Int J Biometeorol (2004) 49:18–25
DOI 10.1007/s00484-004-0211-9

ORIGINAL ARTICLE

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Visualization of UV exposure of the human body based on data from a scanning UV-measuring system

Received: 24 September 2003 / Revised: 13 April 2004 / Accepted: 22 April 2004 / Published online: 30 June 2004

Abstract In general, measurements of UV radition are related to horizontal surfaces, as in the case of the internationally standardized and applied UV index, for example. In order to obtain more relevant information on UV exposure of humans the new measuring system ASCARATIS (Angle SCAnning RAdiometer for determination of erythemally weighted irradiance on TIlted Surfaces) was developed and built. Three systems of ASCARATIS have been in operation at different locations in Bavaria for 3 years, providing erythemally weighted UV irradiation data for 27 differently inclined surfaces every 2 min. On the basis of these data virtual three-dimensional models of the human body surface consisting of about 20,000 triangles could be created and each of these triangles coloured according to its UV irradiation. This allowed the UV exposure of the human body to be visualized for any kind of body posture and spatial orientation on the basis of real measuring data. The results of the UV measurements on inclined surfaces have shown that measuring UV radiation on horizontal surfaces, as done routinely worldwide, often underestimates the UV exposure of the human skin. Especially at times of the day or year with low solar elevations the UV exposure of parts of the human skin can be many times higher than that of the horizontal surface. Examples of three-dimensional modelling of the human UV irradiation are shown for different times of the day and year, altitudes above sea level, body postures and genders. In these examples the UV "hotspots" can be detected and, among other things, used to inform and educate the public about UV radiation.

Keywords UV radiation · Solar radiation · Sun · UV Index · UV exposure · Inclined surfaces

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Introduction

Ultraviolet (UV) radiation (wavelengths in the biosphere 290–400 nm) is one of the environmental agents most relevant to health and has been proven as such in a multitude of epidemiological studies. UV radiation contributes to the ageing of the skin (Fisher et al. 2002) and, in different ways, to the generation of skin cancers like basal cell and squamous cell carcinoma and malignant melanoma (Blum und Volkenandt 2002). Primarily because of behavioral changes resulting in higher UV-exposure of the skin to UV the incidence rates of skin cancer have increased dramatically in many industrialized countries with a larger Caucasian population. Currently for example the annual incidence rate for basalioma and squamous cell carcinoma in Germany is about 70 per 100,000 population (it was 15 in 1970) and for melanoma 14 per 100,000 citizens (3 in 1970) (Blum und Volkenandt 2002). In the USA the corresponding data for melanoma currently is 19 cases per 100,000 citizens (Geller and Annas 2003). In the 1960s the risk for melanoma in the USA was about six times lower. Part of the increase in incidences of skin cancers certainly can be ascribed to a longer life expectancy and also to a higher skin cancer awareness amongst physicians and consequently an increased diagnosis rate. Besides these factors, UV-exposure as a result of both UV radiation levels and behavior plays an important role.

UV exposure of the human skin depends on the distribution of direct and diffuse UV radiation and the spatial

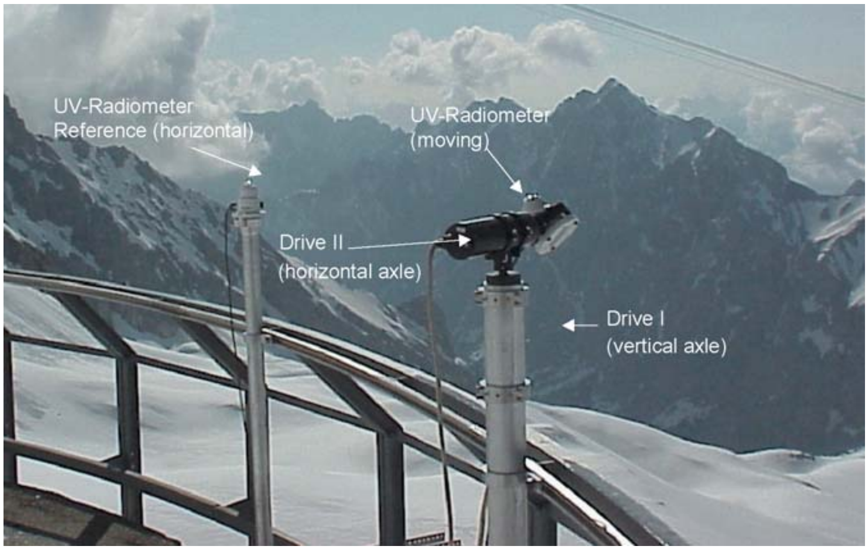

Fig. 1 Measuring system ASCARATIS at Mount Zugspitze (2,800 m above sea level)

orientation of the human surfaces (body posture). Especially for the direct UV radiation, the angle of orientation of the skin is very important. The UV distribution and the total level of the UV radiation depend on solar elevation (geographical latitude, time of year and time of day), total ozone, aerosols, clouds, elevation above sea level, orography and albedo. For vertical sufaces of the human body (most surfaces when standing or walking) the UV albedo of the ground can play an important role in the total UV exposure.

