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Review

Weather-Related Human Outdoor Behavior with Respect to Solar Ultraviolet Radiation Exposure in a Changing Climate

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Abstract: Climate-related changes in human sun exposure behavior can be an important influence on future ultraviolet radiation (UVR) related disease risks. In particular, active leisure mobility and leisure activities are more dependent on weather conditions than routine activities. However, the direction and extent of the effects vary. For temperate and cold climates, the available studies provide indications that a possible increase in UVR exposure would primarily result from a reduction in clothing and only secondarily from changes in the time spent outdoors. Existing studies suggest a nonlinear, bell-shaped relationship with threshold value effects for the relationship between outdoor time and thermal conditions. If the local climate is already very warm and there are only minor seasonal differences, there is no statistically significant evidence of changes in behavior. If there is significant warm discomfort, there is a tendency to avoid being outdoors or in the sun. It is not justified to simply transfer and generalize results and conclusions to different climates and seasons and between different leisure activities and forms of active mobility. The geographical context must be considered also in terms of cultures and habits, adaptations, traffic and land use (urban, rural). In addition, changes in behavior can develop differently depending on individual characteristics of people such as heat affinity, leisure type, age and gender. Differentiated analyses are required that take into account and balance opposing effects.

Keywords: human behavior; UV exposure; climate change; time outdoors

Citation: Laschewski, G.; Matzarakis, A. Weather-Related Human Outdoor Behavior with Respect to Solar Ultraviolet Radiation Exposure in a Changing Climate. *Atmosphere* **2022**, *13*, 1183. https://doi.org/10.3390/atmos13081183

Academic Editor: Kostas Eleftheratos

Received: 31 May 2022
Accepted: 25 July 2022
Published: 26 July 2022

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1. Introduction

When discussing the human health consequences of global climate change, it is often argued that global warming would likely change human outdoor behavior. Climate-related changes in human sun exposure could be the most important influence on future ultraviolet radiation (UVR) related disease risks. For example, the incidence of skin cancer would likely increase, caused by increased exposure to solar UVR [1–6].

The environmental conditions related to the solar UVR at the earth's surface have changed in the last few decades as a result of changes in the ozone in the stratosphere and the changing climate. Climate change and stratospheric ozone depletion interact in several direct and indirect ways [7]. Climate change can influence the depletion of ozone in the stratosphere by changing temperature, humidity and wind conditions in the stratosphere and troposphere [8]. Greenhouse gases such as N_2O and CH_4 can disrupt the formation of ozone [9]. In the southern hemisphere, ozone depletion is a direct contributor to climate change. In the northern hemisphere, the effects of ozone depletion on the climate are lower [10] because there the variability of the meteorological conditions is greater from year to year compared to the southern hemisphere. The depletion of stratospheric ozone causes increased UV-B radiation on the earth's surface, although the increase—due to the success of the Montreal Protocol—was only pronounced in the Antarctic. In the middle latitudes, it was low (5–10% based on the maximum value of the UVR at noon with a clear sky) and negligible in the tropics [7]. With the recovery of the stratospheric ozone layer over the next few decades [9], it is expected that the maximum values of UVR will decrease at noon with a cloudless sky (e.g., by 2–8% in mid-latitudes depending on the season and exact location) [7,10,11]. As a result of climate change, further effects are to be expected from changes in cloud cover, aerosols and albedo, which will not only affect UV-B but also UV-A radiation. The effects will vary from region to region [12] and can subsequently lead to both an increase and a weakening of UVR [10]. Typically, a decrease in cloud cover and aerosols cause an increase in UVR, while a decrease in ground albedo has a reducing effect on UVR. It is therefore expected that global climate change will continue to change UVR inconsistently and influence the response of humans and the environment to UVR in a region-specific manner [7,10,13].

Solar UVR is biologically very effective and UVR exposure can have both positive and negative effects on human health [14,15]. The best-known positive effect of UVR exposure is the initiation of vitamin D synthesis in the skin, which is essential for bone health and can reduce the risk of a variety of diseases [14,16]. On the other hand, UVR exposure is considered to be the most important risk factor for the development of melanoma and non-melanoma skin cancer [17–22] as well as eye diseases such as cataract and pterygium [23–26]. In addition, UVR-induced immunosuppression can reactivate latent virus infections [27].

At the population level, UVR exposure (in addition to demographic factors such as age and gender and the distribution of the various skin types in the population) contributes to the overall burden of disease. UVR exposure is a function of the UVR present in the environment and the individual exposure behavior of people. With rising UVR values in the environment, the incidence of non-melanoma skin cancer in populations of similar ethnic origin increases [28]. Each individual influences their own risk of UVR-induced illness through their exposure behavior outdoors, such as the length of their stay, the time of day and season, the geographical location, the extent of the exposed body parts and staying in direct sun or shade.

Therefore, human behavior is one of the most important control variables. A model for estimating the exposure of the population to solar UVR examines the variability of exposure at different times of the year [29]. In the geographical latitude of 50° N, the daily erythema-effective UVR doses at the summer and winter solstice differ by around 20 times when the sky is clear. This contrasts with an approximately 1000-fold variation in the daily personal dose throughout the year and thus illustrates the potential extent of behavioral influences. The time that people spend outdoors is generally characterized by great heterogeneity [30]. Different weather conditions such as the daily maximum temperature and precipitation contribute to the variance [31]. With regard to the health consequences of UVR exposure, however, the understanding of how sun exposure behavior of people can change with regard to meteorological factors is crucial in connection with the prediction of UVR-related health risks with future climate change scenarios [32] and the timely planning, development and implementation of suitable adaptation measures.

2. Methods

This review article combines a systematic and a manual search to answer the research question: ‘Do people spend more time outdoors in a changed climate and are they more exposed to UVR?’. A systematic search was carried out in the databases Pubmed, Scopus, ScienceDirect and Cochrane for the period from 1998 to 2020. The search linked weather-related search terms (temperature, heat, sunshine duration, weather, thermal comfort, cloudiness, precipitation) with search terms for recording human behavior and different areas of life (behavior [behavior] pattern, habit, behavior [behavior] change, sunburn, erythema, UVR exposure, setting, living environment, work environment, occupation, school, kindergarten, day care, leisure). The search included title and abstract and was limited to ‘humans’. From the large number of hits from this systematic search, only 6 actually relevant studies could be selected. For this reason, a manual search was also carried out in the sense of a scoping review, so that 59 studies are available for evaluation. The studies can be classified into the following study types:

- Type I: Studies that actually directly or indirectly investigated this question (3 studies);
- Type II: Studies that investigated the relationship between weather influences and behavioral aspects without direct reference to UVR exposure (41 studies);
- Type III: Studies that exclusively examined UVR exposure and discussed possible explanations or indirectly provided indications of weather influences (15 studies).

Figure 1 shows the geographical distribution of the evaluated studies. It is considered useful to differentiate the key statements from the publications and the conclusions according to the various climatic zones (cold, temperate, subtropical, tropical). There are mainly studies available from temperate and subtropical climatic regions, to a lesser extent also from cold and tropical climatic regions.

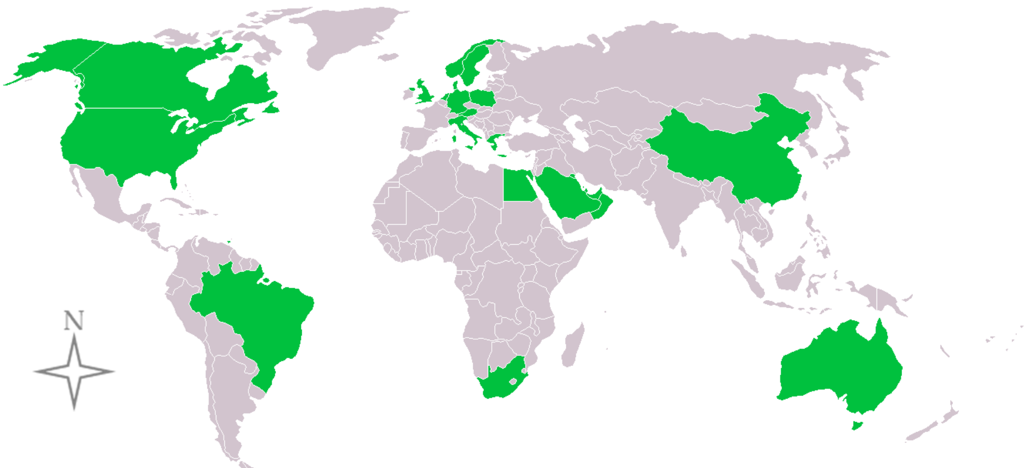

Figure 1. Geographical distribution of the evaluated studies: the green color shows the countries in which studies were carried out (map scale 1:220,000,000).

3. Type I Studies

Type I studies actually directly or indirectly investigated the research question "Do higher temperatures or climate change lead to more time spent outdoors and increased personal UVR exposure?". Only three studies were identified. They have been carried out in Australia and the southeastern United States.

3.1. Comparison of Climatic Zones: Temperate, Subtropical and Tropical Climates

A study that provides essential findings for the above question [32] examined the impact of meteorological factors on individual sun exposure behavior at weekends in four Australian cities (Townsville (19° S), Brisbane (27° S), Canberra (35° S) and Hobart (43° S)), each about 8 latitudes apart. The latitude range of the study sites ensures significant differences in meteorological factors, but also in UVR values of the environment. In terms of the prevailing climate, Townsville is in the tropics, Brisbane in the subtropics and Canberra as well as Hobart are in the temperate climate. Between May 2009 and December 2010, 1002 adults aged 18 to 75 were recruited, roughly equally distributed by gender, age group and study region. Participants recorded the time they spent outdoors. This was done every hour from 5:00 a.m. to 7:00 p.m. on 10 consecutive days, with the present study evaluating the first weekend within the period. The categories were: 0 min, <15 min, 15–29 min, 30–44 min, 45–60 min. It was also recorded what clothes the participants wore on their torso, lower body, head and feet during each hour of the day outdoors. Daily personal UVR exposure was measured with a polysulfone dosimeter on a bracelet. Overall, participants spent an average of 105 min per day outdoors and received 4% (median: 4%; average:

8%) ambient UVR. This value decreased to 1% after taking into account clothing coverage (median: 1%; average: 2%).

Only one study site (Hobart) saw an increase in the time spent outdoors at weekends when the maximum daily temperature was higher. This city is located at the highest of the examined latitudes. However, taking into account the age and sex of the participants, this relationship was not statistically significant. In the other three places, there was no trend towards an increase in time spent outdoors at higher maximum temperatures. If the analysis is limited to days with maximum temperatures above 30 °C, in Brisbane, the time spent outdoors at higher maximum temperatures actually decreased somewhat. An analogous evaluation for a thermal index, the apparent temperature [33,34], essentially also yielded these results. The same applies if the deviations from the seasonal average values are used instead of the absolute values of the meteorological variables. Consequently, the assumption of acclimatization effects within the seasons cannot be supported by this study. If the relationships between outdoor time and UVR in the environment for each of the places are looked at, they are similar to the relationship to temperature. This is probably due to the comparatively close correlation between the maximum daily temperature and the average daily UVR in the environment.

However, as important parameters in terms of health protection, the individually obtained UVR doses are more important than the time spent outdoors, which is often used as an approximation for personal sun exposure. The study found only a moderate correlation between outdoor time and measured UVR exposure. The correlation between time spent outdoors and the clothing-adjusted UVR dose was even lower. Spearman's correlation coefficients were 0.51 vs. 0.61.

The relationship between the individual clothing-adjusted UVR doses and the meteorological factors shows a heterogeneous appearance in the four locations studied. Table 1 illustrates the results in color. In order to obtain information as to which causes may be responsible for the increased individual clothing-adjusted UVR doses, the relationships between the time spent outdoors or the clothing of the participants and the meteorological factors were examined. The color red shows that, with higher values of the meteorological factor, more time was spent outdoors or clothing was reduced. Both of these would result in higher UVR exposure, which, given the prevailing level of UVR in Australia, must be classified as a health risk.

Table 1. Relationship between the individual clothing-adjusted UVR doses and meteorological factors (maximum temperature, relative humidity, ambient UVR) in Australian locations (data base: [32]). Causes of the changes in the individual UVR doses: changes in the time spend outdoors (t_{out}) or changes in clothing (clo). Color white: no association (0); color red: statistically significant positive association (+); color slightly red: positive, but not statistically significant association; color green: statistically significant negative association.

