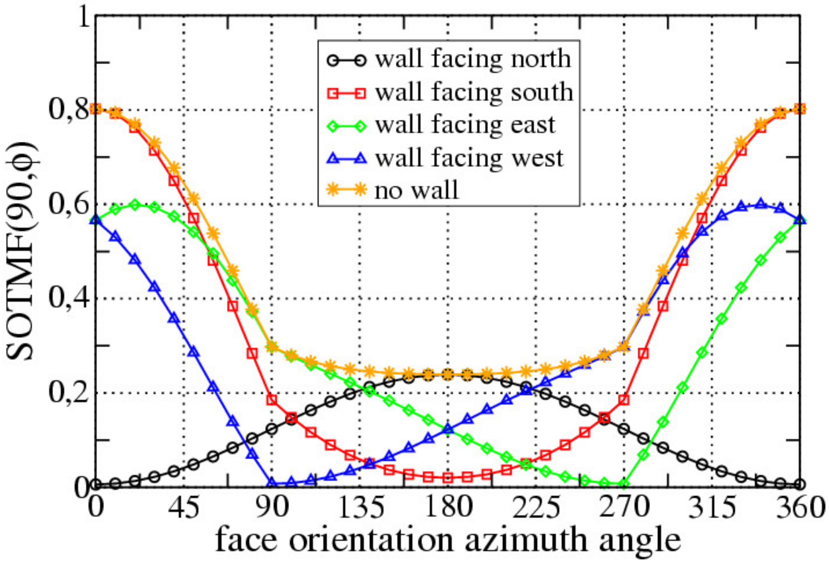

Fig. 2. Sky obstruction and tilt modification factors (SOTMF), calculated for four vertical walls facing north (black, azimuth=180°), south (red, azimuth=0°), east (green, azimuth=90°), and west (blue, azimuth=270°) respectively. The receiver surfaces are also oriented vertically (*ZA*=90), but rotated around the vertical axis, and thus having different face orientation azimuth angles *f*. They are positioned directly in front of the walls such that the walls cover exactly half of the sky.

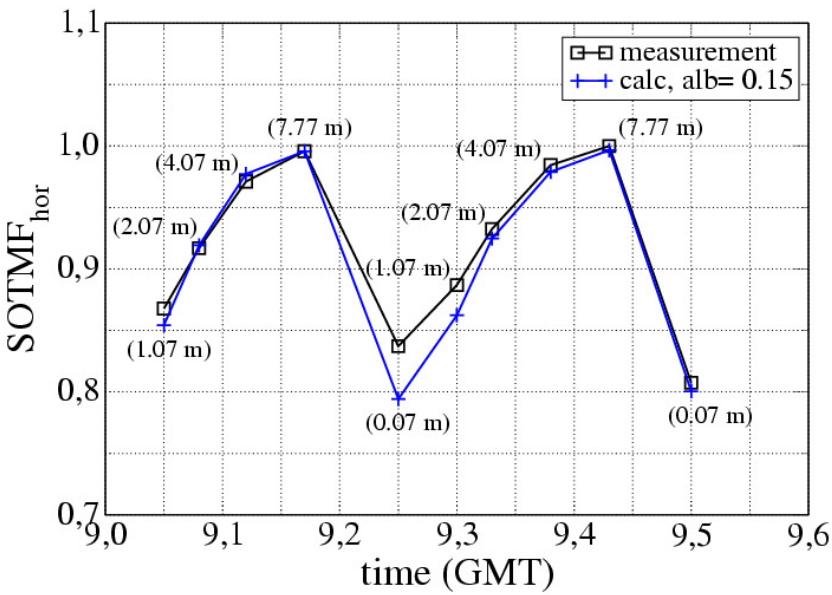

Fig. 3. Sky obstruction and tilt modification factors (SOTMF), derived from measurements in front of a wall with different distances to the wall (the distances are indicated), and corresponding model calculations.