Most of the routine measurements of UV radiation worldwide are related to horizontal surfaces, as in the case of the internationally standardized and applied UV index for example (WMO 1997). Such sensors can only represent the UV irradiation of horizontal surfaces of the human body, e.g. for a person standing upright this means the top of the head, shoulders and the upper sides of the feet. In order to obtain more relevant information with respect to UV exposure of the whole human body, and eventually for particular parts of the skin also, there is a need for quantitative data on radiation fluxes in the directions of typically oriented surfaces of the human body (Webb et al. 1999; Schauberger 1990). In order to measure these fluxes the new measuring system ASCARATIS (Angle SCAnning RAdiometer for the determination of erythemally weighted irradiance on TILted Surfaces) was developed and built (Oppenrieder et al. 2003). The results of 3 years of measurements with ASCARATIS are the basis for visualizations of the UV exposure of the human body shown in this paper.

Materials and methods

ASCARATIS consists of two radiometers (Kipp & Zonen UV-S-E-T) measuring UV radiation in an erythemally weighted way. The internationally standardized UV index (UVI) (WMO 1997) can therefore be directly calculated from the measuring signal (voltage). One radiometer is mounted horizontally, the other can be oriented to any direction by means of two computer-controlled stepper motors. In contrast to the WMO definition of UVI as the erythemally weighted solar irradiation of a horizontal surface, in this paper we also use the UVI approach for the irradiation of inclined surfaces. Detailed information on the mechanical construction of the ASCARATIS system is published in Seefeldner et al. (2004). The orientable radiometer is programmed to scan 27 positions—12 positions with vertical orientation and 30° steps of azimuth angle, 12 positions with an inclination of 45° also with 30° azimuth steps, one position facing the zenith, one position facing the nadir and one position facing the sun. Both simultaneously measuring radiometers are mounted about 2 m from each other, each 1.7 m above the ground (see Fig. 1). The data are stored on a computer, which communicates once per day via modem with a server located at the Meteorological Institute of Ludwig-Maximilians University. Detailed information on the measuring procedure of ASCARATIS, calibration of the UV radiation sensors and data acquisition and processing is published in Oppenrieder et al. (2003, 2004).

In total, three ASCARATIS measuring units have been in operation simultaneously at five different locations: Mount Zugspitze (latitude 47° 25′ north, longitude 10° 59′ east, 2,800 m above sea level), Hohenpeissenberg (latitude 47° 48′ north, longitude 11°1′ east, 1000 m.a.s.l.), Munich centre and periphery (latitude 48° 8′ north, longitude 11°34′ east, 500 m a.s.l.) and Würzburg (latitude 49° 56′ north, longitude 9° 58′ east, 200 m a.s.l.). The locations were chosen to cover the whole range of altitudes in Bavaria and to be able to detect the effects of urban pollution on UV radiation. The routine measurements started in autumn 2000 on Mount Zugspitze and have been extended to other locations since spring 2001. Currently the UVI data sets (27 directions every 2 min from sunrise to sunset) for more than 2,000 measuring days are stored in a database. The data comprise all seasons and types of cloud cover as well as a range of elevations from 200 m to 2,800 m. The geographical latitudes of the measuring sites range between 47° and 50° north.

The basis for the visualizations of UV exposure of the human body is the software package Anthropos 3.0 (Tecmath AG, Kaiserslautern, Germany). This is working as a Plug-in to 3D-Studio-Max (Autodesk GmbH, Munich, Germany). By Anthropos three-dimensional human models can be created in a wide range of physiognomy, with different body postures and azimuthal orientation. The surface of these models is composed by a grid consisting of about 20,000 triangles.

In addition to these generally available software packages customized programs were designed for us by the producers of ANTHROPOS. The first of these programs defines a spatially absolute system of coordinates, i.e. creating a model with the front oriented forward will mean that this model always looks to the north even if it is turned subsequently to be looked at from the other sides. The second special program allows the export of the *x*, *y*, and *z* coordinates of the corner points and a material code (colour index) of each triangle into an ASCII file and their re-import with the material code replaced by a custom-specific code.

Additional programs created by our team calculate the inclination and azimuth angle of the normals of each triangle, characterizing the view directions, from the coordinates of the corner points. By two-dimensional interpolation of the ASCARATIS measuring data the UV index can be calculated for all inclinations and azimuths and so for all triangles of the surface of the human model. Refering to a colour gradation scheme consisting of 40 distinct colours each UVI value is assigned to a certain colour index, which then replaces the material code of the triangles. The final model can be flipped and rotated in any direction without changing its properties, allowing the UV exposure of all surface areas of the model body to be viewed.

In order to achieve comparable conditions for all examples of irradiation measurements on the human body, only clear days without any clouds were chosen. The exemplary days chosen for the UV irradiation visualizations were 12 June 2001, 23 September 2000, and 22 December 2000. On these days the total ozone column for Southern Bavaria (Munich and Zugspitze area) was 307 DU, 291 DU, and 332 DU respectively.