City	Adjusted Personal UVR = f (Maximum Temperature)		Adjusted Personal UVR = f (Relative Humidity)		Adjusted Personal UVR = f (Daily Ambient UVR)	
Townsville 19° S	0		0		0	
	t_{out}	clo	t_{out}	clo	t_{out}	clo
Brisbane 27° S	0		0		0	
	t_{out}	clo	t_{out}	clo	t_{out}	clo
Canberra 35° S	+		0		0	
	t_{out}	clo	t_{out}	clo	t_{out}	clo
Hobart 43° S	0		0		+	
	t_{out}	clo	t_{out}	clo	t_{out}	clo

In Townsville and Brisbane, no association was found between meteorological factors and the clothing-adjusted individual UVR dose. In Canberra, however, the clothing-adjusted individual UVR dose increased statistically significantly with the daily maximum temperature. In Hobart, it increased statistically significantly with higher ambient UVR. In these cases, it was statistically significant that the participants in Canberra and Hobart wore less protective clothing (no long-sleeved top or long pants). In addition, an opposite trend could also be shown: in Canberra, a statistically significant reduction in the time spent outdoors was found with higher relative humidity (Table 1).

Table 1 makes it clear that there is no clear answer to the research question asked at the beginning for study type I either. A hint was found, but no statistically significant evidence for the claim "higher temperatures lead to more time spent outdoors". Rather, there is evidence for the claim "higher temperatures or higher values of ambient UVR are associated with a reduced likelihood of wearing a long-sleeved shirt or wearing long trousers during time spent outdoors in some locations". Changes in sun exposure behavior, which lead to increased individual UVR doses, appear to be mainly due to the type of clothing worn.

The differentiation according to locations with different local climatic conditions makes it possible to obtain information on the causes for the different behavior. Townsville and Brisbane are in regions of lower latitude. Townsville is located in the tropical climate zone, Brisbane in the subtropical climate zone. It is relatively warm all year round there with daily maximum temperatures during the study period in the range of approximately 24 to 37 °C (Townsville) and 20 to 35 °C (Brisbane). This fact may explain the lack of variation in sun exposure behavior both over the year and in connection with meteorological factors. In Townsville, the participants tended to be lightly clothed, and there was little opportunity to wear even less in warmer temperatures. The places at higher latitudes (Canberra and Hobart) are located in the temperate climate zone and are characterized by greater seasonal differences in the local climate. The daily maximum temperatures during the study period were in the range of approx. 9 to 35 °C and thus also cover a wide range where long (-sleeved) clothing is usually worn. Local climatic characteristics can also provide an indication of reducing the time spent outdoors at higher relative humidity in Canberra. While Townsville, Brisbane and Hobart are coastal cities at sea level, Canberra is the only city inland at an altitude of 580 m. It is usually much drier there with an annual relative humidity of 37%, while it is well above 50% in the other study regions. People in Canberra may avoid being outdoors because they are not used to high humidity.

This study [32] expands an earlier work from Australia [35] to include data over a whole year. In the previous study of 2003–2004, Australian adolescents and adults were interviewed by telephone about the time spent outdoors and other behaviors in relation to sun exposure during the UVR peak times (10:00 a.m. to 2:00 p.m. AEST) on the previous summer weekend [35]. The sun protection behavior of adults was most strongly influenced by the temperature (at 3:00 p.m.). When the temperature was higher than 22 °C (temperature < 22 °C as the reference category), adults spent more time outdoors and were more likely to wear hats and sunscreen, but much less often clothing that covered arms or legs. Other meteorological factors such as cloud cover and wind speed were not associated with the sun exposure behavior of people in this analysis. However, on hotter days (>28 °C), some participants spent less than 15 min outdoors, i.e., they stayed indoors during peak UVR times.

In the follow-up study [32], the temperature could be modeled as a continuous variable and covers a larger temperature range from 9 to 37 °C. The behavior was recorded in more detail and UVR exposure was measured objectively. In the earlier analysis [35], there was no separate investigation for the different locations of the participants. It can be assumed that, in the older study [35], the influence of temperature on behavior was influenced by the climatic conditions of the region, but that this influence remained hidden due to the study design. The influences of confounder variables, such as acclimatization effects and clothes usually worn, could therefore not be analyzed.

3.2. Subtropical Climate

To what extent it depends on individual characteristics how people behave in relation to heat and sun exposure, investigated [36] in Athens (34° N) in the southeastern United States. They conducted an online survey of 1400 students. It turned out that there are fundamental differences in people's heat affinity, namely heat-liking and heat-disliking people. The thermal and radiation conditions in the study region are characterized by very high to extreme values of the UV index in the period from April to September and by mean temperature maxima between 11.8 and 32.3 °C, with values higher than 30 °C in all summer months (June, July, August). In March, the average daily maximum temperature is 18.3 °C and in October 23.3 °C. The evaluation shows that Americans of the Caucasian type are heat-liking with a share of 51.3%. For the other ethnic types, this only applies to a proportion of 44.9%. The heat affinity of men and women does not seem to differ significantly. With a view to the risk of UVR overexposure, people who like heat are particularly at risk in the summer months because a larger proportion of them prefer to be outdoors. People who dislike heat show bimodal preferences for the months of the year when they like to be outside, with 75% in March and 94% in October, which is in contrast to a very small proportion of just 4% in July. The heat-liking people use proportionally less sun protection than the heat-disliking people.

The conclusion that emerges is the need for a more differentiated approach. It is important to consider individual characteristics, such as heat affinity with regard to temperature-dependent behavior and UVR exposure. To assume a general, uniform behavioral trend of people is too simplistic. With regard to possible changes in behavior associated with climate change and corresponding prevention strategies in the public health system, there is a need to analyze the expected changes in weather conditions, both in the transitional seasons and in summer, or in other words with regard to the occurrence of thermal comfort and discomfort. In addition, it would make sense to examine the effects on the respective parts of the population of heat-liking and heat-disliking people separately and to think about developing more specific information and sun protection strategies for these subgroups of the population. The key findings and conclusions of type I studies are summarized in Table 2.

Table 2. Summary of the key messages and conclusions from the type I studies.

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
Temperate	Australia, Canberra 35° S, Hobart 43° S	• With currently rather moderate local climate conditions and with larger seasonal differences, there is statistically significant evidence of possible behavioral changes associated with climate change. • Increased individual UVR doses can mainly be proven statistically by changes in the type of clothing worn (reduced likelihood of wearing a long-sleeved shirt or wearing long trousers). • There is also statistically significant evidence of avoiding staying outdoors in unusually high humidity. • There is also some evidence of the tendency to extend the time outdoors at higher maximum temperatures, but this is not statistically significant.	[32]

Table 2. *Cont.*

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
Subtropical, (* tropical)	Australia, Townsville * 19° S, Brisbane 27° S	• Given that the local climate conditions are already very warm and with minor seasonal differences, there is no statistically significant evidence of behavioral changes associated with climate change. • There is some evidence of the tendency to avoid being outdoors in extreme heat.	[32]
	USA, Athens 34° N	• There are individual differences in people's heat affinity, which have a strong influence on people's behavior in terms of sun exposure. • The heat-liking people spend more time outdoors in the summer months and are more exposed to the risk of UVR overexposure, while the heat-disliking people tend to do so in spring and autumn.	[36]
Over All Exa-Mined Climates	➢ Changes in weather conditions, such as temperature and humidity, can change people's behavior with regard to sun exposure. ➢ The direction and extent of the effects vary according to the prevailing local climate. Therefore, the transferability of results from climatically different regions and from different seasonal conditions is not directly guaranteed and always requires a critical examination as to whether it is permissible. ➢ Depending on people's different heat affinity, behavioral changes associated with climate change could develop differently, depending on the season or depending on the thermal comfort or discomfort conditions.		

4. Type II Studies

Type II studies have analyzed the connections between weather influences and behavioral aspects without directly investigating UVR exposure. In order to systematize the 41 studies here, the focus can be placed either on behavioral aspects or on weather influences. With regard to the behavioral aspects, studies are available on three basic subject areas and provide contributions to the following research questions:

- How do meteorological conditions influence the type and scope of leisure activities?
- How do meteorological conditions influence active mobility?
- How do meteorological conditions influence the use of public space?

Despite a partial content-related overlap of the subject areas, redundancy should be avoided. Therefore, active forms of mobility (cycling or walking) are listed separately in favor of better systematization and are not classified under leisure activities.

In some cases, climate zones are summarized if the results of comparative studies are shown.

4.1. How Do Meteorological Conditions Influence the Type and Scope of Leisure Activities

4.1.1. Temperate Climate

A study from Canada [37] is developing a data-driven weather index for the number of visitors to beach parks in the Great Lakes area (Ontario, 43° N). The evaluation shows that the overall index is predominantly (75%) determined by thermal comfort, with sunshine or cloud cover accounting for 15% and precipitation and wind accounting for 5% each. It turns out that the weather sensitivity of the beach tourists' decision to stay is not linear. A relatively large change in visitor numbers can result from a relatively small change in weather conditions, when a key threshold is exceeded. In addition, institutional seasonality has an impact on beach visits.

In Canada (Halifax, 44° N), the method of making entries in time diaries was used to derive insights into weather influences on leisure time behavior [38]. The influence of the weather was rather small, but it was about twice as great for sporting activities as for non-sporting activities (5.8% vs. 2.9% change). On days when there is longer daylight and warmer temperatures, more time is spent outdoors, with the length of the day having the greatest influence. The seasonal effect of other publications [39–41] is confirmed by this study. A negative correlation was found for precipitation (all activities) and for wind as well as maximum temperature (sport).

In another study in Canada (Montreal, 45° N), the behavior of adolescents was surveyed using questionnaires [39]. In the warmer months of the year, there was increased physical activity among adolescents, although no distinction was made between indoors and outdoors. Unfortunately, the summer months were not recorded, so that in most cases of the transitional seasons, which are warmer than winter, the thermal conditions will have been in the comfort range, even if no details are given. The study evaluates the relationship to the mean daily temperature and finds an increase in activities of 1 to 2% (spring vs. autumn) for every 10 degrees Celsius increase. The influence of day length was not considered.

In the Netherlands, a study [42] investigated the relationship between the daily weather and watching TV as a leisure activity. As expected, unfriendly outdoor conditions (darkness, precipitation, cold, strong wind) lead to increased television consumption. However, the study did not investigate whether more time is actually spent outdoors when outdoor conditions are more favorable. With regard to the mean daily temperature, the evaluation showed that TV consumption was 10 to 18 min less when it was 20 °C instead of 10 °C.

A study [43] in Poland (Warsaw, 52° N) examines the thermal sensations of people staying outdoors in urban environments for the purpose of tourism and recreation. A preference for slightly warm thermal conditions and sunny weather with little wind was identified. The study gives indications of an alliesthesia, i.e., a different thermal perception of comparable biometeorological conditions in the different seasons. The results suggest that tourists' thermal sensations differ from the reactions of other respondents and are influenced also by psychological factors (such as attitudes and expectations). A significant influence of the climate of origin of the respondents on the thermal sensations and preferences was observed. In addition, it is found that older people are less sensitive to temperature fluctuations and less often prefer changes in their thermal environment.

Studies from the temperate climate zone [37–39,42] allow the following conclusions: The relationship between thermal conditions and the frequency of people staying outdoors is nonlinear with threshold effects. Exceeding the threshold leads to a marked increase in the time spent outdoors. Knowledge of the threshold values and their future frequency of occurrence is important for making statements about changes in behavior caused by climate change. In addition, lower linear effects are found in the area of thermal comfort. An extrapolation of results that refer exclusively to this is likely to be an oversimplification. Since the length of the day has a great influence on outdoor activities and is not influenced by climate change, temperature influences on behavior should also be investigated within the seasons in order to be able to separate the temperature influences from the effects of the length of the day.

4.1.2. Subtropical Climate

In the subtropical climate of Australia (Sydney, 33° S), the behavior of older people during heat waves was studied [44]. The research method consisted of group discussions and interviews and did not give a completely uniform picture of the behavior. However, there were often changes in the daily activities (fewer activities; different times for the activities; different, for example, air-conditioned places for the activities). The commonality of the behavioral changes is the avoidance of exposure to intense heat.

In a review article [45], obstacles and factors conducive to physical activity in the Middle East and North Africa were examined. Hot climates, along with a lack of appropriate sports facilities, time, social support and motivation, gender and cultural norms, were the most commonly reported obstacles to physical activity. The review article names studies from Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Bahrain, Oman and Egypt. In a study from the United Arab Emirates, cooler weather is considered to be a conducive factor for physical activity. The studies only confirm qualitatively that people tend to avoid outdoor activities in hot conditions. In addition, there might be less need for action with regard to UVR exposure, due to cultural norms.

