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Impact of Long-Term Changes in Ambient Erythema-Effective UV Radiation on the Personal Exposure of Indoor and Outdoor Workers—Case Study at Selected Sites in Europe

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Abstract: Given the persistently high incidence of skin cancer, there is a need for prevention-focused information on the impact of long-term changes in ambient solar ultraviolet radiation (UVR) on human personal radiation exposure. The exposure categories of the UV Index linked to protection recommendations show long-term shifts in the frequency of occurrence with regional differences in direction and magnitude. The patterns of change for sites in the humid continental climate differ from those for sites in other climate zones such as the humid temperate or Mediterranean climate. The diversity of the individual exposures of indoor and outdoor workers can be described using probability models for personal erythema-effective UVR dose (UVD). For people who work indoors, the largest share of the total individual annual UVD is due to vacation, whereas for people who work outdoors, it is occupational exposure. The change in ambient UVDs at the residential locations is only partially reflected in the individual UVDs. For eight selected European sites between 38° and 60° northern latitude, the median of the individual annual total UVD (excluding travel) during the period 2009–2019 is 0.2 to 2.0% higher for indoor workers and 0.6 to 3.2% higher for outdoor workers compared to the period 1983–2008. Changes in the choice of an exemplary holiday destination offer both indoor and outdoor workers the potential to compensate for the observed long-term trend at their place of residence and work.

Keywords: ultraviolet radiation; health prevention; long-term change; individual radiation exposure; radiation exposure on vacation

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1. Introduction

Solar UV radiation (UVR) is a component of the natural environment to which humans can be exposed when spending time outdoors. Ambient UVR is subject to numerous influences that lead to pronounced temporal and spatial variability as well as long-term trends [1–5]. The question of the extent to which long-term changes in ambient UVR are reflected in individual UVR exposure is important because UVR has strong biological effects and poses risks and opportunities for human health [6,7]. Persistently high incidences of skin cancer in the fair-skinned population worldwide including Europe [8–13] illustrate the obvious necessity and urgency of adaptation measures to prevent UVR-associated diseases [5,14]. The aim of the present study is to analyze prevention-oriented information based on the UVI (as a globally uniformly established measure of UVR protection [1], which represents the daily maximum of ambient erythema-effective UV irradiance) and the individual erythema-effective UVD (as temporally integrated information that specifically represents personal UVR exposures).

The UVI conveys its goal via protection recommendations, which are specified by dividing the UVI scale into exposure categories (ECs) [1]. Changes in UVI within an EC do not lead to adjustments in the recommended UVR protection. For the communication of long-term changes from a prevention perspective, it is, therefore, of interest to investigate whether there are changes in the occurrence of the ECs [1]. To the best of our knowledge, no such analysis has yet been published. Existing studies usually state UVI trends as a percentage of the UVI [4,15,16] or consider selected spectral ranges and not the integral UVI [3,17]. The results available to date can be summarized as follows: the trends observed have small absolute amounts, are often not significant, and are ambiguous in their direction when looking at different locations [3,4,15–17].

The UVD received by the individual is considered one of the decisive influencing factors with regard to health effects [6,7,18]. Ambient UVR correlates only to a certain extent with personal UVR exposure [19–22]. People who work outdoors are subject to particular risks and prevention requirements [23–25]. When analyzing individual UVR exposure, recreational exposure must also be included, whereby holiday exposure has to be considered separately, as radiation conditions can differ significantly from those at the locations of residence and work [19].

Currently, no measurements of UVR exposure for large numbers of people and over a period of decades are available. Therefore, the current study uses satellite-based measurements of UVR and applies a method of modeling of individual UVR exposure. It aims to answer the question of how long-term changes in ambient UVR affect the individual proportion of health-related UVR of people at selected locations in Europe as a function of outdoor or indoor employment and possible holiday stays in other places. Existing studies mainly consider average UVR conditions [19,26], or the investigation refers to defined exposure cases, different body regions, and their different exposures [20,21,27]. Ref. [19] developed a behavioral model for estimating population UVR exposure with respect to indoor workers. So far, one independent validation of the model has been published [22]. It quantifies the variation in the objectively measured personal UVR exposure that could be explained by the ambient UVR, time spent outdoors, and modelled UVR level based on [19]. It is concluded that the time outdoors and the modeling approach are “reliable predictors and of value to be applied in epidemiological studies of the health effects of current exposure to UVR”. In the present study, the model [19] is extended to include outdoor workers and different holiday stays, and is applied to a long time series (1983–2019) of satellite-based UVR measurements. Analyses of the long-term trend of individual UVR exposure in combination with the question of the contribution of different holiday stays are presented for the first time in this study to the best of our knowledge.

2. Materials and Methods

This study considers eight sites at different latitudes in Europe (Bergen, Norway 60.4° N; Warsaw, Poland 52.2° N; Reading, UK 51.5° N; Freiburg, Germany 48.0° N; Budapest, Hungary 47.5° N; Bucharest, Romania 44.4° N; Madrid, Spain 40.4° N; Athens, Greece 37.9° N). The ambient UVR data used are based on the evaluation of satellite-based measurements from 1983 to 2019 ([4], period extended until 2019). The wavelength-dependent weighting of the UV irradiance with the erythema effect provides the health reference. The hourly values of the erythema-effective UV irradiance are added up to the daily dose. In addition to the ambient UVR dose, the daily maximum of the erythema-effective UV irradiance on a horizontal surface is used: the internationally standardized “UV Index” (UVI) [1]. The UVI range is divided into five exposure categories (ECs) to which suitable globally harmonized protective measures are assigned [1]. The UVI ECs are associated with the following UVI ranges: ‘negligible to low (S)’ $0 \leq \text{UVI} < 3$, ‘moderate (M)’ $3 \leq \text{UVI} < 6$, ‘high (L)’ $6 \leq \text{UVI} < 8$, ‘very high (X)’ $8 \leq \text{UVI} < 11$, and 'extreme (E)' UVI $\geq$ 11 [1]. Long-term changes in the annual and seasonal frequency of UVI ECs are analyzed. The data are based on 11-year moving averages in order to specifically capture changes that are beyond the approximately 11 year cyclical solar activity. The most recent available 11-year period 2009–2019 is compared with the previously available period 1983–2008.