Results

Two circadian courses of the UVI at differently inclined surfaces on Mount Zugspitze are shown in Figs. 2 and 3 (note the different scales of the y axis). Figure 2 represents a clear winter day (22 December 2000) and Fig. 3 a clear summer day (12 June 2000). The diurnal courses of the UVI are shown for the directions facing the sun (27), zenith (25), and the nadir (26) as well as directions vertically orientated to the north (1), east (4) and south (7). On 22 December 2000 at noon (Fig. 2) the UVI values measured directly towards the sun and vertically orientated to the south (195°), were about 70% higher than that

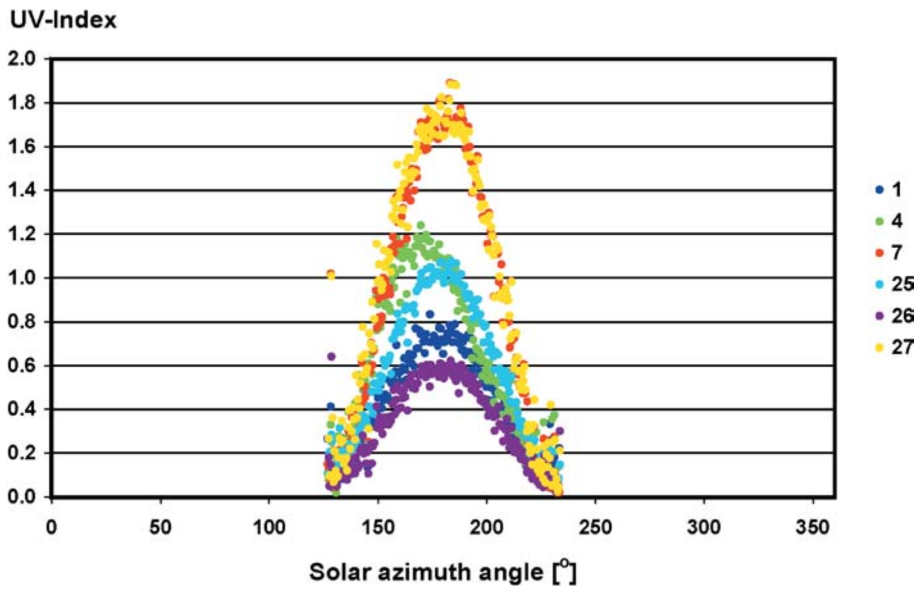

Fig. 2 Temporal courses of measured UV Indices on 22 December 2000 at the Zugspitze measuring site (2,800 m above sea level) at differently inclined surfaces. Directions 1 oriented to the north, 4 oriented to east, 7 oriented to south, 25 zenith, 26 nadir, 27 facing the sun

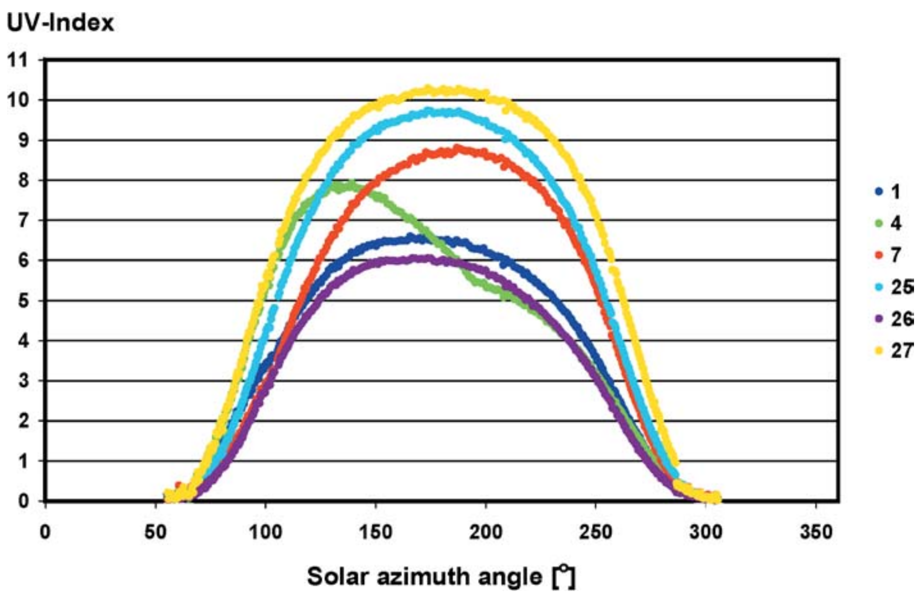

Fig. 3 Temporal courses of measured UV Indices on 12 June 2001 at measuring site Zugspitze (2.800 m above sea level) at differently inclined surfaces. Direction 1 oriented to the north, 4 oriented to the east, 7 oriented to the south, 25 zenith, 26 nadir, 27 facing the sun