4.1.3. Tropical Climate

The influence of weather and climate on walking behavior in the fields of leisure and tourism has been reviewed [46]. The authors found no consistency in the studies. Studies that refer to individuals aged 60 years or older in Brazil (Florianópolis, 28° S) mention heat or hot climate serve as limits or barriers to outdoor physical activity [47], but do not provide objective data.

Another study [48] carries out meteorological measurements on several Caribbean beaches on the islands of Tobago (11° N), Barbados (13° N) and St. Lucia (14° N), and uses a questionnaire survey to determine the thermal comfort of beach tourists. Most beach users would not change the thermal conditions, with some preferring even warmer conditions. Beach users' thermal preferences are up to 18 °C warmer than preferred thermal conditions in urban parks. Beach users have fundamentally different comfort perceptions and preferences than people who use urban spaces.

Studies from the subtropics and tropics [44,45,47,48] allow the following conclusions: The consideration that higher temperatures are directly associated with more time outdoors and significantly increased UVR exposure is likely too much of a simplification of the relationships. With a further increase in hot conditions and heat waves, the avoidance of physical activities outdoors is to be expected in these climatic zones. There is also evidence that results and conclusions can not easily be transferred and generalized between different types of recreational activities and different climates.

4.2. How Do Meteorological Conditions Affect Active Mobility

4.2.1. Temperate Climate

Ref. [49] examines aggregated hourly bicycle usage data from Australia (Melbourne, 38° S). Up to a certain optimal driving temperature, the volume of cycling increases with the Apparent Temperature (AT). The AT is a thermal index, which, in addition to the air temperature, takes into account the effect of air humidity and wind speed [33,34]. Beyond the optimal AT, the volume of bicycle use decreases with increasing temperature. The optimal AT varies from location to location (in the Melbourne region) and lies in the range between 25 and 28 °C. In relation to a reference point of 0 °C, bicycle use is around 60% higher under optimal thermal conditions (AT). It should be noted that this result cannot be directly applied to the issue of climate change. For this, a reference to the climatologically typical annual course of the AT and the consideration of the deviations from this previously typical course would be useful.

Ref. [50] analyzes the number of bicycles per hour for five automated counting stations in Canada (Montreal, 45° N) using an absolute and a relative cyclist regression model. They find that absolute cycling increases by 4–5% when the air temperature increases by 10% in relation to the average air temperature. However, an increase in the air temperature can reduce the number of bicycles when the air temperature is above 28 °C and the relative humidity is above 60%. Moderate or heavy rain in combination with fog, drizzle or freezing rain reduces the driver base by 19%. Ref. [51] carries out a similar analysis and includes both recreational and utilitarian bicycle counting stations. They find nonlinear effects of air temperature and humidity and also observe that recreational cycling is more sensitive to the weather, as was [52–55] in the daily bicycle count.

Ref. [56] examines hourly bicycle counting data from 188 bicycle counting stations in 37 different cities and regions throughout Germany (48–54° N) and find a nonlinear effect of the air temperature. Cycling increases with rising air temperature and peaks at around 29.5 °C. When the air temperature reaches even higher values, the number of bike rides decreases again. A higher intensity of precipitation also leads to a greater decrease in the number of bicycles. Relative humidity, wind speed and cloud cover have a negative impact on the hourly cyclist population.

Ref. [54] examines temporal fluctuations in daily cycle traffic, based on time series of daily cycle counts in two cities in the Netherlands (Ede and Gouda, 52° N). The authors develop linear and nonlinear regression models and find that an exclusively linear model does not represent an optimal approach. Above a certain threshold of hot temperature, people cycle less, as has also been found in other studies [49–51,55,56]. Nonlinearity also exists with respect to the influence of sunshine duration (positive), precipitation and wind (negative). As in other studies [52,53], the study [54] found out that there is a significantly greater influence of the weather on recreational cycling than on utilitarian cycling.

Ref. [53] shows similar effects for the greater Rotterdam area (52° N), the Netherlands. Air temperature shows a highly significant bell-shaped effect on cycling, mainly for recreational trips [49,52,55]. The weather effects vary in different regions, and the weather has a smaller influence on cycling trips in densely populated areas than in sparse areas.

Also in the greater Rotterdam area (52° N), the Netherlands, Ref. [57] analyzes the effects of weather on daily travel frequencies and the choice of means of transport for older people. The results show differences between elderly and non-elderly people in terms of overall travel frequency (elderly people travel less) and mode of transport (older people walk more and use the car less) and temperature effects (no positive effect on the elderly). The last is most likely a consequence of the higher heat sensitivity of the elderly. The results of previous studies [58,59] indicate that observed dry, windless, sunny and warm, but not too hot weather conditions, favor cycling over other modes of transport, but temperatures above 25 °C have negative effects. In addition, the outdoor thermal perception differs depending on the means of transport and population group.

Using travel diary data from Uppsala (60° N), Sweden, a study [52] examines the use of bicycles as a function of the weather in spring. They find positive (air temperature) and negative (cloud cover) effects on the proportion of bicycle rides. The relationship between air temperature (−1 to +15 °C) and bicycle use for this temperature range is linear with no threshold value effects. However, these midday temperatures enable thermal comfort.

Ref. [60] uses data from two automated bicycle counters in the USA (Seattle, 48° N) in 2014 and find that the explanatory power of the weather indicators varies in the models for the different seasons. Interestingly, positive temperature deviations have the strongest influence in spring. In agreement, for example, with the results for northern and central Sweden [61], the effects of high temperatures in summer are missing. Here, the number of rides fluctuates around a steady value when the average daily temperature exceeds 20 °C. This model differs from the results of [62], who also evaluate data from Seattle, but uses data from additional years, and finds a bell-shaped model of temperature cycling behavior, with the peak temperature being around 20 °C. The limited amount of data here could be one of the possible explanations for the different results.

Weather effects can also be estimated using data from public bike-sharing programs. Ref. [63] analyzes data from such a program in New York (41° N), USA. Moderate thermal conditions (up to 28 °C), little wind, moisture and no precipitation have a positive effect on cycling.

In addition to these findings, the effects of climate change on the use of bikeshare in New York (41° N), USA are presented by [64]. The total hours driven increase significantly with the temperature up to a threshold temperature of 26 to 28 °C, above which they decrease significantly as the maximum temperature increases. On this basis, the study predicts the future use of bikeshare, depending on long-term air temperature forecasts from various climate models and emission scenarios. For the period 2040–2069, there is a net increase in total annual cycling hours for all emission scenarios and climate models by an average of 2.6 ± 1.3% and 3.1 ± 1.6% for the emission scenarios RCP4.5 and RCP8.5. For the summer season (June–August), it is forecasted that the total number of hours driven will decrease (RCP4.5 scenario 2.9 ± 0.13%, RCP8.5 scenario 4.5 ± 1.6%). On an annual basis, however, the projected declines in summer would be more than offset by the increases in the winter, spring and autumn seasons. Conclusions for a corresponding assessment of the UVR exposure are not yet available and are not even possible qualitatively. In general, in the temperate climatic zones, there is a higher UVR exposure in summer, so that a decrease in summer would have a greater impact on the UVR dose than an increase of the same magnitude in the other seasons. In addition, there is a strong dependency on the times of day, which in turn could be subject to changes, at least for leisure traffic.

A study from Vermont (44° N), USA shows that the use of bicycles as a means of transport to work depends heavily on weather conditions [65]. The number of cyclists increases on sunny days with higher temperatures but decreases above 28 °C. Days with wind, rain and high humidity are associated with less cycling.

Studies from the temperate climate [49–56,60,65] allow the following conclusions: Recreational cycling is more sensitive to the weather than utilitarian trips and hence an important study area with regard to potentially increased UVR exposure in the course of climate change. Similar to leisure activities as a whole, there is a nonlinear (bell-shaped) relationship to temperature with this active mobility, with less cycling at low and high temperatures and possibly an almost linear course in the area of thermal comfort. In addition, there are different effects on older and non-older people, which can be interpreted as a consequence of the higher heat sensitivity of older people. A separation of the influences of day length and temperature is still missing in the studies. In addition to the temperature, there is also a positive effect on the duration of sunshine, while days with wind, rain and high humidity are associated with less cycling. In densely populated areas, weather conditions have less of an impact than in areas with a low population density. The weather effects are consequently different in different regions.

A simple, straightforward conclusion that higher temperatures due to climate change and a possibly increased number of hours of sunshine, leading to an increase in active mobility with possibly increased UVR exposure, can not be derived. Rather, one would inevitably infer the need for a differentiated analysis that takes opposing effects into account and balances them. Climate change scenario calculations provide initial indications of an overcompensation for projected decreases in active mobility in summer by increases in the other seasons, although an assessment of the development of the UVR dose derived from this is not yet available.

4.2.2. Comparison of Climatic Zones: Cold and Temperate Climates

A study from Sweden [61] is designed in such a way that the evaluations provide some information on the question of the separation of the influences of day length and temperature. Ref. [61] investigates the influence of the variability of the weather characteristics on the individual choice of the mobility mode in different seasons and regions in Sweden using 13 years of data. The daily average temperature is normalized depending on the region and season and divided into five categories "very cold", "cold", "normal", "warm" and "very warm". With this approach, the influence of the perception of regional and seasonal temperature fluctuations is examined. At the same time, a climate change-related interpretation of the study results, with regard to the behavior in warmer ambient conditions, is made possible. For illustration, selected qualitative results of the study [66] are shown in color in Table 3.

Obviously, the relationships between human behavior (with regard to mobility decisions) and thermal conditions are not constant, but are shaped by other regional characteristics and can also show seasonal differences. In the overall view of all seasons, under conditions that are warmer and significantly warmer than normal, with regard to the form of mobility of cycling, behavior across all regions of Sweden is largely synchronized: the bicycle is increasingly used as a means of mobility, in autumn in all regions, in spring and winter mainly in central and southern Sweden, while in summer only people in southern Sweden move significantly more by bike. When walking, in spring, summer and autumn, contradicting behavioral trends in relation to the various regions of Sweden can be seen in more than half of the categories of temperature deviation. If, for example, it is much warmer than normal in summer, walking is used increasingly as a form of mobility in northern Sweden, while the opposite is recorded in central and southern Sweden, where walking in very warm conditions is less common.

Table 3. Change direction of the active mobility mode (walking or cycling) depending on the categories of temperature deviation from normal conditions, differentiated according to seasons (Sp spring, Su summer, Au autumn, Wi winter) and three regions of Sweden (north, central, south); Color red: significant increase; Color light red: increase, but not statistically significant; Color green: significant decrease; Color light green: increase, but not statistically significant; Color white: no change (data base: [61]).

dT	**Region**	**Walking**				**Cycling**			
		Sp	**Su**	**Au**	**Wi**	**Sp**	**Su**	**Au**	**Wi**
Much warmer	North	light green	red	green	green	white	white	red	white
	Central	red	green	green	green	red	white	red	red
	South	white	green	red	green	red	red	light red	light red
Warmer	North	green	white	light green	light green	red	white	red	white
	Central	red	green	green	white	white	white	red	red
	South	white	green	light red	green	red	red	red	red
Colder	North	red	red	red	green	light green	red	white	white
	Central	light red	green	white	white	light green	white	white	white
	South	white	green	light green	green	green	white	white	light green
Much colder	North	red	light green	light red	white	light green	green	white	white
	Central	red	green	white	white	light green	white	white	white
	South	red	white	red	white	light green	light green	light green	light green

The question also arises, whether there is a uniform temperature-dependent tendency for active mobility compared to motorized mobility. When viewed in relative terms, the proportion of outdoor mobility increases continuously with temperature and reaches the highest value (34%) at temperatures above 20 °C, although the absolute number of outdoor trips is lower at these temperatures. It is therefore essential to distinguish between absolute and relative considerations.

Regarding the seasonal and regional differences in the effects of the daily amount of precipitation, there is a positive influence of the precipitation on the probability that people choose the walking mode in summer. In addition, the precipitation in summer leads to a shortening of the travel distance. Conversely, during dry conditions in summer, longer distances are more likely to be covered by bike.