Individual exposure to UV radiation is primarily determined by the time spent outdoors [22]. On working days, this differs for outdoor workers from that for indoor workers, and it also differs between working days and weekends or public holidays and during holidays. In addition, the exposure time can vary greatly from person to person. Apart from time-limited measurement campaigns, the behavior of individuals is generally not accessible. One way to take it into account for evaluations is the mathematical modeling of exposure times using probability distributions [19]. Table 1 lists the parameters that are assumed to apply to working days (differentiated between outdoor and indoor workers), weekends (differentiated between summer and winter), and holidays (summer). In the present study, a number of 60,000 persons per site are considered, to whom the exposure times are assigned individually on the basis of the probability distributions in Table 1 by means of a machine-generated random number. The months April to September are regarded as the summer half-year and the months October to March as the winter half-year.

Table 1. Exposure time models for working days (W1, W2), weekends (W3), and holidays (H) [19], expanded. Probability distribution: log-normal distribution log ND; normal distribution ND. * [hour].

Type of Exposure		Half-Year	Place of Stay	Probability Distribution	Mode [hours]	Standard Deviation [log]
Working day	W1	summer, winter	indoor	log ND	0.5	0.3
	W2	summer, winter	outdoor	log ND	8	0.5
Weekend	W3	summer	outdoor	log ND	2	0.3
	W3	winter	outdoor	log ND	1	0.3
Holiday	H	summer	outdoor	ND	5	1 *

UVR on the human body is much lower than the intensity of UVR on an unshaded horizontal surface due to factors such as posture, shading by nearby structures, clothing, and activity. To estimate the erythema-effective UVR dose $UVD_{i,d}$ received by individual i during day d, the following model was used [19].

$$UVD_{i,d} = UVD_d \times EA_{i,d} \times (1 - (1 - h_{i,d}/H_d)^2) \tag{1}$$

UVD_d is the erythema-effective UVR dose in the human environment on day d. $EA_{i,d}$ is the exposure fraction, i.e., the fraction of UVR, that hits the body of individual i in relation to the environment during the same exposure duration on day d. Individual i spends the exposure time $h_{i,d}$ outdoors on day d (see Table 1). H_d is the daylight duration for the middle of the respective month at the latitude of the site under consideration. The exposure fraction $EA_{i,d}$ of an individual i on a specific day d is described by a rectangular probability distribution.

$$EA_{i,d} = EA_{min} + Z_{zi} \times (EA_{max} - EA_{min}) \tag{2}$$

EA_{max} and EA_{min} are the maximum and minimum exposure fractions on day i and Z_{zi} is a random number between 0 and 1. Since personal details (such as orientation to the sun, body posture, clothing) are not known and are usually also variable, the diversity of the values of the exposure fraction is estimated using random numbers within defined limits. EA_{min} is assumed to be 0.05. The values selected for EA_{max} are 0.25 for weekdays, 0.30 for winter weekends, 0.40 for summer weekends, and 0.50 for holidays [19]. EA_{max} is lower on weekdays than on weekends or holidays, as more frequent stays in urban environments are assumed. As holidays may sometimes take place in regions where UVR conditions differ significantly from the situation at the places of residence or work, three scenarios are considered as possible examples, which are summarized in Table 2. For each of the eight sites, the monthly and annual erythema-effective UVD of individuals is calculated for the period 1983 to 2019, whereby the individuals work indoors or outdoors and spend their holidays according to one of the three example scenarios. There are three exposure scenarios for indoor workers labelled I (exposure W1 + W3 + HA), II (exposure W1 + W3 + HB), and III (exposure W1 + W3 + HC), and for outdoor workers labelled I (exposure W2 + W3 + HA), II (exposure W2 + W3 + HB), and III (exposure W2 + W3 + HC). This results in a total of 532.8 million cases. The period of the most recent 11 years (2009–2019) is compared with the previous period (1983–2008), with the length of the total period resulting from the availability of data. In the following, the term 'personal or individual exposure/UVD' refers not to a single individual, but to a larger number (usually 60,000 individuals per location and scenario) with the aim of reflecting the diversity of individual UVR exposures of the (working) population.

Table 2. Characteristics of the exemplary holiday scenarios (HA, HB, HC) with stays at different geographical latitudes. Place of residence (each of the eight sites evaluated), Spain (Balearic Islands, 39.6° N), and Scandinavia (Bergen, Norway, 60.4° N).

Holiday Scenario	Place of Stay and Duration in April/May	Place of Stay and Duration in June/July/August	Place of Stay and Duration in September	Total Duration
HA	place of residence 1 week	Spain 2 weeks	place of residence 1 week	4 weeks
HB	place of residence 1 week	place of residence 2 weeks	place of residence 1 week	4 weeks
HC	place of residence 1 week	Scandinavia 2 weeks	place of residence 1 week	4 weeks

3. Results

3.1. Status Quo and Changes in the Number of Days with the UVI ECs in the Period 2009–2019 Compared to 1983–2008

Figure 1 shows the annual share of days with the various UVI ECs across all eight locations considered (from 60.4° N to 37.9° N) in the period from 1983 to 2019.