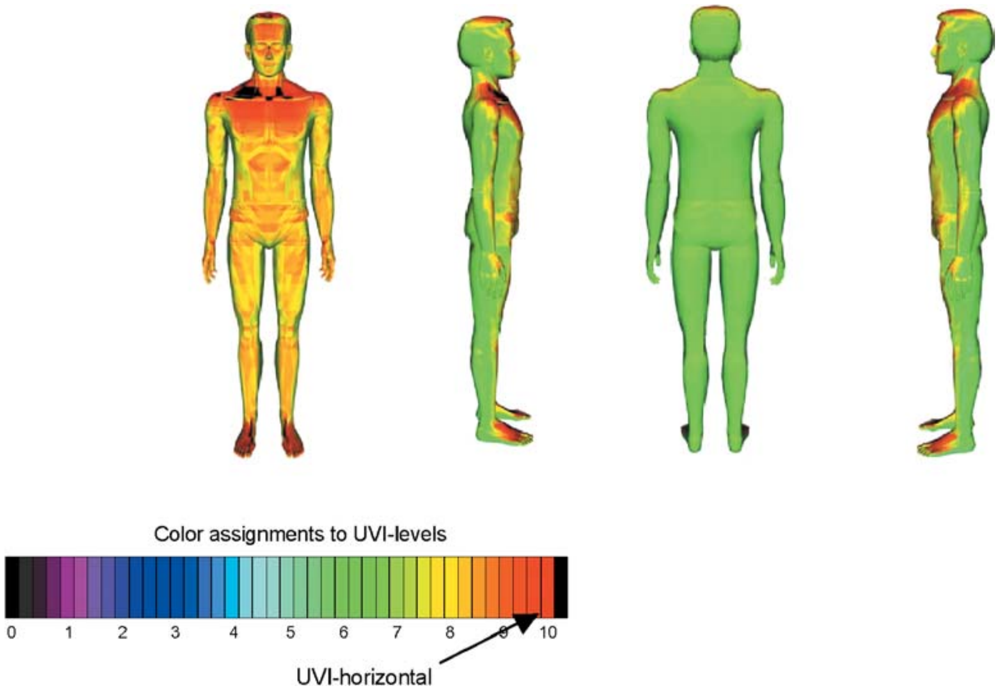

Fig. 4 Distribution of UVI-levels on the body of a standing man facing south (180°) on Mount Zugspitze (2,800 m above sea level) on 12 June 2001 at 1.15 p.m. (solar azimuth 180.4°, elevation 65.7°), front side (facing south), right side of body (facing west), back (facing north) and left side of body (facing east); UV irradiance of a horizontal plane marked by an arrow at the colour bar

for a horizontal surface. Also the values from the radiometer orientated vertically eastward were higher during the morning hours. It is important to mention that, at this time of the year, close to the winter solstice, the maximum of the UVI is quite low (<2).

Figure 3 shows the corresponding conditions on a day about 1 week before the summer solstice (12 June 2001). The UVI at noon exceeds 10 in the position facing the sun. The difference between the UVI of the zenith measurement and that directly towards the sun is relatively small compared to the winter scenario, in absolute units; however, in both cases it is a little lower than 1 unit of UVI. In both scenarios the albedo of the ground due to snow cover on this high mountain was about 60%.

Figures 4–10 show examples of the visualization of erythemally effective UV irradiation of a human model at different times of day and year, in varying body positions, for male and female models and at different places. The first of these figures (Fig. 4) relates to the distribution of the UVI on the body of an man standing upright on Mount Zugspitze, facing south close to the time of the summer solstice (12 June) and at the highest elevation of the sun on that cloudless day. The figure shows views of the body from the front (facing south), both sides (facing east and west), and the back (facing north). On this cloudless summer day the highest levels of the UVI were between 10 and 11 (black spots). Large sections of the front of the body received irradiation with a UVI between 8 and 10. There are some spots on the sides of the body that reached irradition levels up to UVI = 8; the largest areas, however, have UVI values around 7. The back of the body shows almost homogeneous irradiation at UVI levels around 6. The relatively high UV irradiation of body parts, that are not irradiated directly by the sun (like the back) can be explained by the relatively high propotion of diffuse UV radiation. The diffuse UV radiation here is especially influenced by the albedo of 60% due to the snow cover of the ground and the orography of the measuring site (the ground slopes to the north and west).

Figure 5 compares the UV irradiation in the mountain scenario of Fig. 4 with a similar one in Munich (500 m above sea level). The day of the UV measurements selected for these figures was cloudless at both locations; the data refer to the same solar azimuth of 180° (the highest sun position of the day). The UV albedo at the Zugspitze site for this scenario was 64%; it was 12% at the Munich site. The view of the body of the human model is from the front with an elevation of about 45° , to focus on the parts of the body surface with the highest irradiation. The difference between the highest values of the UVI at the Munich and Zugspitze sites is about 3 units (11 versus 8).

Figure 6 shows the temporal course of the UV irradiation of the front of a man standing upright and always facing into the sun's azimuth on Mount Zugspitze on a clear day close to the summer solstice. In terms of the irradiation of the face and front of the body this is always a "worst-case" scenario. On rotating to other azimuth angles the irradiation of these areas decreases. The four figures represent the time between 7.30 a.m. (CEST) and 1.30 p.m. in steps of 2 h. The maximum UV irradiation of the body increases from UVI = 1 at 7.30 a.m. over UVI = 5 at 9.30 a.m. over UVI = 9 at 11.30 a.m. and UVI = 11 around the time of the highest solar elevation. At low solar elevation in the early morning there is a nearly uniform irradiation of the front of the body while at the high solar elevations around noon the more upward-oriented surface areas receive distinctly more UV irradiation