A preliminary study [66] analyzes weather effects on the mobility of non-commuters and differentiate between routine activities (e.g., daily shopping) and leisure activities (e.g., visiting friends). For a climate change-related interpretation of the study results, the daily evaluation with regard to days that were warmer than normal is of particular interest. It shows that, over the whole year, these days stimulate the proportionately greater use of slow means of transport for routine journeys and thus indirectly increase routine travel times. However, this is partially offset by other effects due to fewer routine trips and shorter duration of trips for routine purposes, which ultimately leads to an insignificant overall effect. A similar trend can also be seen in the slow mode share of trips for leisure purposes and leisure travel time.

Overall, it can be said that it is important to take regional characteristics into account, as the thermal conditions in different regions can even have opposite effects on active mobility. In addition, routine and leisure mobility can be influenced differently by thermal conditions and there can in turn be regional differences in these effects.

Ref. [67] compiles findings from different geographical contexts with the help of a literature review. They informally identify a rough geographic pattern of possibly stronger daily weather effects on mobility in temperate (maritime) climates, in contrast to possibly stronger seasonal mobility variances in continental climates, which often have cold (snowy) winters and hot summers.

Ref. [68] uses an international cross-comparison to investigate how the weather influences on mobility differ in cities with different climatic conditions. For Utrecht (52° N) (Netherlands), Oslo (60° N) and Stavanger (59° N) (Norway) and Stockholm (59° N) (Sweden), national travel data is linked to meteorological records. Of all atmospheric conditions, the darkness of the sky has the strongest significant influence on active mobility in all four study areas. In general, warm, dry, windless and sunny weather favors the use of active forms of mobility (especially cycling) over motorized mobility (especially car use). The effects for recreational purposes are greater than for non-recreational purposes, as found in other studies [51–54]. In line with existing studies, e.g., [69,70], there are indications of nonlinear (bell-shaped) air temperature effects on bicycle use (in Stockholm and Oslo) and outdoor leisure activities (in Oslo), with positive effects flattening or slightly reverse above 20–25 °C, indicating possible negative effects of heat.

The effects of weather on mobility are by no means universal in the study regions. Differences in statistical significance, extent and sometimes even direction of the impacts underline the need to always consider the geographical context in terms of climate conditions, cultures and habits, adaptations, traffic and land use when drawing conclusions about possible changes in behavior caused by climate change.

4.2.3. Comparison of Climatic Zones: Temperate and Subtropical Climate

Possible conclusions about weather-dependent mobility behavior on a larger geographical scale require, in particular, the consideration of different climatic zones.

A study from the USA [62] makes a systematic comparison of the behavior of cyclists and pedestrians in response to the weather. The authors consider seven continental climate zones [71] and find differences in responses to weather, both within and across regions. The results speak against the transferability of study results to other regions and other active modes of mobility.

Unfortunately, the method does not consider the deviations from the typical regional values of weather parameters or the total volume of active mobility, so that beyond the basic knowledge about the variable dependency of mobility behavior on the regional climatic regions, it is difficult is to draw further conclusions about temperature-dependent behavioral changes with reference to possibly climate change-induced changes in UVR exposure of the population.

4.3. How Do Meteorological Conditions Influence the Use of Public Space?

4.3.1. Cold and Temperate Climates

Ref. [72] examines the influence of meteorological conditions on the use of public space in Canada and Scandinavia. The publication unfortunately does not reveal which Scandinavian countries were specifically included in the study. The interactions between meteorological conditions and the built environment determine how people perceive public space and whether they decide to visit it. The results for winter conditions show that the perceived enjoyment of radiation plays a greater role than cold and wind. In addition, darkness turns out to be one of the main obstacles. Even if this seems irrelevant for UVR exposure at first glance, it is still an essential indication of the need for climate change studies to examine the temperature-dependent behavior of people within the seasons instead of across the seasons in order to eliminate the dependence on the length of the day.

Ref. [73] examined the relationship between human behavior in relation to the use of public parks and thermal comfort in the subarctic climate of northern Sweden (Umea 64° N). Under conditions that are objectively classified as "light heat load", most park visitors rate the environmental conditions as "thermal comfort". In addition, 49% of locals say they prefer even more solar radiation. The example illustrates the overlaying of objective standards with subjective expectations and desires, in this case the affinity for the sun in the subarctic climate. Deviations between an objective thermal evaluation and the subjective thermal sensation were also reported by [74] in a hot and dry climate and partly attributed to subjective expectations. However, the authors emphasize that it is necessary to test their hypothesis through further studies.

4.3.2. Subtropical Climate

Ref. [75] reports on some results of the European project RUROS, which investigates the effects of microclimatic conditions on the use of open spaces in an urban Mediterranean environment, especially pedestrian activity on a coastal boulevard and a protected inner-city square in Athens (38° N), Greece. The use of open spaces shows pronounced daily and seasonal differences. In particular, there is a strong correlation between thermal conditions and solar radiation. The seasonal pattern of preference for the sun is such that visitors prefer to sit in shady areas in summer, while sunlit areas are more popular in autumn and winter. In general, shady areas are preferred when the air temperatures are higher. At very high air temperatures, which means thermal discomfort, the use of open spaces decreases significantly. The greatest sensitivity to the summer heat can be seen in the age group > 65 years. The daily pattern of the use of open spaces also shows a strong dependency on meteorological parameters. If the time of maximum attendance is considered, this takes place in the evening in summer. When the season changes from summer to winter, the time of maximum attendance shifts towards noon. In autumn and winter, the number of daily visitors is 3 to 4 times higher than in summer. The connections found seem to be much stronger on the coastal square than on the inner-city square. Overall, there are comprehensive indications for avoiding direct UVR exposure in heat.

A study in Rome (42° N), Italy found that the thermal perception of people who are outdoors as pedestrians is also shaped by the small-scale variability of the environment, for example by a complex urban morphology, and is subject to strong individual differences [76].

4.3.3. Tropical Climate

Ref. [77] carried out a case study in Bauru (22° S), Brazil, which examined the influence of thermal comfort on the time users spend in the area of open spaces. In hot weather conditions (temperatures in the range of 30 to 32 °C), the usage times of two sub-areas of a zoo were examined, which are characterized by different shading, but basically the same user interest (attractiveness). Mainly, the sky view factor influences people's thermal perception. In situations with thermal stress, surfaces that are less exposed to direct solar radiation contribute to greater thermal acceptance and increase the exposure time for users. In other words, when it is hot, people prefer to be in the shade. This evaluation would therefore not directly support the thesis that higher temperatures mean more UVR exposure at the same time, as there are clear indications of avoiding direct UVR exposure in heat.

Table 4 gives a summarizing overview.

Above, the type II studies are systematized according to behavioral aspects. The studies of this type can also be systematized with regard to the effects of the weather. The studies can then be divided into five subject areas and provide contributions to the following research questions:

- How does thermal comfort influence human outdoor behavior?
- How do heat and heat waves affect human outdoor behavior?
- How does the perceived enjoyment of radiation influence human outdoor behavior?
- How does small-scale variability in environmental conditions influence human outdoor behavior?
- How do wind, precipitation, air humidity and cloud cover influence human outdoor behavior?

Table 4. Summary of the key messages and conclusions from the type II studies differentiated according to leisure activities, active mobility and use of public space.

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
		Leisure activities	
Temperate	Canada Great Lakes Region (43° N)	• Beach use is mainly determined by thermal comfort to 75%, by sunshine or cloudiness to 15% and 5% each by precipitation and wind. • Frequency of people staying outdoors is nonlinear with threshold effects in the thermal conditions. • Exceeding the threshold leads to a marked increase in the amount of time spent outdoors. • Outdoor activities increase during warm days with more daylight.	[37]
	Halifax (44° N)	• The day length (season) has the greatest positive impact on the time budget spent on activities outdoors. • Negatively correlated are the maximum temperature, wind and precipitation on time spent on sporting activities and precipitation on time spent on non-sporting activities.	[38]
	Montreal (45° N)	• All weather effects can only explain a small fraction of the variation in participation rates in outdoor activities. The influence on outdoor sports is around 6%, twice that of non-sports activities. • In the thermal comfort zone, the physical activity of the adolescents increases with increasing temperature. • Within one season, the activity increased in spring and winter by 1% and in autumn by 2% for every 10 °C increase in mean daily temperature.	[39]
	Netherlands	• Main meteorological variables that affect television time are temperature and sunshine duration; people watch TV more when it is colder, cloudy and wet, with stronger winds and longer nights.	[42]
	Poland Warsaw (52° N)	• There is a preference of those looking for urban recreation for slightly warm thermal conditions, sunny, low-wind weather with a significant influence of the climate of origin.	[43]
	➢ Knowledge of the thermal threshold values, which lead to a marked increase in the amount of time spent outdoors and their future frequency of occurrence is important for making statements about changes in behavior caused by climate change. ➢ An extrapolation of results that only refers to possible linear effects in the area of thermal comfort is very likely an oversimplification. ➢ Since the length of the day has a great influence on outdoor activities, the effects of temperature on behavior within the seasons should also be investigated in order to draw conclusions related to climate change.		
Subtropical	Australia Sydney (33° S)	• In extreme heat or during heat waves, the pattern of daily activities changed to a reduction in physical activities and to avoid spending time outdoors in most cases.	[44]
	Middle East and Northafrica	• People tend to avoid physical activity outdoors in hot conditions. • Cooler weather is seen as a contributing factor to physical activity.	[45]
Tropical	Brazil Florianópolis (28° S)	• Heat or hot climate serve as limits or barriers to outdoor physical activity.	[47]
	Caribbean Tobago (11° N) Barbados (13° N), St. Lucia (14° N)	• Beach users have different comfort perceptions and preferences than people who use urban spaces; warmer conditions are preferred.	[48]
Subtropical and tropical	➢ There is some evidence that results and conclusions cannot be easily transferred and generalized between different types of recreational activities and different climates. ➢ The consideration that higher temperatures are directly associated with more time outdoors and significantly increased UVR exposure is very unlikely to apply to these climatic zones, since hot conditions are more likely to be avoided.		

Table 4. *Cont.*

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
		Active Mobility	
Temperate	Australia Melbourne (38° S)	• Air temperature has a nonlinear, bell-shaped effect on cycling. Beyond an optimal temperature with maximum cycling, there is less cycling at lower and higher temperatures. • The optimal temperature varies from location to location, even within a region.	[49,55]
	Canada Montreal (45° N)	• Air temperature and humidity have nonlinear, bell-shaped effects on cycling. • Recreational cycling is more sensitive to the weather than utilitarian cycling.	[50,51]
	Germany 37 locations (48–54° N)	• Air temperature has a nonlinear, bell-shaped effect on cycling. • Precipitation, humidity, wind speed and cloud cover have negative effects on the hourly number of cyclists.	[56]
	Netherlands Ede und Gouda (52° N)	• 80% of the daily number of bicycles variations are caused by weather conditions. • A nonlinearity of the interrelationships between weather parameters of cycling trips is determined. • Recreational cycling is more influenced by the weather than utilitarian cycling.	[54]
	Rotterdam (52° N)	• Air temperature shows a highly significant bell-shaped effect on cycling. • Weather effects are different in different regions with less influence on bike tours in densely populated areas. • A higher air temperature has no positive effect on the active mobility of older people. • Dry, not very windy, sunny and warm, but not too hot weather conditions, favor cycling over other means of transport.	[53,57–59]
	Sweden Uppsala (60° N)	• In an area that enables thermal comfort, there is a linear relationship between air temperature and bicycle use in spring, with no threshold value effects.	[52]
	USA New York (41° N)	• Air temperature has a nonlinear, bell-shaped effect on cycling. • Forecasts of future bicycle use for the period 2040–2069 show a net increase in total annual bicycle hours of the order of 3% for various emission scenarios and climate models. • Projected decreases in summer are more than offset by increases in winter, spring and autumn seasons.	[63,64]
	Vermont (44° N)	• Air temperature has a nonlinear, bell-shaped effect on cycling. • Days with wind, rain and high humidity are associated with less cycling.	[65]
	Seattle (48° N)	• Positive temperature deviations have the greatest influence on cycling i spring.	[60]
		➢ Active leisure mobility is characterized by a strong dependency on weather conditions and is therefore an important study area with regard to a potentially increased UVR exposure in the course of climate change. ➢ A simple, straightforward conclusion that higher temperatures due to climate change and a possibly increased number of hours of sunshine lead to an increase in active mobility with possibly increased UVR exposure cannot be derived across the board. ➢ There is an urgent need for a differentiated analysis that takes opposing effects into account and balances them. ➢ Climate change scenario calculations provide initial indications of an overcompensation for projected decreases in active mobility in summer by increases in the other seasons, although an assessment of the development of the UVR dose derived from this is not yet available.	