The median (MED) has the highest value for the 'moderate' category at 44 per cent of days. This category shows only a very small variation with 4 per cent interquartile range IQR (IQR: 42–46%). Mainly due to the position of the sun, days with low UVI occur less frequently with decreasing latitude and days with high, very high, and extreme UVI occur more frequently. Therefore, the variation in the number of days with the respective UVI ECs is generally greater. One exception is the UVI EC 'extreme', which only occurs in two of the eight locations and whose mean annual share of days has an IQR of 0.2 per cent. The greatest variation can be seen in the number of days with the UVI EC 'low' with an IQR of 25 per cent (IQR: 21–46%). The MED of the mean annual percentage is 39 per cent of the days. The variation in the number of days with the UVI EC 'high' is at an IQR of 9 per cent (IQR: 7–16%), and that of the UVI EC 'very high' at an IQR of 12 per cent (IQR: 0.3–12%). The MEDs of the mean annual percentages are 13 per cent for the UVI EC 'high' and 3 per cent of days for the UVI EC 'very high'.

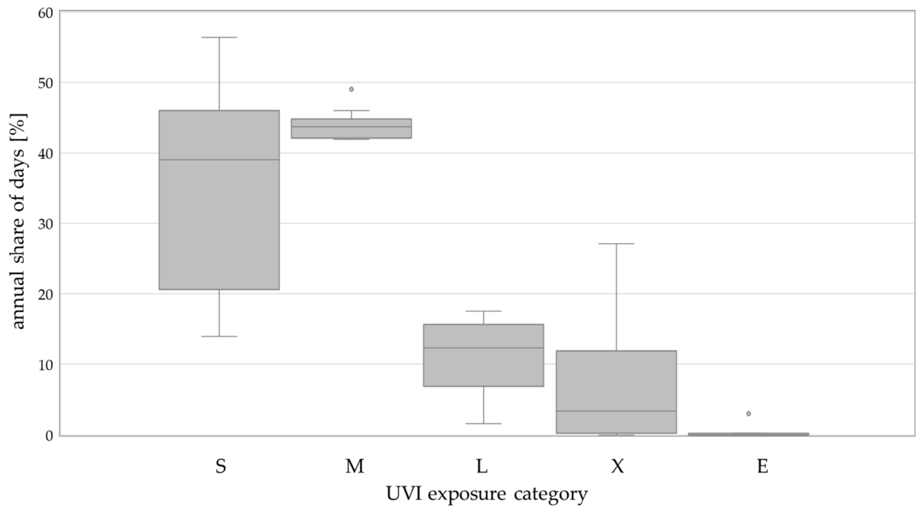

Figure 1. Annual share in the number of days with the various UVI ECs ('negligible to low (S)' $0 \leq \text{UVI} < 3$, 'moderate (M)' $3 \leq \text{UVI} < 6$, 'high (L)' $6 \leq \text{UVI} < 8$, 'very high (X)' $8 \leq \text{UVI} < 11$, and 'extreme (E)' $\text{UVI} \geq 11$) across all eight locations considered (from 60.4° N to 37.9° N) in the period 1983–2008.

Statistically significant changes in the number of days with the UVI ECs in the period 2009–2019 compared to 1983–2008 occur at all of the eight European sites considered and are shown in Table 3. There are regional differences with regard to the affected categories as well as the direction and extent of the changes.

Table 3. Mean differences dEC of the annual number of days with the UVI ECs S, M, L, X, E in the period 2009–2019 compared to 1983–2019. Green: statistically significant decrease (probability of error $p < 0.05$). Red: statistically significant increase ($p < 0.05$). Color saturation represents the magnitude of difference: $0 < |\text{dEC}| \leq 3$ days: light, $3 < |\text{dEC}| \leq 6$ days: medium, $6 < |\text{dEC}| \leq 9$ days: dark. Gray: no statistically significant change. No coloring: category does not occur. The season with the strongest change is indicated (winter: December, January, February; spring: March, April, May; summer: June, July, August; autumn: September, October, November). Sites are grouped according to their climatic location on the basis of the Köppen–Geiger climate classification [28].

Climate Zone	**Humid Temperate**			**Humid Continental**			**Cold Steppe**	**Mediterranean**
EC \ **Site**	**Bergen**	**Reading**	**Freiburg**	**Warsaw**	**Budapest**	**Bucharest**	**Madrid**	**Athens**
S	winter	spring	autumn	spring		winter	winter	winter
M	spring	spring	spring	summer	summer	summer	winter	winter
L	summer	summer	spring	summer	summer	summer	spring	summer
X	-	summer	summer		summer	summer	spring	summer
E	-	-	-	-	-	-	summer	summer

When sorting the sites according to latitude, no obvious similarities can be systematized regarding the changes in the number of days with the various ECs. However, if the sites are grouped according to their climatic location on the basis of the Köppen–Geiger climate classification [28], a common structure of changes at different sites can be identified.

Regarding the changes in the number of days with the UVI ECs, changes in the order of ±3 days occur most frequently. It can be summarized that an increase in the number of days with the highest local ECs (L, X) can only be observed in those sites that are located in the humid continental climate zone (Warsaw, Budapest, Bucharest). The sites in the other climate zones show a decrease in the average number of days with the highest local ECs occurring there (L, X, E). Typically, the site-specific peak exposures occur predominantly in summer, so the changes that occur also relate mainly to this time of year.