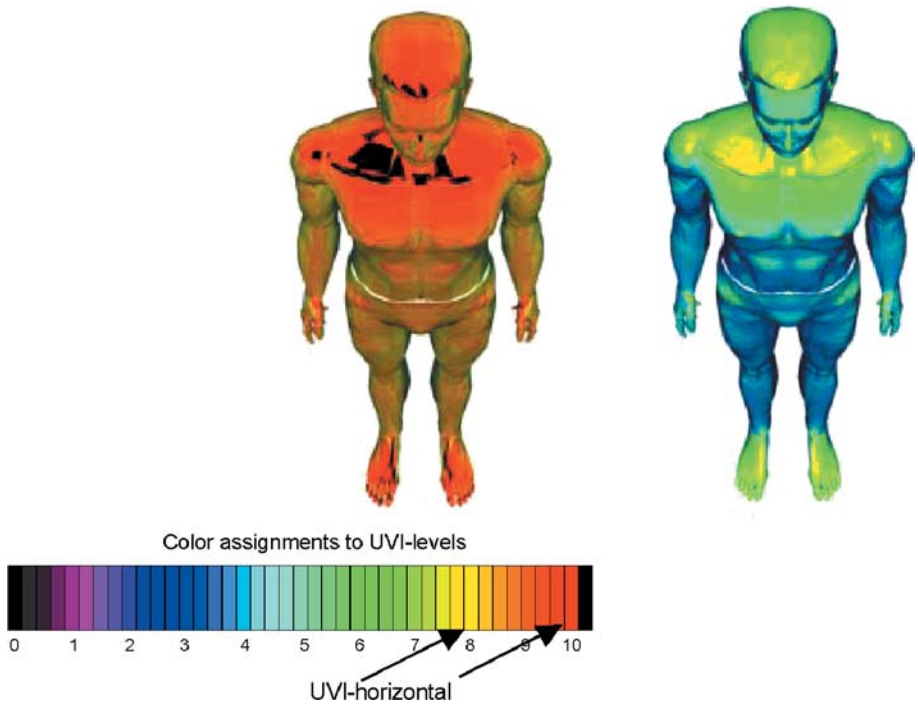

Fig. 5 Comparison of the distributions of UVI levels on the body of a man standing upright facing south (180°) on Mount Zugspitze (*left*) and in Munich (*right*) on 12 June 2001 at 1.15 p.m. CEST (solar azimuth 180°, elevation 65.7° Zugspitze/ 65.0° Munich

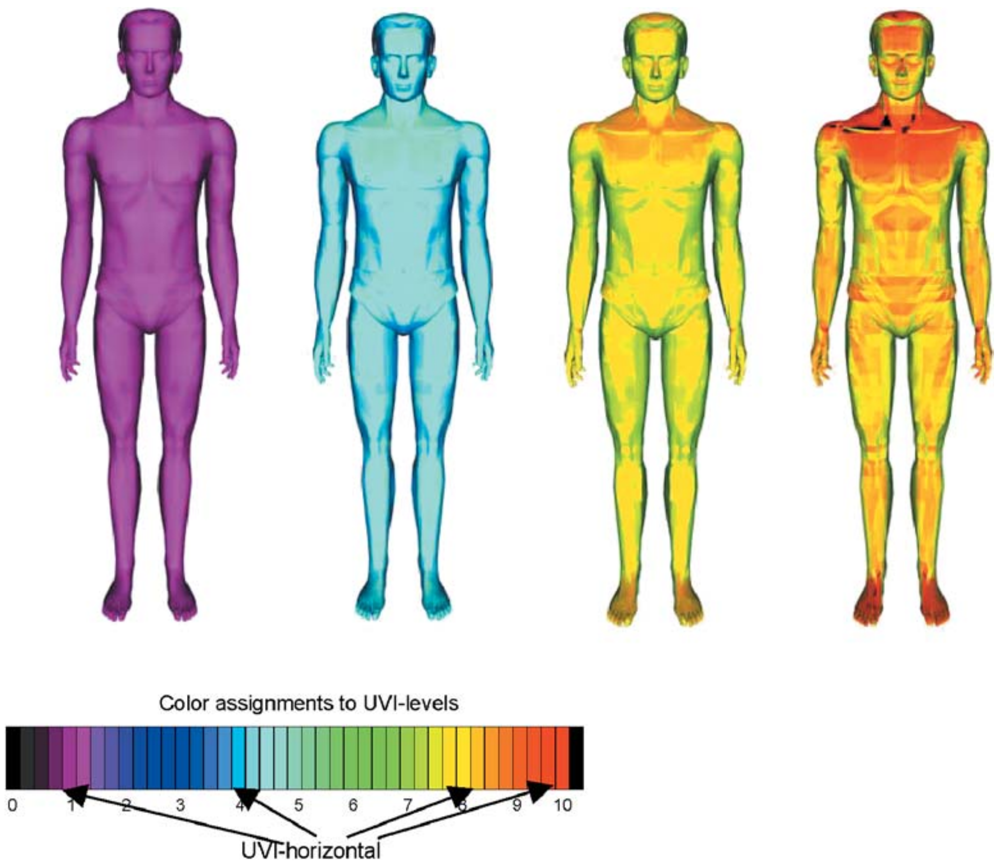

Fig. 6 Comparison of the distributions of UVI levels on the body of a man standing upright always facing to the sun's azimuth on Mount Zugspitze on 12 June 2001 at 7.30 a.m. (solar azimuth 76.3°, elevation 19.2°), 9.30 a.m. (solar azimuth 98.1°, elevation 39.3°), 11.30 a.m. (solar azimuth 130.0°, elevation 57.9°) and 1.30 p.m. (solar azimuth 188.7°, elevation 65.5°)

than the vertical surfaces. The range of UV irradiation at the front of the body shown for 1.30 p.m. covers 4 units of UVI (7–11) while e.g. at 9.30 a.m., for example it only spans 1 unit of UVI (4–5).