Table 4. *Cont.*

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
Comparison: cold and temperate zone	Sweden	• Temperatures that deviate from the regional and seasonal typical values can have different effects on outdoor mobility. • A systematization with regard to the north lying in the cold climate zone and the south lying in the temperate climate zone cannot be derived.	[61]
		• The thermal conditions in different regions can even have opposite effects. • Routine and leisure mobility can be influenced differently by the thermal conditions and there can in turn be regional differences in these effects.	[66]
	Norway, Sweden, Netherlands	• The effects of weather on active mobility are by no means universal in the study regions. • There are differences in the statistical significance, extent and sometimes even direction of the impact.	[68]
	➢ There is a need to always consider the geographical context in terms of climate conditions, cultures and habits, adaptations, traffic and land use when drawing conclusions about possible changes in behavior due to climate change in active mobility. ➢ It is important to take regional characteristics into account, as the thermal conditions in different regions can even have opposite effects on active mobility. ➢ In addition, routine and leisure mobility can be influenced differently by thermal conditions and there can in turn be regional differences in these effects.		
Comparison: temperate and subtropical zone	USA	• The weather-dependent behavior of cyclists and pedestrians differs both within the regions and across the climatic regions. • The description of the changes in cycling and walking mobility depending on the daily weather influences can be done regionally differently using both linear and quadratic models. • A coherent system for the connection between the climatic zones and the temperatures at which the highest levels of mobility occur cannot be identified.	[62]
	➢ There is a variable dependency of active mobility behavior on both the regional climate characteristics and the mobility mode. Both factors speak against the transferability of study results to other regions and other active modes of mobility		
		Use of public space	
Cold and temperate	Canada and Skandinavia	• In winter conditions, the perceived enjoyment of radiation plays a greater role than cold and wind. • Darkness is one of the main obstacles to the use of public space.	[72]
	Sweden	• The local climatic conditions influence the subjective attitude and behavior (such as the affinity for the sun in the subarctic climate).	[73]
	➢ Since darkness is a major obstacle to being outdoors, it is likely that longer periods of daylight will lead to increased exposure to the outdoors. ➢ In climate change studies on temperature-dependent behavior of people, the dependence on the length of the day should be eliminated. ➢ In order to separate the influences of temperature and duration of daylight, investigations within the seasons are important.		
Subtropical	Greece Athens (38° N)	• In the case of higher temperatures and in summer, it is preferred to stay in the shade. • At high temperatures, open spaces are used much less and their use shifts to the evening.	[75]
	Italy Rome (42° N)	• The small-scale variability of the environment shapes the thermal perception of people who are outdoors as pedestrians. • There are strong individual differences.	[76]

Table 4. *Cont.*

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
Tropical	Brazil Bauru (22° S)	• When it is hot, people prefer to be in the shade.	[77]
Subtropical and tropical	➢ The consideration that higher temperatures are directly associated with more time outdoors and significantly increased UVR exposure is very unlikely to apply to these climatic zones, since hot conditions or exposure to the sun when it is hot are more likely to be avoided.		

Table 5 gives a summarizing overview of the key messages.

Table 5. Human biometeorological factors and the key messages about their influence human outdoor behavior.

Human Biometeorological Factors	Key Messages about Influencing Human Outdoor Behavior	Regions or Countries with Contributing Studies	Studies
Thermal comfort/ slight thermal discomfort	• Indications of a direct supportive influence of thermal comfort on outdoor stays in the form of leisure activities, active mobility and the use of public spaces • Nonlinear shaped increase in time outdoors at higher temperatures • Indications of threshold effects with a significant increase in the time outdoors after exceeding • Indications of seasonal effects due to the superimposition of the influences of daylight duration and temperature (which are not separated in the majority of studies)	Australia Canada Germany Netherlands Norway Sweden United States	[49,55] [37–39,50,51] [56] [42,53,54,57–59] [68] [52,68] [60,63–65]
Heat and Heatwaves	• Indications of avoidance strategies for staying outdoors in the form of leisure activities, active mobility and the use of public spaces in the heat • Nonlinear shaped decrease in time outdoors with increasing heat • Indications of threshold effects with a marked shortening of the time outdoors after exceeding • Indications of the existence of people with fundamentally opposing behavior (heat-affine and non-heat-affine) and thus of significantly different, individual threshold values	Australia Bahrain Brazil Canada Egypt Germany Greece Kuwait Netherlands Oman Qatar Saudi-Arabia United Arab Emirates United States	[44] [45] [47,77] [39] [45] [56] [75] [45] [54,57–59] [45] [45] [45] [45] [64,65]
Solar radiation enjoyment	• Particularly from cool and moderate climates, indications of a supportive influence of solar radiation enjoyment on outdoor stays by the use of public spaces, even under slightly unfavorable thermal conditions	Canada Scandinavia	[37,72] [72,73]
Small-scale thermal diversity	• Indications of a positive correlation between small-scale thermal diversity and spending time outdoors by the use of public spaces	Italy United Kingdom	[76] [76]
Wind, precipitation, humidity, cloud cover	• Indications of a negative correlation between wind, precipitation, air humidity, cloud cover and spending time outdoors in the form of leisure activities, active mobility and the use of public spaces	Canada Germany Netherlands Scandinavia United States	[37,39,50,51] [56] [53,54] [68] [63,65]

5. Type III Studies

Type III studies have primarily examined UVR exposure and provide information on the subject examined here through the discussion of possible explanations or indirectly. The UVR exposure dose is assumed to be the most important parameter here and the other parameters, such as exposure time, duration and pattern are taken into account with regard to their contribution to the total UVR dose.

Some studies examine the temperate climate together with the subtropical/tropical climate [78–81]. In these cases, both are discussed in the temperate climate category in order to avoid redundancies.

5.1. Temperate Climate

Ref. [78] examines the effects of season and latitude on the relationship between ambient UVR and personal UVR exposure for four Australian cities. Due to their location in different climatic zones—from tropical (Townsville, 19° S), to subtropical (Brisbane 27° S) to moderate (Canberra 35° S, Hobart 43° S) climates—these cities also provide insight into the influences of the prevailing climatic conditions on exposure behavior.

Daily personal UVR exposure accounts for an average of 5% of the total available UVR ambient dose. There are strong positive correlations between ambient UVR and personal UVR exposure in winter and at high latitudes and no or even slightly negative correlations in summer and at low latitudes. Several regression models show significant changes according to season and latitude. The results can also be interpreted in such a way that the prevailing climatic conditions change the relationship between ambient UVR and personal UVR exposure.

The average UVR exposure proportion of 5% in this study is similar to that of other studies and populations [13,82]. The strong influence of the seasons on this proportion was also reported in other studies [83,84]. In an earlier study in subtropical Australia, the proportion of personal exposure in winter was more than twice as high as in summer (6.5% vs. 2.7%) [84].

Interestingly, a Danish study found a much lower percentage of personal exposure in winter (0.82%) than in summer (3.4%) [83]. Both studies therefore indicate a strongly modifying effect of the season on exposure behavior, but in the opposite direction. This in turn can be explained by the influences of the prevailing climatic conditions on the exposure behavior. In tropical or subtropical Australia, the UV index often reaches the extreme level (11+) in the summer months [85] and is often associated with high temperatures and high humidity. These factors, in combination with widespread sun protection campaigns in summer, can lead to the avoidance of sun exposure. In contrast, residents of the temperate climate at higher latitudes in the northern hemisphere may only be able to use UVR in their surroundings to a very limited extent due to the shortened day length and cold temperatures in winter.

In general, the transferability of results on UVR exposure from climatically different regions and from different seasonal conditions is not directly guaranteed and always requires a critical examination of whether it is permissible.

This study from Australia [78] allows the following conclusions: Changes in behavior are likely to vary with the seasons or depending on the respective thermal level. If the thermal level is outside the comfort range, a possible increase in UVR exposure cannot be assumed directly due to the increase in stays outdoors, but rather avoidance strategies with a potential decrease in UVR exposure.

Another study from Australia [79] examines, among other things, temporal and spatial variations of self-reported sun exposure in Australian adults, predominantly Caucasian types, in the four regions Brisbane City (27° S), Newcastle City and Surrounds (33° S), Geelong City and the Western Districts of Victoria (37° S) and the island of Tasmania (43° S). It turns out that the individual exposure behavior of childhood tends to be maintained over the entire life course. That is, those who spend more time in the sun in childhood than others of the same age tend to spend more time in the sun during adolescence and into adulthood. This also applies to the behavior in summer compared to winter. The exposure time in summer decreases over the course of life in all regions, age cohorts and for both sexes. Participants from the warmer region with higher UVR in the area spent less time in the sun than participants in the other locations. This contradicts earlier work [35] in which higher temperatures were associated with an increased risk of sunburn. These conflicting results could reflect that solar behavior differs depending on whether short-term warming occurs in cooler weather conditions or whether warmer conditions are the norm and the population is used to it.

This study from Australia [79] allows the following conclusion: Possible changes in the variability of thermal conditions could also have effects on behavioral UVR exposure, not just gradual changes in the thermal conditions.

A study examines the clothing habits of young women in the urban region of Vienna, Austria, depending on meteorological conditions [86]. The observations were made in daylight from spring to autumn. Clothing is one of the most important factors influencing exposure to personal UVR. The authors find that air temperature is the dominant factor in exposure. As the temperature rises, the first area of the body to be exposed to solar UVR, next to the face and hands, is the cleavage, followed by the neck, ankles, instep and forearms. The observations also suggest that the frequency of being outdoors decreases significantly at temperatures above 30 °C. In the temperature range from 10 to 30 °C, the frequency of being outdoors remains almost constant, while in the temperature range from 30 to 36 °C, it decreases by 5% per 1 °C. The findings on clothing and temperature behavior were found in a similar way for individual locations in Australia [32].

This study from Austria [86] allows the following conclusion: a possible increase in UVR exposure could result from a reduction in clothing rather than from a possible increase from staying outdoors at higher temperatures.

A study in China [80] examines the personal UVR exposure in a cohort of pairs of mother and adolescents at two locations, a rural (higher latitude, 39° N) and an urban (lower latitude, 31° N) personal UVR dosimetry. Despite the differences in geographical latitude, there was a comparably high average daily UVR at both locations on the study days. With regard to the time outdoors of interest here, it can be seen that urban mothers spend less average daily time outdoors than rural mothers (1.5 h compared with 5.5 h) combined with a significantly lower daily average personal UVR exposure (0.8 minimal erythema dose (MED) compared with 4.5 MED). Among the young people, there were also clear differences between the sexes, which also show no uniform systematics between urban and rural areas. The average daily personal UVR exposure in the city is lower for adolescent men than for adolescent women (0.5 compared with 0.8 MED) and in rural areas the order between adolescent men and women is reversed (2.2 compared with 1.1 MED).

Often, latitude is used as a practical proxy for personal UVR exposure. However, contrary to expectations, the present results show higher personal UVR exposures in the rural location further away from the equator. The results indicate the need to consider personal living conditions and gender differences with regard to UVR exposure. For China, they also confirm results from Australia, that the season and latitude change the relationship between the UVR of the environment and personal UVR exposure [78]. Care should be taken when using latitude and ambient UVR as indicators of personal UVR exposure.

This study from China [80] allows the following conclusion: Changes in behavior associated with climate change could develop differently depending on geographic region, city or country, gender and age.

A study from Denmark [87] determines the personal UVR exposure doses during a sun holiday on the Canary Islands in early March. Participants' behavior had a major impact on their personal UVR doses. There is a positive correlation between the personal UVR doses and the exposed body area, the use of sunscreen and the parts of the body with sunscreen use. Participants were outdoors 88% of the time between 12:00 p.m. and 3:00 p.m. when the sun is at its highest. On average, each participant received around 43% of the annual UVR dose of a Danish indoor worker over the six days.

A preliminary study from Denmark [83] examines UVR exposure patterns in winter compared to summer based on time-stamped personal dosimeter values of indoor employees. The sun exposure behavior was recorded in diaries. Similar data were collected for 28 volunteers on sun holidays outside Denmark in the winter months.

The ambient UVR dose during the winter in Denmark (at 56° N) was 394 standard erythema doses (SED) or 10.5% of the total annual UVR dose in the environment. In winter compared to summer, the test subjects had a lower proportion of personal UVR exposure compared to ambient UVR (0.82% vs. 3.4%). A lower personal UVR dose is received in winter (3.1 SED (range 0.2–52) vs. 133 SED (range 69–363)). The subjects spend less time outdoors per day with positive dosimeter measurements, 10 min vs. 2 h. In winter, the case also occurs more frequently without any UVR exposure (0 SED per day on 77% vs. 19% of the days). Sun holidays outside Denmark in winter resulted in a median of 4.3 SED per day (range 0.6–7.6) and 26 SED (range 3–71) per trip. This means that trips abroad can completely change the individual UVR dose pattern if, on average, a trip already contributes a fifth of the total summer exposure and 13 times the winter exposure. Few individuals received 70 SED in 14 days in Mexico in February or in Greece in October, which are equivalent to the total annual UVR dose for subjects with low UVR exposure in Denmark.