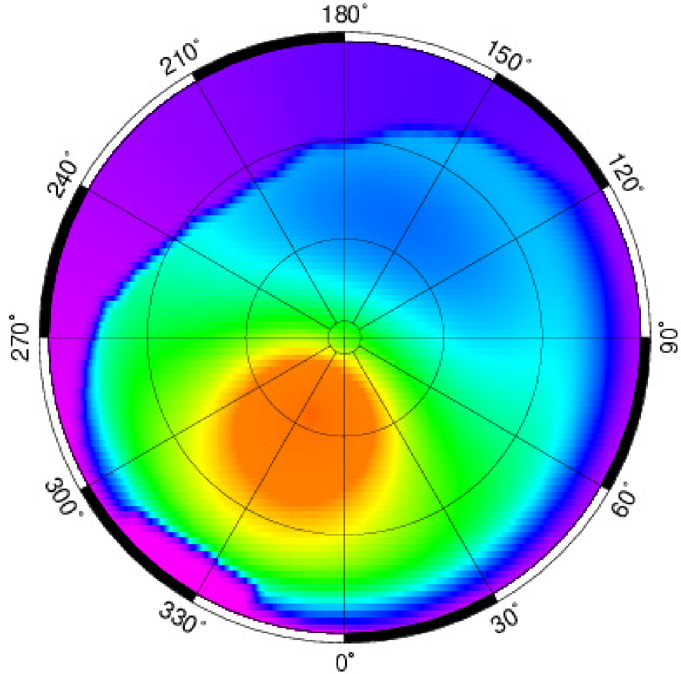

Fig. 4. Calculated UV radiances (315 nm) at Schneefernerhaus at 21 June, 13:00 GMT with sky line as seen from the measurement platform. The figure shows an intermediate result of our model, representing step e) from Sect. 2.3. The mountains have been included in the original STAR-radiance field, accounting as well for their angular extent as for their UV brightness determined by Radoninc , see steps b)–d). The rainbow colour scale represents radiances, non-linearly distributed between 0.024 (violet) and 0.412 (red) ($W\,m^{-2}\,sr^{-1}\,nm^{-1}$).

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UV irradiances: effects of sky obstructions

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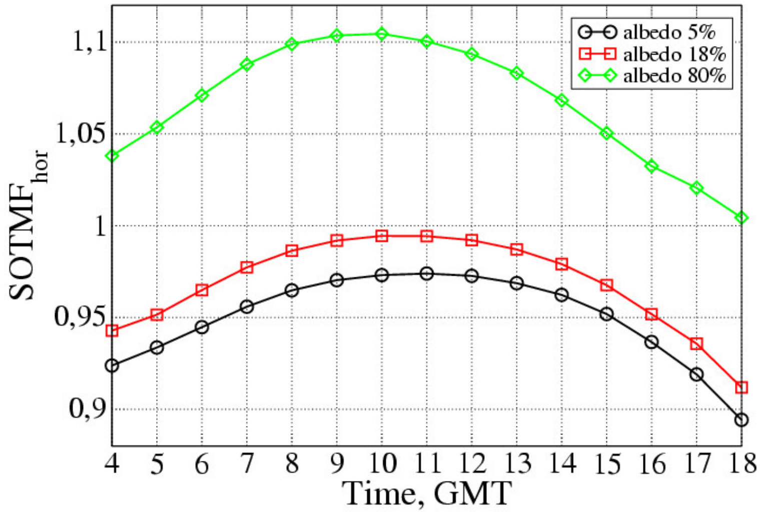

Fig. 5. Sky obstruction and tilt modification factors (SOTMF) on horizontal surfaces for the diurnal variation at Schneefernerhaus on 21 June. Three values of local surface albedo are considered for the region around Schneefernerhaus.

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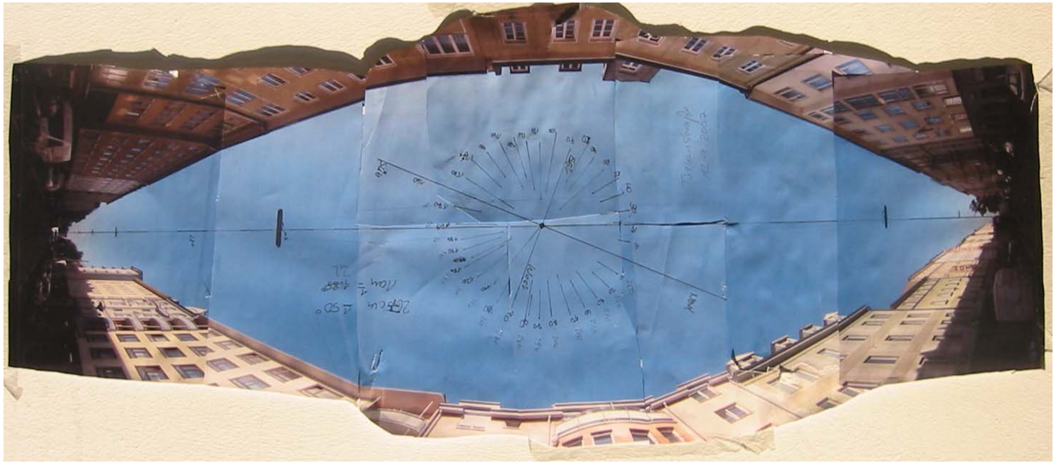

Fig. 6. Collage of photographs for representation of the street canyon Türkenstraße in Munich. The street is oriented from SE to NW. Its width is 18 m and the typical height of the houses is also about 18 m.