In Figure 7 the UV scenario corresponding to Fig. 4 is shown for the September equinox, when the maximum elevation of the sun reaches 42° . Here the highest UVI-levels at the surface of the body of the man standing

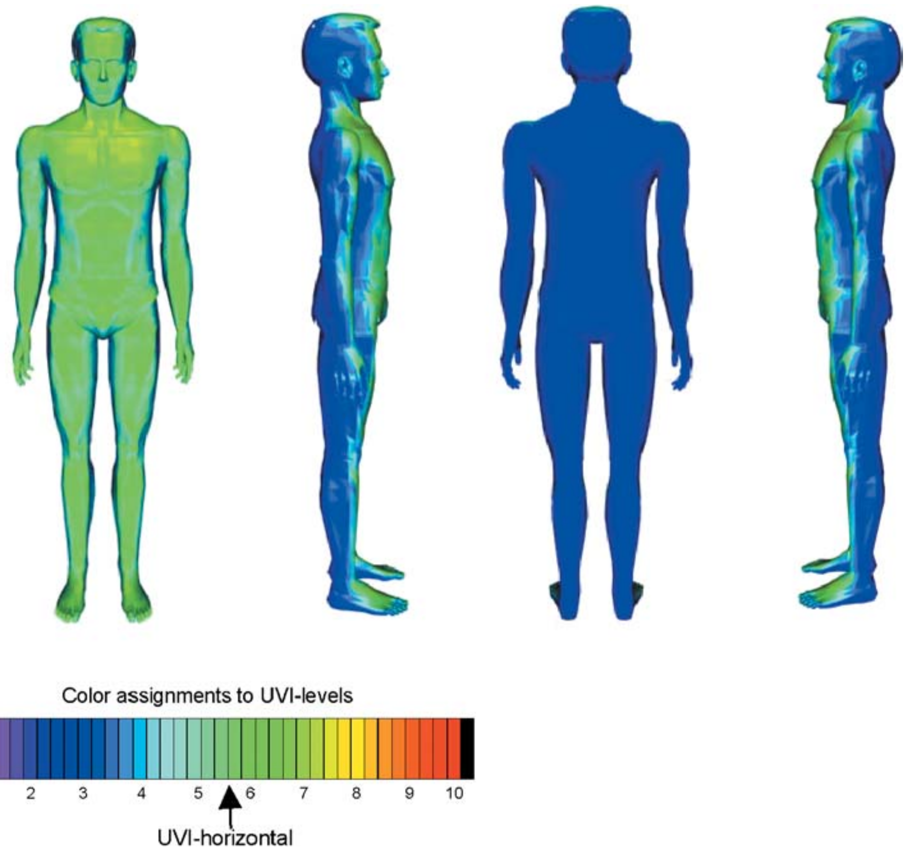

Fig. 7 Distribution of UVI levels on the body of a man standing upright facing south (180°) on Mount Zugspitze (2,800 m above sea level) on 23 September 2000 at 1.07 p.m. (solar azimuth 180.1°, elevation 42.3°)

upright reach 8 (frontal shoulder and chest area), while the largest portion of the body surface (both sides and back) is only exposed to a UVI around 3. At the time of the highest solar elevation (19°) at the winter solstice (Fig. 8) the highest UVI levels are in the range of 2 and for most of the body UVI does not exceed 1. Owing to the low sun in this season there are spots on the whole frontal side (not only the shoulder and chest) receiving the maximum UV irradiation.

In Fig. 9 the UV irradiation around the time of the summer solstice is modelled for a male model lying down (sun bathing). The model is looking directly southwards in the direction of the solar azimuth. In this scenario there are some spots with irradiation levels up to UVI = 11 at the lower chest and calves. Large areas with UVI = 10 comprise the face, upper arms, chest, calves and the ridges of the feet.

In Fig. 10 the UV irradiation of the upper part of a standing female model is compared with that of the male model for the summer solstice scenario on Mount Zugspitze. Owing to the differences in body structures between the two genders (especially in the chest area) there are distinct differences in UVI distribution. While the maximum irradiation (UVI = 11) of the male model is located in the shoulder area for the female model the same UV levels are found at the upper side of the breasts. The female shoulder area is more horizontal than that of the male and therefore receives a little less UV irradiation. The lower parts of the female breasts with surfaces oriented more to the ground receive less UV irradiation (UVI = 6) than those of to the male model (UVI = 8).

Discussion

The automatic spherical scanning system for UV radiation on inclined surfaces ASCARATIS has proven to be a reliable measuring system even under extreme climatic conditions. With three of these measuring systems, which have been in routine operation simultaneously at different locations since 2001, a large set of UV data covering all seasons and a large range of elevations above sea level has been collected. The results in general are of great relevance for public health and have shown that measurements of UVI on horizontal surfaces, as done routinely, tend to underestimate the real UV exposure of at least parts of the human body, and overestimate others.