3.2. Impact of Long-Term Changes in Ambient UVD on Individual UVD in the Period 2009–2019 Compared to 1983–2008

The individual annual UVDs are characterized by distinct differences between occupational exposures (W1 and W2) and recreational exposures (W3 and HA, HB, HC), as well as between individuals, so that the annual exposures of individuals can range from a few tens of standard erythema doses of SEDs (1 SED = 100 J/m^2) as a minimum to several hundred SEDs as a maximum. Table 4 shows the modelled MED and the dose range over the lower and upper quartiles of the annual erythema-effective UVD of individuals in SEDs according to the three exposure scenarios for indoor workers at the eight locations, and Table 5 shows this for outdoor workers, respectively.

Table 4. MED and lower and upper quartile of annual erythema-effective UVD of individuals [standard erythema dose SED, 1 SED = 100 J/m^2] and three exposure scenarios for indoor workers at the eight locations; change in MED UVD per degree decrease or increase in latitude [%]; change in MED UVD in 2009–2019 compared to 1983–2008 [%].

Site (Latitude)	Exposure Scenario (Indoor Worker)	UVD Median [SED]	UVD Lower and Upper Quartile [SED]	UVD Change per Degree Decrease in Latitude [%]	UVD Change per Degree Increase in Latitude [%]	UVD Change 2009–2019 Compared to 1983–2008 [%]
Bergen (60.4° N)	I	184	138, 245	+1.7		+0.4
	II	135	98, 170			+0.4
Reading (51.5° N)	I	234	182,291	+2.2		+0.3
	II	183	137, 232			+0.4
	III	154	122, 185		−1.9	+0.8
Freiburg (48.0° N)	I	263	199, 315	+1.6		+1.1
	II	242	162, 277			+1.7
	III	173	138, 213		−1.9	+2.3
Warsaw (52.5° N)	I	228	172, 280	+1.6		+0.3
	II	190	141, 239			+0.7
	III	153	125, 183		−2.4	+0.3
Budapest (47.5° N)	I	271	217, 333	+1.6		+0.5
	II	238	181, 299			+1.7
	III	192	152, 232		−1.6	+1.3
Bucharest (44.4° N)	I	287	229, 349	+1.5		+1.9
	II	265	205, 336			+2.0
	III	212	172, 254		−1.3	+1.9
Madrid (40.4° N)	I	365	290, 436	±0		+0.4
	II	365	271, 462			+0.4
	III	280	224, 347		−1.2	+0.5
Athens (37.9° N)	I	369	296, 444		−2.3	+0.1
	II	384	288, 480			+0.2
	III	294	234, 377		−1.0	+0.1

Table 5. MED and lower and upper quartile of annual erythema-effective UVD of individuals [SED] and three exposure scenarios for outdoor workers at the eight locations; change in MED UVD per degree decrease or increase in latitude [%]; change in MED UVD in 2009–2019 compared to 1983–2008 [%].

Site (Latitude)	Exposure Scenario (Outdoor Worker)	UVD Median [SED]	UVD Lower and Upper Quartile [SED]	UVD Change per Degree Decrease in Latitude [%]	UVD Change per Degree Increase in Latitude [%]	UVD Change 2009–2019 Compared to 1983–2008 [%]
Bergen (60.4° N)	I	421	336, 504	+0.8		+1.6
	II	361	276, 444			+1.9
Reading (51.5° N)	I	563	438, 684	+0.7		+1.6
	II	513	392, 631			+1.6
	III	478	364, 602		−0.9	+1.7
Freiburg (48.0° N)	I	656	508, 792	+0.6		+2.7
	II	622	472, 755			+2.8
	III	580	423, 707		−0.5	+2.9
Warsaw (52.5° N)	I	537	431, 685	+0.3		+1.2
	II	519	400, 636			+2.3
	III	465	354, 587		−1.3	+2.0
Budapest (47.5° N)	I	690	543, 852	+0.4		+2.7
	II	667	508, 811			+3.2
	III	616	459, 768		−0.6	+3.2
Bucharest (44.4° N)	I	765	601, 936	+0.4		+2.7
	II	748	575, 912			+3.1
	III	686	522, 857		−0.5	+3.1
Madrid (40.4° N)	I	1050	782, 1299	±0		+1.5
	II	1050	797, 1276			+1.6
	III	958	710, 1192		−0.4	+1.3
Athens (37.9° N)	I	1062	816, 1318		−0.5	+0.5
	II	1071	820, 1336			+0.6
	III	977	730, 1238		−0.4	+0.6

Exposure scenario II, which assumes that the holiday is spent entirely at the place of residence and work without traveling (HB), results in the MED of the individual UVDs, which generally increases from north to south in line with the position of the sun. For indoor workers at the northernmost location of Bergen (60.4°N) with 135 SED, only around 35% of the UVD is determined compared to the southernmost location of Athens (37.9°N) with 384 SED. For outdoor workers, the absolute values of the UVDs are 2.7 to 3 times higher, while the mentioned ratio in terms of location is comparable (34% with 361 SED vs. 1071 SED). An exception in terms of the north–south change in UVDs is Warsaw, which, at 52.5°N, is just one degree north of Reading at 51.5°N, but has MED UVDs that are 3.8% higher for indoor workers and 1.1% higher for outdoor workers. One explanation for this may be Warsaw's location in the continental climate, where there is normally less cloud cover on average than in more maritime locations. The inter-individual differences in the UVDs are considerable and vary for half of the employees by 48 ± 7% of the MED (mean value across all exposure scenarios), which, for the sites considered, covers a range of 98 SED to 480 SED for indoor workers and 276 SED to 1336 SED for outdoor workers.