These two studies from Denmark [83,87] allow the following conclusion: Possible changes in vacation behavior could have stronger effects on the personal UVR dose than changes in the time spent in the outdoors in the home region. Therefore, in connection with the possible changes in UVR exposure, there is also a need to investigate possible changes in holiday behavior.

Refs. [40,41] determine the mean UVR exposure of the population in Germany. Air temperature, precipitation and sunshine duration affect how long people stay outdoors and the likelihood that they expose themselves to the UVR. On working days, the UVR exposure is largely determined by the work tasks. It is rather less influenced by a reaction to current meteorological conditions. For the UVR exposure in leisure time, different behavior types have to be distinguished: people with active behavior (70–80%) and those with passive behavior (20–30%). With the same behavior type, the UVR personal doses (mean value, distribution) of outside and inside employees do not differ. At weekends, there was a connection between the length of time spent outdoors and the daily maximum temperature as well as the time of year. The study does not consider the season and temperature independently. It is therefore not possible to distinguish between the effects of changing day length (season) and different temperature levels.

The evaluation in [40] shows a linear increase in the length of time spent outdoors with increasing daily maximum temperature. Measurements were taken in February, May, September and December, so that probably no summer values could be covered. Climatological values for the maximum daily temperature in Dresden (measurement location) are in the range of 4 to 19 °C in these months. The knowledge gained is therefore only valid for the transitional seasons and most likely the thermal comfort range. The measurements also showed that the vacation UVR dose makes up a significant proportion of the annual UVR exposure, as is also the case with studies for other temperate countries such as Denmark and the UK [83,87–89].

These studies from Germany [40,41] allow the following conclusion: As long as the thermal level is within the comfort range, a possible increase in UVR exposure could result from the increase from staying outdoors at higher temperatures. Changes in behavior could manifest themselves differently depending on people's leisure time type. Possible changes in vacation could have stronger effects on the personal UVR dose than slightly changed times of stay outdoors in the home region.

The sun exposure of indoor workers was recorded in a study in Great Britain [88] using a lifestyle questionnaire. In addition, 894 Public Health England office and laboratory workers attended. The time employees spend outdoors was divided into days of the week, weekends and vacation. The majority of times before and after commuting to work on weekdays is before 8:00 a.m. and after 5:00 p.m., and they are negligible in terms of UV radiation. With regard to UVR, the lunch break on weekdays is of interest, but only 7% of the participants regularly spend 21 ± 12 min outdoors. Weekday exposure is less than 13% of the available ambient UVR dose.

In the months from April to October, the participants spend an average of 5.0 ± 2.6 h outdoors on rain-free days at the weekend. It is very likely that this time will be outdoors between 10:00 a.m. and 4:00 p.m. and more exposed body surfaces can be expected during activities such as walking, gardening, picnicking and playing with children. In this case, around 50% of the available UVR exposure can be achieved in the summer months. Similar times were already found for exposure on weekends in an earlier study [29] with an average of 2 ± 0.3 h per day. In the months of November to March, the combination of the very low UVR in the area and unfavorable weather conditions results in negligible UVR exposure.

As already found in previous studies in Germany and Denmark [41,83,87], vacation stays contribute a large part to annual UVR exposure. In the summer, 45% of participants travel to destinations where UVR levels are typically up to 2 times higher than in the UK. The duration of the vacation abroad is also longer than that of the domestic vacation. The UVR dose of two weeks of vacation in extreme UV index destinations would be comparable to a hypothetical 1.5–2 month vacation in the UK in summer.

With regard to a change in the overall balance of UV exposure due to climate change, two considerations arise. On the one hand, it must be taken into account that a possible extension of the length of stay outdoors in the event of an extension of previous stays could occur predominantly outside the lunchtime date already used on the weekend, for example, if the UVR in the area is already lower due to the position of the sun. There would only be a smaller contribution to the overall balance of UVR exposure. On the other hand, possible changes in holiday behavior, due to their significant share in the annual UVR exposure, could have more significant effects on the personal UV radiation balance than slightly changed times of stay outdoors at home. Depending on whether, due to climate change, more or less time is spent in regions with extreme UVR conditions, different constellations of lower to further increased UVR exposure of people are conceivable.

Another study from the UK [89] examines the effects of overseas sun exposure on the number of nevi in white English women. Having a large number of melanocytic nevi is considered to be the strongest known risk factor for melanoma in whites. In 1997–2000, a total of 754 women aged 18 to 46 were included in a cross-sectional study to investigate the effect of UVR exposure on the number of nevi. Ever vacationing in hotter countries was already associated with a higher median number of whole-body nevi (percent increase = 74; 95% confidence interval: 24, 144; p = 0.001), especially for vacation ages 18–29 and for counts of the trunk and lower limbs. Therefore, holiday exposure to increased UVR has a serious impact on the risk of melanoma and possible changes in holiday behavior due to climate change can have massive effects on it.

These studies from the UK [88,89] allow the following conclusion: A possible extension of the duration of stay outdoors could (in the constellation as a temporal extension of the previously lunch date used) only make a limited additional contribution to the UVR dose. Possible changes in vacation behavior could have stronger effects on the personal UVR dose than changed times of stay outdoors in the home region. Different constellations of lower to further increased UVR exposure of people are conceivable.

A study [90] examined the UVR exposure of young people (9–10-year-old children from a primary school and 14–15-year-old adolescents from a secondary school) in three geographically different regions of Great Britain (northeast, south-central and southwest England). UVR exposure was measured on weekdays and weekends over a period of 3 months (mid-April to mid-July 1994) and the time spent outdoors was recorded. The results show a higher UVR exposure of the primary school children compared to the adolescents in the secondary schools. However, on weekdays, the time spent outdoors does not differ between the two age groups of school children. This result is probably behavioral, in the sense that elementary school children tend to play in open spaces. There are no geographical differences in UVR exposure on weekdays, when there is limited time available for outdoor activities. On the weekends, however, there are geographical differences in UVR exposure. Young people in northeast England received lower UVR doses and spent less time outdoors compared to their peers who lived further south. These differences cannot be explained by differences in ambient UVR alone and suggest other reasons. The authors [90] write "This difference ... suggests that other factors, either cultural or associated with the climate (e.g., temperature), may be involved ... ". This consideration of possible causes was taken up in other publications, and instead of being given as a consideration, it was given as an established fact or proven knowledge.

However, the authors only mentioned the question of the possible influence of temperature; they did not investigate it. The actual temperatures during the study period can be checked with the help of historical measurements from the UK Metoffice (https://www.metoffice.gov.uk/research/climate/maps-and-data/historic-station-data (accessed on 30 July 2021)). There is a weather station at the Durham investigation site (54.5° N, 1.3° W). The data for the investigation site Wallingford (51.4° N, 1.1° W) are approximated by the nearest station that has available data for this period. This is the station in Oxford (51.7° N, 1.3° W). Similarly, for Plymouth (50.2° N, 4.1° W), the data from Camborne station (50.2° N, 5.3° W) are used.

Figure 2 contains the weather data now retrieved for the stations mentioned during the months April to July 1994 together with the results of the study [90]. The exposure time (calculated as a weighted mean of weekday and weekend exposure) over the mean daily maximum temperature is shown in Figure 2. Contrary to the common assumption that the northern hemisphere has higher temperatures in more southerly places, in this specific case, the lowest temperatures are recorded in the southernmost place. In Plymouth, both primary and secondary school children exposed themselves longer than their peers at the northernmost location of the study in Durham, despite the lower temperatures, with the difference being particularly pronounced among primary school children. Overall, there was no longer exposure time at higher temperatures among the primary school children. This is only the case with secondary school students. Looking at the UVR dose, people of both ages receive a higher UVR dose at higher temperatures.

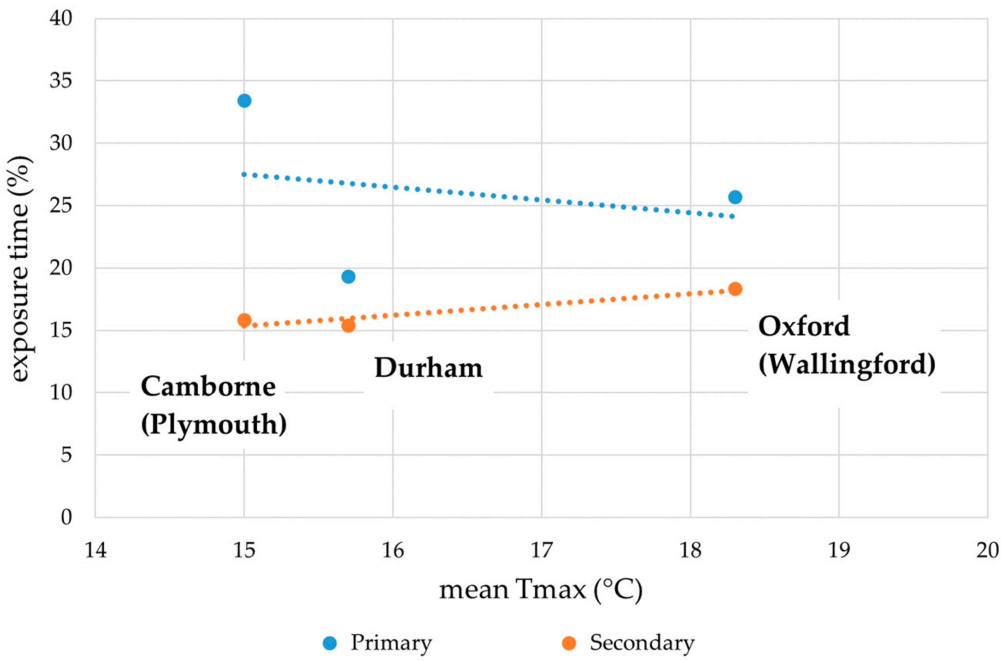

Figure 2. Exposure time (calculated as a weighted mean of weekday and weekend exposure) of primary and secondary school students (data base: [87]) over the mean daily maximum temperature in Camborne, Durham and Oxford, April to July 1994 [UK Metoffice].

The study [90] does not provide any conclusive evidence for the question of behavioral changes caused by climate change, which is of particular interest here, with the assumption of potentially longer periods of time outdoors, because the conclusion that higher UVR doses result from longer exposure times at higher temperatures does not apply here for the elementary school children. As already described, however, many influences overlap and usually do not allow such simple conclusions.

This study from the UK [90] allows the following conclusion: Changes in behavior could develop differently depending on age.

A study from the USA determined not only individual and environmental predictors but also meteorological predictors for the daily personal UVR exposure [81] of 123 participants from a professional cohort of indoor health professionals. Participants are residents of both northern US latitudes (Minnesota 46° N and Wisconsin 44° N) and southern US latitudes (North Carolina 35° N and Georgia 32° N) and used UV dosimeters for a total of seven days in 2004. The hourly values of temperature, dew point, relative humidity and wind speed are taken as a basis for the investigation period and averaged for the hours between 9:00 a.m. and 5:00 p.m.; the precipitation is totaled.

Environment UVR, latitude, daily precipitation and skin reaction to prolonged exposure to sunlight are the strongest predictors of daily personal UVR exposure in the full model with all relevant variables. Daily personal UVR exposure varies greatly depending on environmental and meteorological factors. All of these variables account for 25–30% of the variation in personal UVR exposure. A large part of the heterogeneity of personal UVR exposure can probably be explained by individual differences in time outdoors [91], although the present study unfortunately did not collect any data on this. For the meteorological variables, the daily precipitation are the strongest predictors for the daily personal UVR exposure. The average daily personal UVR values tend to be higher for lower latitudes and for higher UVR in the area, without rain, with low wind speeds and low relative humidity. Days with temperatures between 18 and 20 °C (3rd quartile of the temperature distribution) have the highest personal UVR, while lower personal UVR values are measured at higher and lower temperatures. These results can be described as a bell-shaped relationship between temperature and daily personal UVR exposure. Because of the short measurement period, no direct comparison with the results of other studies, e.g., on seasonal differences [78,83,84] is possible.