No comparable data set of UV radiation on inclined surfaces has yet been published nor have measuring data been used to visualize the irradiation of the human body. Therefore a discussion of our results in the light of previous similar studies cannot be made. The unique UVI data set for inclined surfaces is used for the creation of UV exposure maps of the human body, some examples of which have been shown here in this paper. Moreover, the measured data are used for comparison with results of a model that is able to determine UV irradiances on arbitrarily oriented surfaces (Mech and Koepke 2004), an

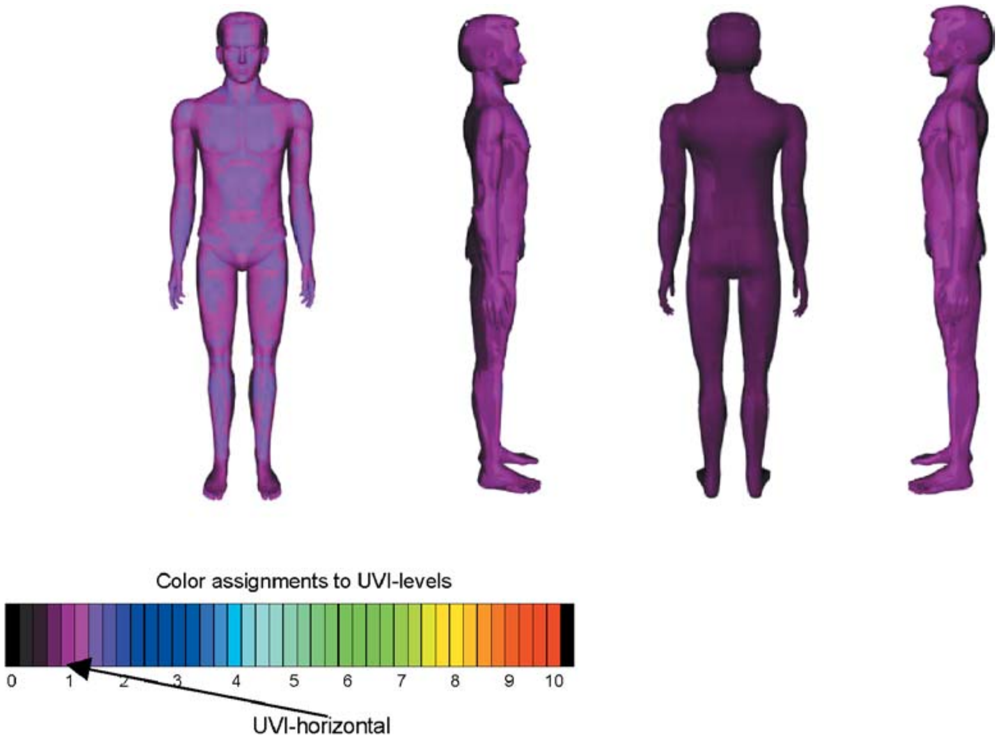

Fig. 8 Distribution of UVI levels on the body of an upright standing man facing south (180°) on Mount Zugspitze (2,800 m above sea level) on 22 December 2000 at 12.15 p.m. (solar azimuth 180.3°, elevation 19.1°)

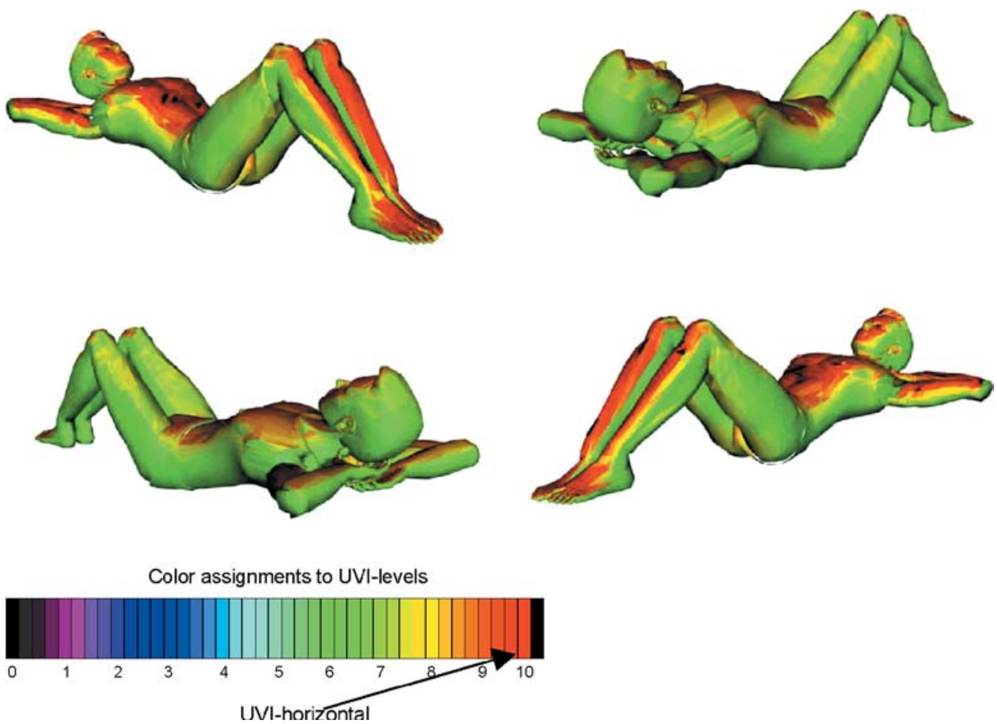

Fig. 9 Distribution of UVI levels on the body of a man lying facing south (180°) on Mount Zugspitze (2,800 m above sea level) on 12 June 2001 at 1.15 p.m. (solar azimuth 180.4°, elevation 65.7°)

extension of the model STAR (System for Transfer of Atmospheric Radiation) developed at the Meteorological Institute Munich (Ruggaber et al. 1994) in its present version (Schwander et al. 2000).