As fixed destinations were specified for holidays (HA, HC) and, consequently, for the scenarios I and III, the absolute values for the eight locations are directly comparable, but the changes in UVDs in comparison to scenario II (without holiday travel) cannot be compared directly. Tables 4 and 5, therefore, also show the changes, normalized to one degree of latitude, that result in scenarios I and III in relation to the MED UVDs of scenario II. The normalized values are associated with additional uncertainties, as the north–south change can only be assumed to be linear as a rough approximation. The results in Tables 4 and 5 demonstrate that holidays have a greater impact on the annual individual UVD for indoor workers than for outdoor workers. This is in line with expectations given the greater exposure of outdoor workers on working days.

Figure 2 shows the share of individual UVD according to the exposure scenarios in Table 1 at the eight sites considered in the period 1983–2019. For outdoor workers, the workday UVDs make the largest contribution in the order of 70% (IQR: 69–73%), while leisure time for indoor workers on workdays only contributes in the order of 17% (IQR: 14–19%). For indoor workers, holidays make the largest contribution with 51% (IQR: 44–55%) of individual UVD, while for outdoor workers this is only 19% (IQR: 14–20%), both excluding holiday travel. Leisure time at weekends contributes 11% (IQR: 10–12%) to individual UVD for outdoor workers and 32% (IQR: 31–37%) for indoor workers.

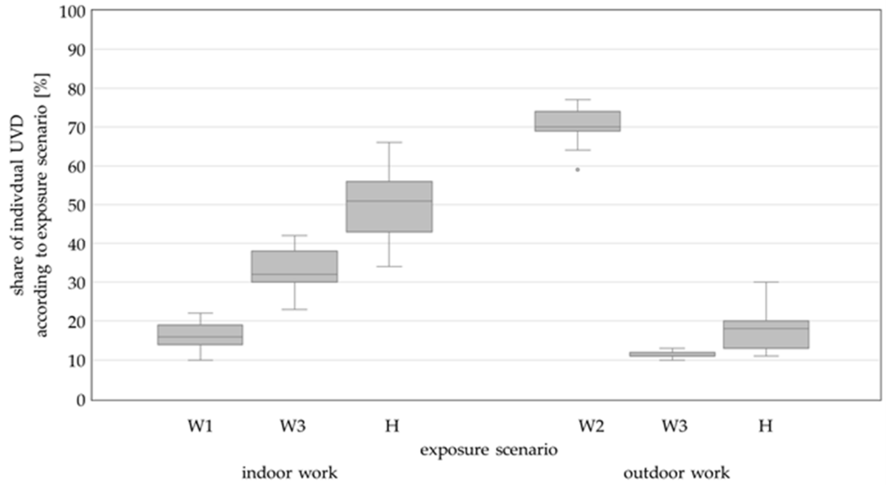

Figure 2. Share of individual erythema-effective UVD [%] according to the exposure scenarios in Table 1 (W1: working days—indoor work, W2: working days—outdoor work, W3: weekends, H: holidays) at the eight sites considered (from 60.4° N to 37.9° N) in the period 1983–2019.

Figure 3 illustrates how the individual annual erythema-effective UVDs, differentiated by working days for indoor workers (W1), working days for outdoor workers (W2), weekends (W3), and by holiday scenarios HA, HB, HC (see Table 2), each change in the period 2009–2019 compared to 1983 to 2008 using the example of Freiburg.

While only slight changes are recognizable for W1 and W3, amounting to +1% to +3% of MED UVD, holiday stays HA to HC show stronger increases in the order of +4% to +6%. The increase is strongest in W2 with +8% of MED UVD.

Figures 4 and 5 show, also using the example of Freiburg, how these changes in the individual annual erythema-effective UVDs are composed more in detail in scenario I for outdoor and indoor workers, i.e., here as contributions of the individual months.

The months with holiday exposures (May, July, and September) are particularly noticeable for indoor workers due to increased UVDs over the course of the year, with July (in scenario I with a stay on the Balearic Islands, which are 8 degrees further south than Freiburg) also standing out for outdoor workers. Due to the greater exposure on weekdays, the annual variation is more pronounced overall for outdoor workers than for indoor workers and there are also greater increases in UVDs in the period 2009–2019 compared to 1983–2008 than for indoor workers.

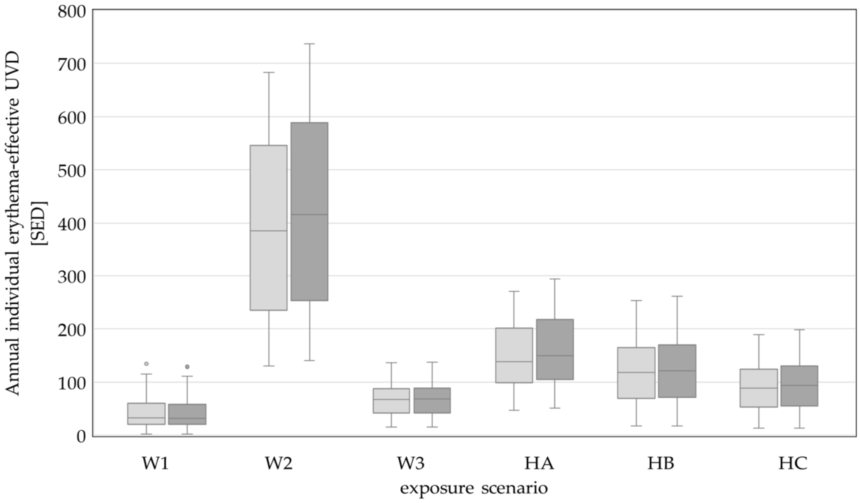

Figure 3. Annual individual erythema-effective UVD [SED] at the site Freiburg; periods 1983–2008 (light gray) and 2009–2019 (gray) and exposure scenarios according to Tables 1 and 2.