This study from the USA [81] allows the following conclusion: As long as the thermal level is in the comfort range, a possible increase in UVR exposure could result from the increase in stays outdoors at higher temperatures. If the thermal level is well in the warm discomfort range, a possible increase in UVR exposure due to the increase in outdoor activities cannot be assumed. Possible changes in precipitation associated with climate change could also have an impact on the personal UVR dose, not just changes in the thermal level.

5.2. Subtropical Climate

Only those studies are presented here that relate exclusively to locations in the subtropical climate. Combination studies can be found in the section on temperate climates.

In a study in Australia [92], the personal exposures of the participants were measured simultaneously with regard to erythema-effective UV, UVA and vitamin D-effective UV in every season. This study also provides indications of seasonal differences in the exposure behavior of people via the recordings of the dosimeters.

All participants were office workers at the subtropical site of Toowoomba (28° S, 152° E). During the course of 2014/15, the test subjects wore a combined dosimeter horizontally on their shoulder for at least one week in each season. The length and time of day that participants spent outdoors varied with each season. Between 10:00 a.m. and 2:00 p.m. during the week, participants spent an average of 101 min outdoors in winter, while that total time dropped to 79 min in summer, despite being outdoors more often.

The results of UV dosimetry show that the median erythemal exposure was highest in spring and lowest in winter, as was the effective vitamin D exposure. The median UVA exposures were at a similar level in winter and summer, autumn was higher (double) and spring was at a lower level.

With regard to the behavior of the people considered here, the study found seasonal differences with regard to the length and time of day which office workers spend outdoors in a subtropical location. The fact that they spend longer outdoors between 10:00 a.m. and 2:00 p.m. during the week in winter than in summer can be interpreted as an indication of the possible avoidance of being outdoors at high temperatures and high levels of radiation, which is also reflected in other studies in Australia [32] and Europe [86].

This study from Australia [92] allows the following conclusion: If the thermal level is outside the comfort range, a possible increase in UVR exposure cannot be directly identified due to increased stays in the open space, but rather avoidance strategies with a potential decrease in UVR exposure.

In another Australian study [93], the personal UVR exposure of school children in Queensland, Australia (25° S, 153° E) between February and June 2008 during school time between 8:30 a.m. and 3:05 p.m. was measured with polysulfone dosimeters. The measured UVR exposures are expressed in the unit standard erythema dose (SED), with 1 SED = 100 J/m^2 [94]. Most of the accidental UVR exposure during a normal school day is in the 0.5 to 1.0 SED range. The cumulative daily UVR is most affected by the tendency of students to be in an outdoor playground during meal breaks. In contrast to accidental exposure during a normal school day, up to 50 SEDs were found during a school swimming festival. This result underscores the importance of outdoor (sports) events, where there is a high likelihood of getting severe sunburns, which is a recognized risk factor for the later development of melanoma and non-melanoma skin cancers.

This study from Australia [89] allows the following conclusion: possible tendencies towards more frequent outdoor events have the potential to contribute significantly to the personal UVR dose, provided they extend over midday.

A study [95] measured the UVR exposure of 30 children and adolescents in three age groups (4–6 years, 7–9 years and 13–14 years) in late summer (February–March) in Durban, South Africa, where no statistically significant differences between the different age groups were found. The mean values of the individual UVR dose are 2 SED, the median values 1.2 SED. On average, participants receive a personal UVR dose of 4.6% of the daily ambient UVR. Participants filled out diaries on UVR exposure. Time in the open air, the type of activity, the clothes worn and the time in the shade compared to the time in the sun were recorded. The mean time outdoors, including weekdays and weekends, is 2.3 h per day as the sum of intermittent short exposure times. Activity patterns were found to be the most important factor in the individual UVR dose. In addition, 70% of the highest UVR doses occurred on weekends, presumably because of the free time available at that time. Surprisingly, there is no connection between the measured UVR dose and the duration of exposure. This can be interpreted as an indication of the complexity of the factors influencing the individual UVR doses.

This study from South Africa [95] allows the following conclusion: a possible increase in UVR exposure could result from changed activity patterns rather than from a possible extension of staying outdoors at higher temperatures.

In Table 6, the key statements and the conclusions are listed separately according to climate zones.

Table 6. Summary of the key messages and conclusions from the type III studies.

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
Temperate	Australia, Canberra 35° S, Hobart 43° S	• The seasons have a strongly modifying effect on exposure behavior. • A significantly greater exposure occurs in winter than in summer. • This is particularly pronounced in higher latitudes (at usually lower temperatures than in lower latitudes).	[78]
	Geelong 37° S Tasmania 43° S	• In less warm regions with a lower UVR of the environment, more time is spent in the sun than in warmer regions. • Sun behavior may be different when brief warming occurs in cooler weather conditions than when warmer conditions are the norm.	[79]
	➢ Changes in behavior associated with climate change are likely to vary with the seasons or are dependent on the respective thermal level. ➢ Possible changes in the variability of thermal conditions associated with climate change could also have an impact on UVR exposure, not just gradual changes in thermal conditions.		
	Austria, Vienna 48° N	• Less clothing and therefore more UVR exposure occur with increasing air temperatures. • Approximately the same frequency of time spent outdoors occurs at temperatures between 10 °C and 30 °C. • The frequency of being outdoors significantly decreases in at temperatures above 30 °C.	[86]
	➢ A possible increase in UVR exposure associated with climate change could result from a reduction in clothing rather than from a possible increase in spending time outdoors at higher temperatures.		
	China, Location 39° N (Name not given)	• There are large differences in outdoor time and personal UVR exposure between urban and rural areas. • Time outdoors and UVR exposure in adolescents varies by geographic region, city and country, and gender.	[80]
	➢ Changes in behavior in connection with climate change can take different forms depending on the geographic region, city or country, gender and age.		
	Denmark, Country 56° N	• Holiday UVR dose provides a significant proportion of the annual UVR exposure. • Traveling abroad to areas with high levels of UVR can significantly increase the individual total UVR dose.	[83,87]
	➢ Possible changes in vacation behavior associated with climate change could have a stronger impact on the personal UVR dose than changes in the time spent outdoors in the residential region.		
	Germany, Dresden 51° N	• In the transitional seasons, outdoor activities decrease with increasing temperature or daylight duration. • Differentiation between active and passive leisure type of people is necessary. • Holiday UVR dose provides a significant proportion of the annual UVR exposure.	[40,41]
	➢ As long as the thermal level is in the comfort range, a possible increase in UVR exposure associated with climate change could result from the increase in stays outdoors at higher temperatures. ➢ Changes in behavior associated with climate change can develop differently depending on the leisure type of people. ➢ Possible changes in vacation behavior associated with climate change could have a stronger impact on the personal UVR dose than changes in the time spent outdoors in the residential region.		

Table 6. *Cont.*

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
	UK Country 52° N Yorkshire 54° N	• In the summer months, an average of 5.0 ± 2.6 h is spent outdoors on rain-free days at the weekend. • Vacation stays are a major contributor to annual UVR exposure. • Holiday exposure to increased UVR has a serious impact on the risk of melanoma.	[88]
		• Ever vacationing in countries with high levels of ambient UVR is already associated with a higher median number of whole body nevi.	[89]
	Durham 54° N Wallingford 51° N Plymouth 50° N	• For elementary school children, the conclusion that higher UVR doses at higher temperatures result from longer exposure times has not been proven.	[90]
		➢ A possible extension of the length of stay outdoors, associated with climate change, could only make an additional contribution to the UVR dose to a limited extent (in a constellation as a time extension beyond the noon time already used). ➢ Possible changes in vacation behavior associated with climate change could have a stronger impact on the personal UVR dose than changes in the time spent outdoors in the residential region. ➢ Changes in behavior associated with climate change could take different forms depending on age.	
	USA Minnesota 46° N Wisconsin 44° N	• Of the meteorological variables, daily precipitation is the strongest predictor of daily personal UVR exposure. • There is a bell-shaped relationship between temperature and daily personal UVR exposure. • Highest personal UVR occurs at temperatures between 18 °C and 20 °C.	[81]
		➢ As long as the thermal level is in the comfort range, a possible increase in UVR exposure associated with climate change could result from the increase in stays outdoors at higher temperatures. ➢ If the thermal level is well in the warm discomfort range, a climate change-associated, possible increase in UVR exposure due to the increase in outdoor activities cannot be assumed. ➢ Possible changes in precipitation associated with climate change could also have an impact on the personal UVR dose, not just changes in the thermal level.	
Subtropical, (* tropical)	Australia Toowoomba 27° S Townsville * 19° S Brisbane 27° S Newcastle 33° S Brisbane 27° S	• The length and time of day office workers spend outdoors is subject to seasonal differences. • In the time between 10:00 a.m. and 2:00 p.m. during the week, they spend longer outdoors in winter than in summer, which can be interpreted as an indication of possible avoidance of high temperatures and high levels of radiation. • The seasons have a strongly modifying effect on exposure behavior. • In summer (with often high temperatures and high humidity as well as extreme UVI), exposure to the sun is avoided. • Less time is spent in the sun in warmer regions with a higher UVR of the environment than in less warm regions.	[92] [78] [79]
	Queensland 25° S	• Solar behavior may differ when warmer conditions are the norm from behavior when short-term warming occurs in cooler weather conditions. • During a single outdoor (school sports) event that takes place over the midday when the sun is high, up to 100 times the UVR dose of a normal school day can be received.	[93]
		➢ If the thermal level is well within the warm discomfort range, a possible increase in UVR exposure associated with climate change cannot be assumed directly due to the increase in spending time outdoors, but rather avoidance strategies with a potential decrease in UVR exposure. ➢ Climate change-associated, possible tendencies towards more frequent outdoor events have the potential to contribute significantly to the personal UVR dose, provided they extend over midday.	
	China Location 31° N (Name not given)	• There are large differences in outdoor time and personal UVR exposure between urban and rural areas. • Outdoor time and UVR exposure vary in adolescents, depending on geographic region, city and country, and gender.	[80]

Table 6. *Cont.*

Climate Zone	Country, Location, Latitude	Key Messages (Bullet Points) and Conclusions (Bullet Arrows)	Studies
	➢ Changes in behavior associated with climate change can take different forms depending on geographic region, city or country, gender and age.		
	South Africa Durban 30° S	• No statistically significant differences exist in UVR exposure between different age groups of children and adolescents. • Activity patterns are the most important factor for the individual UVR dose. • These is no relationship between the measured UVR dose and the duration of exposure.	[95]
	➢ A possible increase in UVR exposure associated with climate change could result from changed activity patterns rather than from a possible extension of stays outdoors at higher temperatures.		
	USA North Carolina 35° N Georgia 32° N	• Of the meteorological variables, daily precipitation is the strongest predictor of daily personal UVR exposure. • There is a bell-shaped relationship between temperature and daily personal UVR exposure.	[81]
	➢ If the thermal level is in the warm discomfort range, a climate change-associated, possible increase in UVR exposure due to the increase in outdoor spending cannot be assumed. ➢ Possible changes in precipitation associated with climate change could also have an impact on the personal UVR dose, not just changes in the thermal level.		

6. Lessons Learned

For the purpose of answering the research question 'Do people spend more time outdoors in a changed climate and are they more exposed to UVR?', mainly studies from temperate and subtropical climatic regions were identified, to a lesser extent from cold and tropical climatic regions.

Active leisure mobility and leisure activities, compared to the corresponding routine variants, are characterized by a stronger dependency on weather conditions and are therefore important study areas with regard to a potentially increased UVR exposure in the course of climate change.

It also shows that changes in weather conditions such as temperature and humidity, duration of sunshine, precipitation patterns and wind conditions can change people's UVR exposure behavior. However, the direction and extent of the effects vary. Changes in behavior associated with climate change are likely to have different effects with the seasons, primarily depending on the respective thermal level. However, possible changes in all weather conditions associated with climate change (such as changed precipitation patterns or increased air humidity) can have an impact on the personal UVR dose.

6.1. Temperate and Cold Climates

For temperate and cold climates, the available studies provide indications that a possible increase in UVR exposure associated with climate change at higher temperatures would primarily result from a reduction in clothing.

Only secondarily can it be assumed that the time spent outdoors plays a role because there is so far no statistically significant evidence for this relationship, based on the respective residential region of the people. Since the time of day or the position of the sun play an important role in relation to the UVR dose during the stay outdoors, a possible reason for the lack of evidence could in principle also be the fact that—in a constellation as a temporal extension outside the times already used when the sun is high—there is only a limited additional contribution to the UVR dose.