The visualization of the UV irradiation of the body can be used to inform the public about the dangers of exposure to the sun and aid the understanding of its role in the genesis of skin damage and skin cancer. The body maps of UV irradiation, for example clearly show how body orientation affects an individual's exposure to UV and this information can be easily made available to the public. As the models for the UV visualization are unclothed, the results are hypothetical and show worst-case scenarios. If parts of the body are covered by clothing the UV irradi-

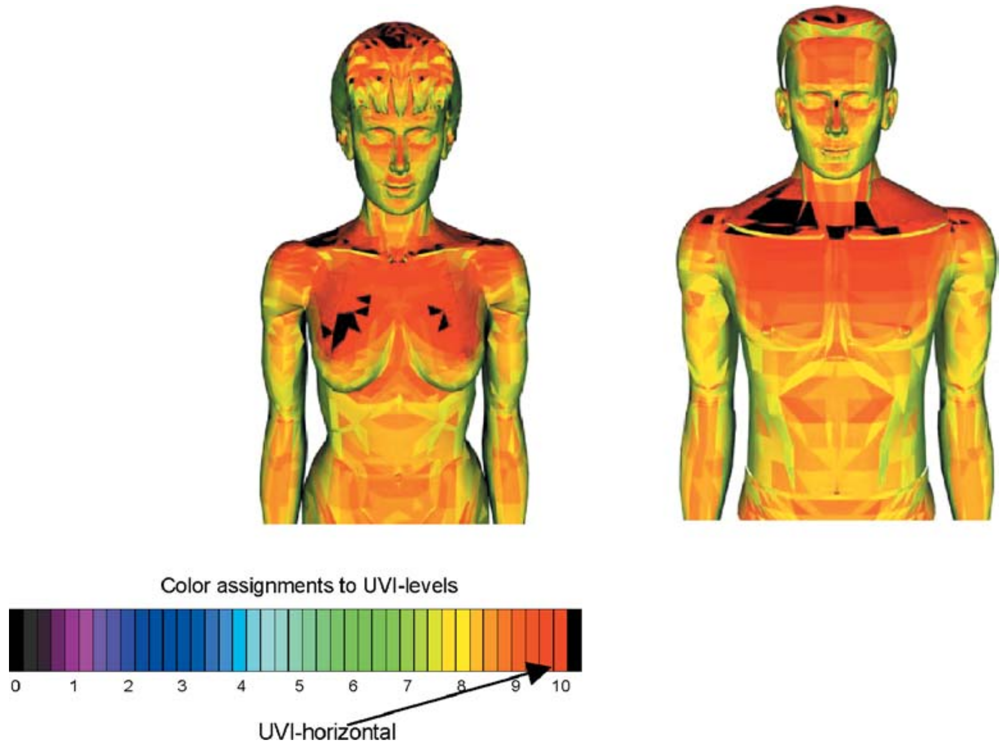

Fig. 10 Distribution of UVI levels on the upper part of the body of a man and women upright (*left*) standing facing south (180°) on Mt Zugspitze (2,800 m a.s.l.) on 12 June 2001 at 1.15 p.m. (solar azimuth 180.4°, elevation 65.7°)

ation of the covered skin areas decreases significantly. Depending on the clothing properties (density of weave, colour) this may result in negligible UV levels as far as adverse health effects are concerned. In general the parts of the body that commonly are not covered by clothing, i.e. the head and neck, are exposed most to UV radiation. The visualizations could thus also be used as the basis for advice about covering the most exposed areas of skin by clothing or shading them by wearing a hat.

By integrating the momentary UV irradiation of the body over period ranges of hours, days or even months and years the distribution of the erythemally weighted UV doses can also be visualized. These temporal integrations makes it possibile to show those skin areas, that are most likely to develop skin cancers such as basal cell and squamous cell carcinoma, both of which are associated with lifetime UV doses.

The ASCARATIS system and the visualizing software can be transferred to other geographical regions like the subtropics and tropics, so there is a potential to create UV irradiation maps of the human body on a global level. By means of radiation models like STAR (Mech and Koepke 2004; Schwander et al. 2000) future UV scenarios could also be visualized in terms of their effects on the UV irradiation of the human body. Another application could be in the field of heliotherapy where the exposure times for the therapeutic optimum UV dose on certain skin areas can be assessed.

Acknowledgements The project is sponsored by the Bavarian Research Network BayForUV and the Environmental Research Station Schneefernerhaus. More information on the study can be obtained at: http://www.bayforuv.de/englisch/topindex.html

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