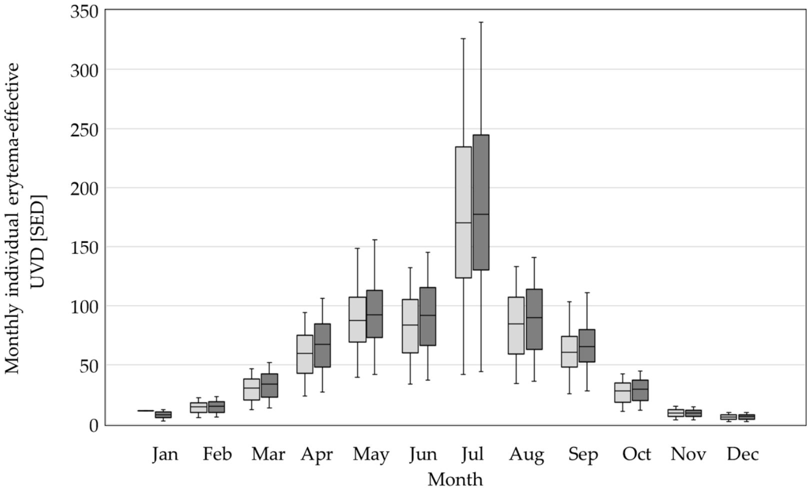

Figure 4. Monthly individual erythema-effective UVD [SED] the site Freiburg; periods 1983–2008 (light gray) and 2009–2019 (gray); and exposure scenario I (case: outdoor work).

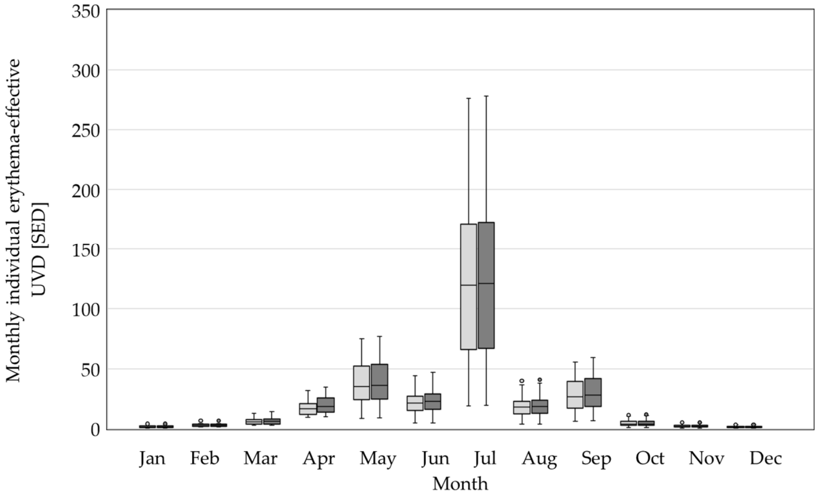

Figure 5. Monthly individual erythema-effective UVD [SED] at the site Freiburg; periods 1983–2008 (light gray) and 2009–2019 (gray); and exposure scenario I (case: indoor work).

Tables 4 and 5 (in the column furthest to the right) show the overall impact of these changes shown here for Freiburg on the annual sum of the individual erythema-effective UVDs for all eight stations considered and for the three combined exposure scenarios and the two types of occupational exposure. For the eight selected European sites between 38° and 60° northern latitude, the MED of the individual annual total UVDs (excluding travel) during the period 2009–2019 is 0.2 to 2.0% higher for indoor workers and 0.6 to 3.2% higher for outdoor workers compared to the period 1983–2008. Considering the scenarios with holiday travel, the ranges are slightly wider with 0.1 to 2.3% for indoor workers and 0.5% to 3.2% for outdoor workers. However, due to the wide range of individual annual exposures, the trends observed are not statistically significant.

The change in ambient UVDs at the residential locations is only partially reflected in the individual total UVDs. Figure 6 shows the share. For outdoor workers, the share of the change in individual UVDs in the changes in ambient UVDs in the period 2009–2019 compared to 1983–2008 amounts to 70% (IQR: 59–72%), 80% (IQR: 64–82%), and 82% (IQR: 59–84%) according to the exposure scenarios I, II, and III, while, for indoor workers, this is 15% (IQR: 13–28%), 24% (IQR: 17–46%), and 36% (IQR: 16–47%), respectively.