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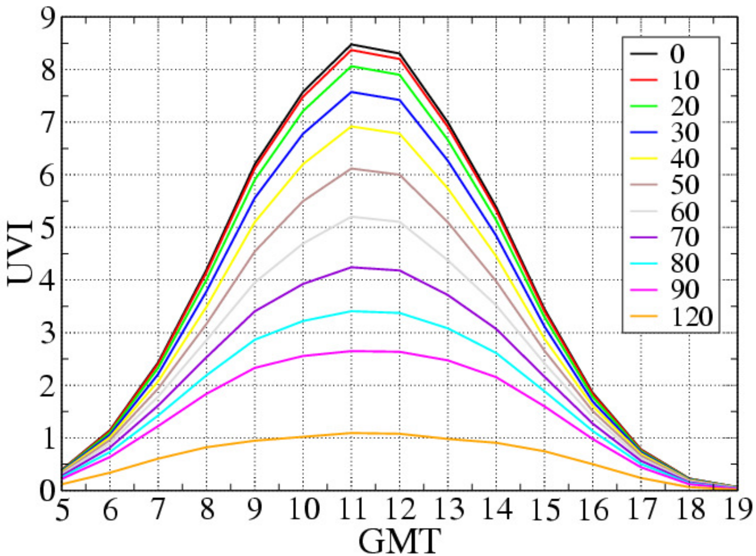

Fig. 7a. UVI(*ZA*) on inclined surfaces, averaged over all orientation azimuth angles. Zenith angles are given as lines with different colours. These data are modelled for Munich under the assumption of climatological mean values of the atmospheric conditions in June. No sky line effects are considered.

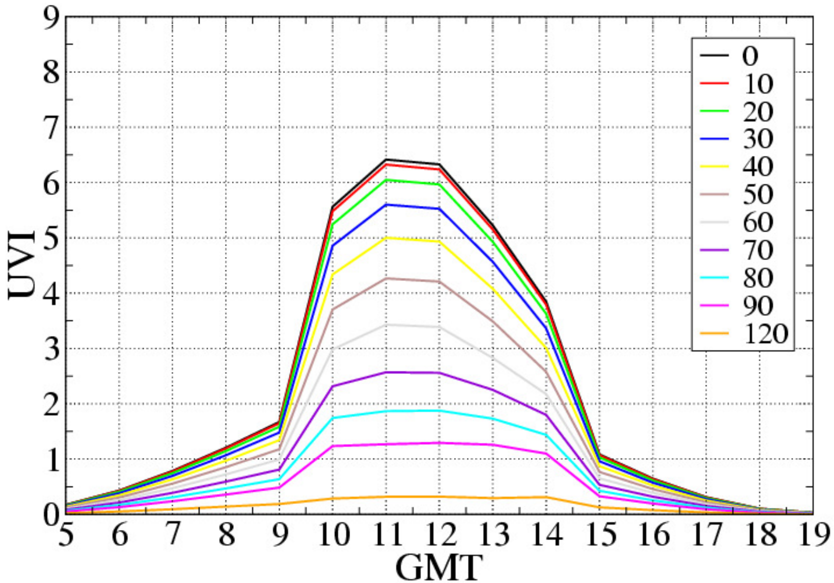

Fig. 7b. As Fig. 7a, but in the middle of the street canyon from Fig. 6.

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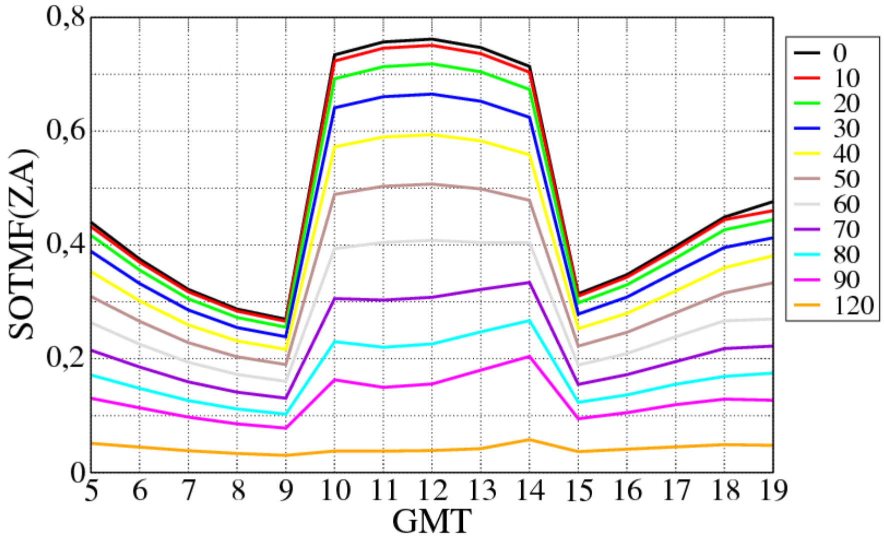

Fig. 7c. SOTMF calculated from Fig. 7a and 7b. These modification factors show the effect of a street canyon on UVI on inclined surfaces, averaged over all orientation azimuth angles. Zenith angles are given as lines with different colours. These data are modelled for Munich under the assumption of climatological mean values of the atmospheric conditions in June.