Furthermore, possible changes in vacation behavior associated with climate change could have a stronger impact on the personal UVR balance than changes in outdoor times in the residential area. Different constellations of lower to further increased UVR exposure of people are conceivable.

On the basis of the available studies, a general validity of the conclusion that higher temperatures caused by climate change lead to a longer outdoor time with possibly increased UVR exposure seems inadmissible. As long as the thermal level is in the comfort range, an increase in UVR exposure could result from longer periods of time outdoors at higher temperatures. However, an extrapolation of results, which refer exclusively to possible linear effects in the area of thermal comfort, is very likely an oversimplification. Existing studies suggest a nonlinear, bell-shaped relationship with threshold value effects. Knowledge of thermal threshold values that lead to significant changes in outdoor times, as well as projections of their future frequency of occurrence, are therefore particularly important.

Changes in the time spent outdoors can be seen both in terms of a significant increase in thermally comfortable to slightly warm conditions and in terms of a significant decrease in thermally uncomfortable, excessively hot conditions. In other words, under hot conditions, a climate change-associated increase in UVR exposure due to the increase in outdoor activities cannot be assumed directly.

Figure 3 illustrates the conceptual model for the relationship between outdoor time and thermal conditions, primarily in temperate and cold climates. The characteristics of the model (such as the position of the threshold values, the position of the maximum and the amplitude) are determined by the influences of the geographical context and the individual characteristics. At the population level, the respective proportions of the various influences will be decisive for the overall effect.

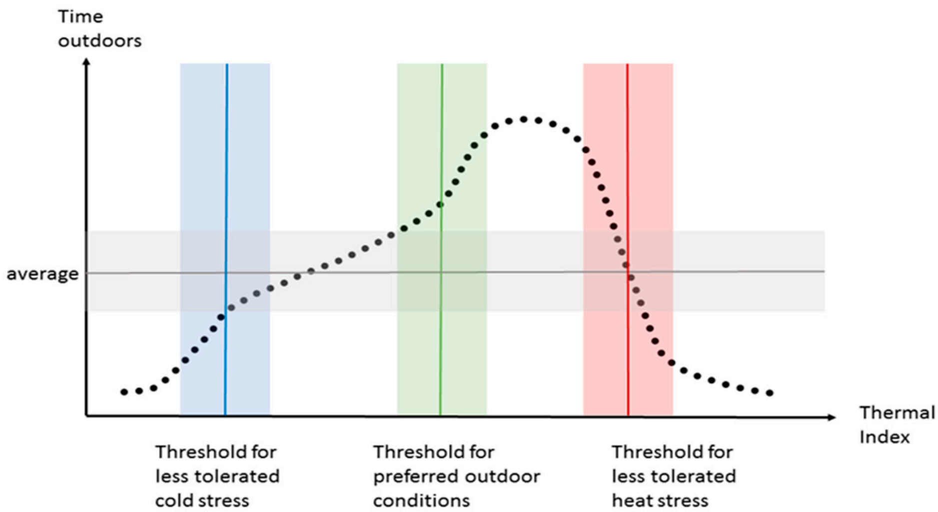

Figure 3. Conceptual model for the relationship between outdoor time and thermal conditions.

Possible changes in the variability of thermal conditions associated with climate change could also affect UVR exposure, not just gradual changes in thermal conditions.

Climate change scenario calculations using segmented linear relationships (but without threshold value effects) indicate that projected decreases in active mobility in summer are overcompensated by increases in other seasons [64]. Unfortunately, no accounting has yet been derived from this for UVR exposure.

Since darkness has been identified as a major obstacle to being outdoors, it is likely that a seasonally longer daylight duration will lead to increased exposure to the outdoors, and thus the effects of temperature and daylight duration will come into play at the same time. In order to be able to draw conclusions about climate change-associated, temperature-dependent behavior of people, the dependence on the length of the day should be eliminated. Investigations into the effects of temperature on behavior within the seasons are important for this.

6.2. Subtropical and Tropical Climates

The idea that higher temperatures caused by climate change are directly associated with more time outdoors and increased UVR exposure is very probably not applicable to subtropical and tropical climates. There is no statistically significant evidence of changes in behavior, especially in a currently warm local climate with minor seasonal differences. If the thermal level is well in the warm range of thermal discomfort, there is a tendency to avoid being outdoors as well as to avoid being exposed to the sun. This could even result in a potential decrease in UVR exposure. This last-mentioned, general conclusion applies with the caveats listed below for all climatic zones, such as the need to carry out differentiated analyses that take into account and balance opposing effects.

Studies in the subtropical climate lead to the following further conclusions, which, however, based on fundamental considerations, could also apply to temperate climates. Climate change-associated, possible tendencies to organize more outdoor events have the potential to contribute significantly to the personal UVR dose, provided that they extend over midday. In addition, a possible increase in UVR exposure associated with climate change could also result from changed activity patterns instead of from a possible extension of stays outdoors at higher temperatures.

6.3. Across All Examined Climates

The evaluated studies result in some basic information that is valid for all climatic regions examined.

The available studies show that the results obtained and the conclusions that can be drawn from them cannot simply be transferred and generalized in a straight line between different climatic zones and different seasons as well as between different types of leisure activities and modes of mobility.

When looking at behavioral changes associated with climate change, the geographical context must be taken into account, not only in terms of climatic conditions, but also in terms of cultures, habits, adaptations, traffic and land use (urban or rural). In addition, changes in behavior can develop differently depending on individual characteristics of people such as heat affinity, leisure type, gender and age. Figure 4 shows that both objective, but variable, external influences and individual factors determine the individual exposure behavior to the sun or the UVR.

Because of the dependency on regional characteristics, there is an urgent need for a differentiated analysis that takes opposing effects into account and balances them.

When comparing human UVR exposure behavior in different countries or regions, the possible external influence through education, information and intervention cam-paigns must also be considered. Depending on whether or not there are successful, broad-based and long-term skin cancer prevention campaigns, it is to be expected and examined whether the results differ. To inform people about the need to adopt protective measures when exposed to UVR, the global solar UV-Index (UVI) was developed [96]. It is a measure for the maximal erythema effective UVR and is linked to value-dependent protection recommendations. In 2019, a systematic review was conducted to examine the awareness, understanding, use and impact of the UVI based on more than two decades of international research [97]. The results were grouped geographically (Australia/New Zealand, USA/Canada, Europe, and other countries). There are clear differences, both between countries and between awareness and understanding on the one hand and use and be-havior on the other. Awareness is highest in Australia, slightly lower in New Zealand and North America, and significantly lower in Europe and other countries. It turned out that the understanding and use of the UVI for information on sun protection behavior is much less than its awareness. It has even been found that greater UVI awareness is partly asso-ciated with riskier UV-related behaviors, such as intentional tanning (increased exposure times and sunburns, decreased sun protection) [97]. The results of the evaluated interven-tions show a heterogeneous picture. In the USA, the use of app-based interventions varies greatly, but can also change sun protection behavior [98]. In contrast, studies from several other countries show no intervention effect on behavior. No significant association be-tween weather forecasts with or without UVI or sun protection alerts and sun protection behavior or sunburn was found in Australia [99]. A study from Italy [100] even showed higher UVR exposure and lower skin protection after the intervention. In summary, this aspect of behavior also shows that there is no automatism that education, information and intervention campaigns are directly reflected in people's behavior in the intended way. For this reason, the current state of knowledge does not offer a reliable basis for differentiating the previous findings on weather-related behavior from this point of view. However, it makes sense to explicitly consider this question when conducting comparative behavioral studies and when assessing the transferability of study results. It may also be possible in this way to draw conclusions about the effectiveness of such measures, which are likely to gain in importance as climate change progresses.

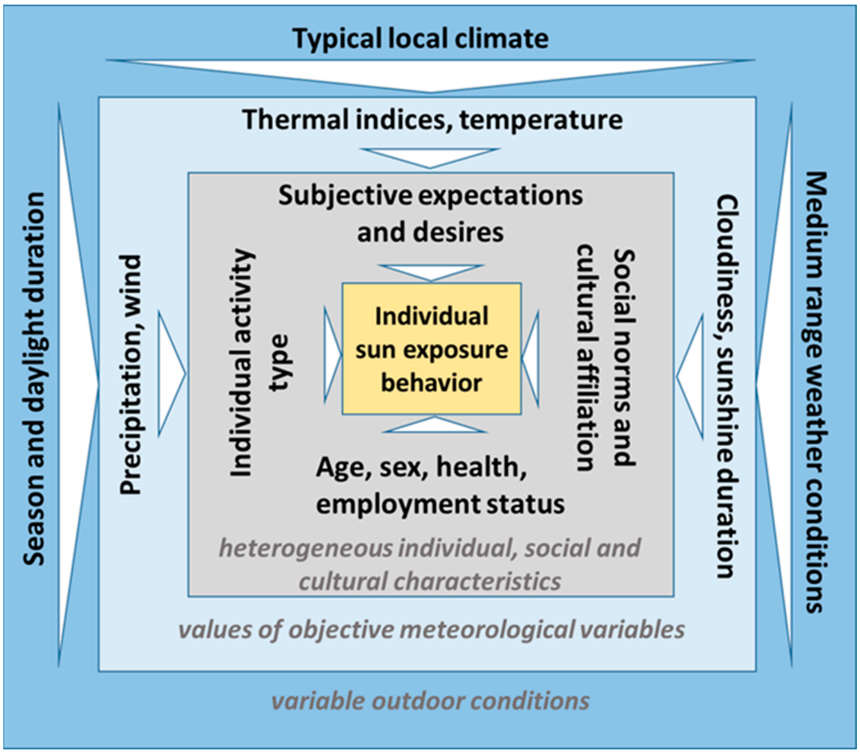

Figure 4. Influence on the individual solar UVR exposure behavior through the combination of objective, but variable, external outdoor conditions and heterogeneous individual, social and cultural characteristics.

This review analyzes behavioral patterns that determine changes in outdoor expo-sure and thus the possibility of UVR exposure. Almost exclusively studies from the leisure time part of life were found. There is currently a lack of studies on temperature-dependent behavior patterns, especially in the workplace, in educational institutions, and in institutions for the elderly. In general, behavior and UVR exposure at work are largely deter-mined by and depend on the organizational framework and specifications for completing work tasks [41]. In leisure time, there is usually more freedom to make decisions, and there is therefore more scope for behavioral changes. Nevertheless, certain analogy con-clusions for changed behavior can also be considered in work activities. As long as no more far-reaching organizational measures such as shifting working and/or break times are installed, it can be assumed that possible changes in behavior will relate less to the time spent outdoors (especially during times of high UVR exposure) and more to changes in clothing and (individual and organizational) sun protection measures. Analogous with the previous results for leisure time, it can be assumed that this applies to temperate and cold climates, not to subtropical and tropical ones. A recent comparative study on the UVR exposure of street construction workers in Colombia and Germany finds that, in temperate climate, seasonal effects are overlaid by behavioral aspects, e.g., in spring, while, in tropical climates, UVR exposure remains constant throughout the year [101]. There is a need for further research here as well as great potential for prevention, since significantly higher annual UVR doses are received at work than during leisure time [102,103].

7. Conclusions

This review article reveals a great need for research in order to have serious answers to the question of how climate change is changing human behavior in relation to UVR exposure. By its very nature, human behavior is very heterogeneous. An important step in assessing behavioral changes associated with climate change and their consequences on UVR exposure would be the development and verification of conceptual behavioral models and their respective regional specification depending on the geographical, climatic and seasonal context and depending on the population structure. Linking such regional behavioral models with the results of regional climate projections, together with (existing or to be carried out) UVR dose measurements, could represent an important step towards scientifically proven, quantitative estimates of behavior-related changes in UVR exposure in a changed climate. The extent to which changes in the UVR itself can also be expected due to climate change would have to be taken into account in further steps. In combination with dose–effect relationships for the health consequences of UVR exposure, the UVR-related health risks under climate change scenarios would be predictable on this basis and well-founded information could be provided for the planning and implementation of suitable adaptation measures.

Author Contributions: Conceptualization, G.L. and A.M.; methodology, G.L.; searching and resources, G.L.; writing—original draft preparation, G.L.; writing—review and editing, G.L. and A.M.; supervision, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Working Group for Dermatological Prevention (Arbeitsgemeinschaft Dermatologische Prävention e.V.) and the members of the working group on the chapter “Climate change and UV radiation” of the German S3 guideline program oncology [104] for their contributions to the starting point of this work.

Conflicts of Interest: The author declares no conflict of interest.

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