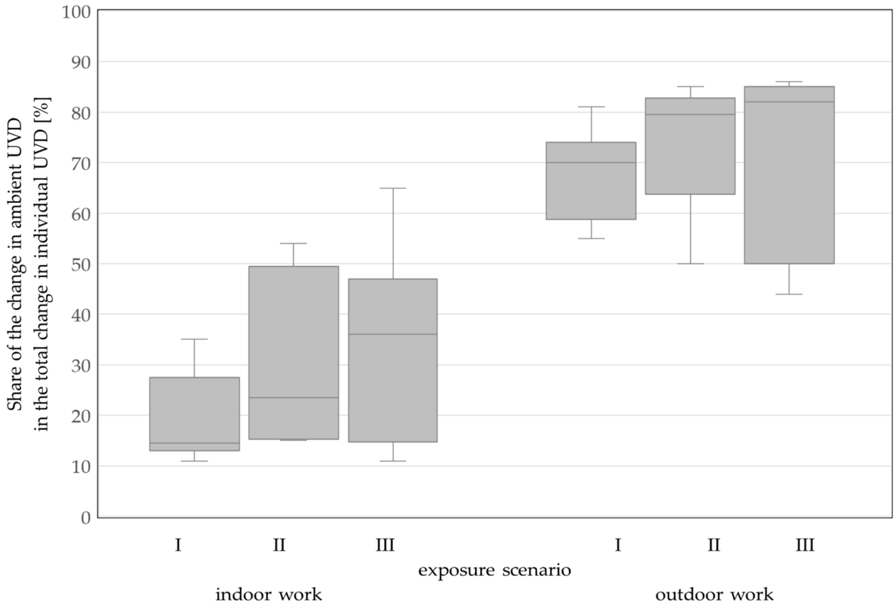

Figure 6. The share [%] of the change in ambient UVD at the residential locations in the total change in individual UVD from 1983–2008 to 2009–2019 for the scenarios I, II, and III for indoor and outdoor work across the eight sites considered.

4. Discussion

4.1. Comparison with Existing Studies

There is currently no publication that evaluates the change in the number of days with the different UVI ECs, to the best of our knowledge. In existing studies that examine trends in relation to the UVI or individual spectral ranges, there are small and not always significant changes and no clear direction of the trends when looking at different sites [3,4,15–17]. For example, Ref. [16] find statistically not significant changes in erythema-effective irradiance for Budapest of 0.24 ± 0.24% per year and Athens of −0.17 ± 0.15% per year, also based on satellite measurements in the period 2005–2018, while Ref. [3] evaluate ground-based spectral measurements of UVR for the period 1996–2017 and find a statistically significant decrease in 307.5 nm irradiance of −0.7% per year for Reading. The present results, which show that the number of days with UVI in the two highest local ECs increased in Budapest and decreased in Reading and Athens, are, therefore, not in contradiction to the previous studies. The results of the present study are also in line with the fact that the direction of the trends is not synchronized at all sites. The changes vary in direction, extent, and regional characteristics, although a basic structure of long-term shifts can be recognized. The different local/regional shifts in the number of days with the different UVI ECs result in different requirements for prevention-orientated communication. For the sites in the humid continental climate zone, the shifts actually follow the pattern that the need for prevention continues to increase at the time of the highest UVR exposure in summer, as the number of days with the highest ECs is characterized by an increase with a focus on this time of year. A different focus arises for the sites in the humid temperate, cold steppe, and Mediterranean climate zones. Since, according to [1], UVR protection is required from EC M onwards, there is a need to communicate the shift in risk to seasons that typically receive less attention in terms of UVR protection, such as winter and spring, given the changes observed. During these seasons, the skin of the fair-skinned population is typically less acclimatized to the sun and, therefore, particularly at risk. Coupled with the thermal conditions, which tend to be cooler than in summer, there is a higher likelihood that radiation exposure will even be explicitly sought [29]. In addition to the relatively well known need for UVR protection in summer, this results in additional prevention content to be communicated.

There are large differences in the personal annual UVDs resulting from the individually different time spent outdoors and the individually different exposure proportions [19,20,22]. As part of the GENESIS-UV study, the exposure of 250 occupations in Germany is recorded [30] and the annual non-occupational exposure is also referenced for the investigation of UVR-related occupational diseases [31]. In the present study, for indoor workers in Freiburg (Germany), an individual annual MED UVD of 263 SED is modelled for exposure scenario I. This is in the order of magnitude of the reference value for the non-occupational annual exposure of 260 SED [31]. The MED UVD attributable exclusively to occupational exposure is in the middle range of dosimeter-measured occupational exposures, which cover a range from 50 SED to 650 SED [30]. This supports the assessment that the method used here can represent the individual annual UVDs in a suitable approximation.

Personal UVDs correlate only to a certain extent with ambient UVDs [19–22]. According to [26], indoor workers are exposed on average to about 3% (2–4%) and outdoor workers to about 10% of the annual ambient UVD, excluding vacations. Without the latter restriction, indoor workers in Northern Europe are estimated to receive, on average, about 5% [19,32]. The present study provides monthly data that add up to annual values of a similar magnitude with a share of around 5% for indoor workers and around 11% for outdoor workers.

4.2. Holidays as a Potential to Compensate for Long-Term Changes

Holiday stays do not play an insignificant role in personal UVDs. However, they are not usually highlighted in UVR protection communication, although they are the main contributor to the annual individual UVD for indoor workers. Indoor workers show changes in personal MED UVDs over the 11-year period from 2009 to 2019 compared to 1983 to 2019, which—in most of the locations considered—are smaller or roughly comparable in magnitude to the changes in MED UVDs resulting from a holiday destination just one degree south or north (Table 4). Consequently, if the changes experienced by indoor workers at their place of residence are related to one year, they are an order of magnitude smaller than the change that would result from a more suitable (in terms of UVR exposure) choice of two-week summer holiday. As a rough approximation, the following compensation option for the observed change in the individual (MED) UVD arises for indoor workers.

Suppose they spend their two-week summer vacation only once in a place that is at least one degree of latitude further north than before. This allows the change to be compensated, whereby the amount of the (cumulative) changes that can be compensated depends on the place of residence. The compensation amount can be specified as the number of years with the corresponding changes in the order of magnitude of the ambient MED UVD. It ranges from around 7 years (Bucharest) to a whole decade (Budapest, Freiburg) and even longer (Bergen, Reading, Warsaw, Madrid, Athens). Outdoor workers are more subjected to the influences of changing ambient UVD. Nevertheless, depending on the place of residence, they would also be able to compensate for the change in individual MED UVDs of at least 1 year (Freiburg, Budapest, Bucharest, Warsaw, Madrid), 4 years (Reading, Bergen), and up to 7 years (Athens) if they were to spend their two-week summer holiday just once in a place that is at least one degree of latitude further north than before (Table 5). The compensation effects discussed are all the more pronounced the further north the holiday destination deviates from the previous one.

4.3. Limitations of the Study

This study draws conclusions based on the UVI ECs according to [1] and based on modelled individual UVR exposures of indoor and outdoor workers. The validity of the ECs/protection recommendations is assumed for all people, even for fair-skinned people with very sensitive skin. Also, in view of the small number of cases, the indication of the possibility of systematization (regarding the patterns of change in ECs) found by grouping the sites according to their position in the Köppen–Geiger climate classification requires further verification by means of larger numbers of cases or, preferably, by evaluating area-wide data.

The individual UVR exposure can, in principle, be determined by dosimeter measurements, but continuous measurements over decades and with a very large number of participants appear hardly practicable [20]. In the present study, models are used instead that depict the diversity of individual UVDs with a certain approximation. The model applied and extended here is based on the results of a survey in Great Britain in 2007 (2060 participants) [19] and a validation in Spain in 2010/2011 (39 participants) [22]. With a more comprehensive validation, which should ideally consider the diversity of personal exposure situations as well as climate- and culture-related behavioral differences [29], the validity of the models could be improved and a greater specification of the modelled exposure cases could be implemented.

In its present form, the modelled assessment of personal exposure behavior can only represent part of the diversity of individual UVDs. However, the two scenarios for indoor and outdoor workers already describe the upper and lower limits of the most likely UVR exposures. Other options (such as part-time employment, walks by senior citizens, school hours and free time for pupils and students, etc.) would most likely fall within the framework defined in the study. A common scenario like a ‘midday walk during lunch’ is explicitly considered in the model via the exposure time model for the working days of indoor workers. For further studies, it is advisable to collect comprehensive data on non-occupational exposure times [22] in order to be able to adequately consider any regional differences in behavior. This also includes differences in leisure behavior at the possible holiday destinations, possible changes in exposure behavior from year to year, and how individual UVR exposure depends on age and the age structure of the population. The model uses the concept of the ‘exposure fraction’ (which describes the ratio between individual UVR exposure and ambient UVR) for the whole body. To simplify matters, various dependencies on body site, certain activities (with body posture and orientation to the sun), and clothing are abstracted, and only a random distribution within specified limits is assumed.

This study considers three holidays scenarios as possible examples. EU tourism statistics show that EU citizens travel a lot within their own country and that Spain and Italy are currently the top foreign destinations [33]. It is currently not possible to allocate this collected data to longer holiday stays, but this would be advantageous for a more precise evaluation. Considerations in connection with the thermal conditions (e.g., selection of the holiday destination with avoidance of excessive heat [34]) or other boundary conditions are recommended for an appropriate picture of the diversity of individual UVDs [29].

5. Conclusions

In Europe, there are long-term changes in ambient UVR that result in both statistically significant shifts in the frequency of occurrence of UVI ECs [1] and a slight increase in individual annual erythema-effective UVDs, whereby the latter is not statistically significant due to the wide range of individual annual UVDs. Although changes can be observed at all eight locations considered, it is not appropriate to generalize the results in the sense that the number of days requiring UVR protection (ECs ‘moderate’ or higher) is generally increasing. Rather, there are indications that there are typical patterns of change for the sites in different Köppen–Geiger climate zones [28]. In some cases, there are seasonal shifts to periods in which UVR protection is usually paid less attention (spring, winter), and, therefore, additional information and prevention needs arise. In order to verify and quantify this more precisely, site- or region-specific analyses of UVR are recommended, preferably with the additional inclusion of ground-based measurements [5,35].

Together with the small increase in the individual annual UVDs between 2009 and 2019 compared to from 1983 to 2008 (change in MED in the order of up to +0.18% per year for indoor workers and up to +0.29% per year for outdoor workers), it can be concluded that UVR-associated health risks are increasing sightly. The long-term changes in individual UVDs only partially reflect the changes in ambient UVDs. Outdoor workers are particularly affected, as their share of working day UVDs (MED) accounts for 70% of their annual UVD and they receive around 80% of the ambient changes. With regard to their health protection, there is a need to review the existence and effectiveness of prevention measures in the occupational context and to optimize them with regard to the trends identified.

For indoor workers, on the other hand, holiday exposure accounts for the largest share (even without traveling to regions with more intense UVR than at the place of residence) and is responsible for about half of individual annual UVDs (MED). Changes in holiday destination can have a much greater effect than the relatively small changes in the place of residence and work and can either significantly reduce or increase the individual annual UVDs. Changes in the choice of an exemplary holiday destination offer both indoor and outdoor workers the potential to compensate for the observed long-term trend at their place of residence and work. Holidays as a potential ‘game changer’ have, so far, been underrepresented in communication on UVR protection and can be a useful addition in terms of behavioral prevention.

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