



OPEN Global assessment of surface ultraviolet radiation and malignant skin melanoma incidence from 1990 to 2021

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Climate change are altering ultraviolet (UV) radiation levels reaching the Earth's surface. Enhanced UV radiation poses significant risks to human health, notably increasing the risk of skin cancer. Malignant skin melanoma (MM) is the most aggressive skin cancer, accounting for 75% of global skin cancer-related deaths. Over the last five decades, MM incidence has surged dramatically, with over 325,000 new cases reported worldwide in 2020, underscoring the urgent need to understand and address the health impacts of rising UV exposure. This study systematically quantified the risk of UV-induced MM, revealing critical spatial patterns, demographic vulnerabilities, and temporal trends. We used the Global Burden of Disease 2021 and ERA5 data sets to analyze MM incidence trends and UV radiation trends, the relationships between population-weighted UV radiation and MM incidence rates, and vulnerability patterns from 1990 to 2021 in 176 countries and 21 regions. Results revealed UV radiation exhibited a general upward trend globally, with significant regional disparities. North Africa, the Middle East, and Europe had the highest risks of MM, indicating a strong association between rising UV radiation and increased MM incidence in these regions. Among 176 countries, 49 showed significant associations, with the highest risks concentrated in countries such as Cabo Verde, Russia, Libya, Belarus, and Egypt. In Europe, subgroup analysis reveals that UV radiation significantly elevates MM risk across all genders and age groups over 15, with the highest vulnerability observed in males and individuals aged over 85. Our findings emphasize the urgency of targeted public health strategies to mitigate UV-related MM risk, particularly in the most affected regions.

Keywords UV radiation, Malignant skin melanoma, Global burden of disease study, Risk assessment

Malignant skin melanoma (MM) is a severe skin cancer that arises from melanocytes¹. MM represents approximately 5% of all skin cancers, but due to its highly aggressive nature and metastatic potential, it accounts for approximately three-quarters of all skin cancer deaths. MM typically appears as darkly pigmented lesions on the skin, displaying varying shades of tan, brown, and black. The presence of a high mole count and clinically atypical nevi (also known as dysplastic nevi) are the most important phenotypic risk factors for the development of MM^{2,3}. Historically, melanoma was a rare disease, but over the past 50 years, its incidence increased substantially, with the highest incidence observed in fair-skinned populations^{4,5}. In 2020, over 325,000 new cases of MM were diagnosed globally⁶. In an analysis of six high-income countries with predominately European heritage, incidence rates of invasive MM doubled to quadrupled between 1982 and 2011⁷.

Ultraviolet radiation has long been recognized as the most significant environmental risk factor for melanoma^{8,9}. The entire UV spectrum (100–400 nm) can be carcinogenic^{10,11}. Importantly, global UV radiation levels are not static, and their long-term variations are influenced by multiple climate-related drivers such as stratospheric ozone depletion, changes in cloud cover, aerosol concentrations and surface reflectivity¹². The implementation of the Montreal Protocol has significantly reduced atmospheric concentrations of ozone-depleting substances, it has reduced damage to the ozone layer and slowed the rate of increase in UV radiation¹³. However, the recovery of the ozone layer has been slow, especially in the polar region, and full recovery is not expected until after 2060^{14,15}. This delay has resulted in a continuing trend of increasing levels of ultraviolet radiation in some regions over the coming decades. In addition, in the mid-latitudes of the northern hemisphere,

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reductions in cloud cover and aerosols have led to an increase in ultraviolet radiation in recent decades^{16,17}. From 1979 to 2010, erythemal-weighted ultraviolet radiation—representing the biologically effective portion of the UV spectrum that causes skin damage—increased by approximately 3% globally, most notably at mid-latitudes^{9,18}. These factors collectively influence the global distribution of ultraviolet radiation. According to model estimates, this complex interaction will lead to a future in which UV radiation will exhibit significant regional differences.

According to the Global Burden of Disease study data¹⁹, there are significant regional differences in MM incidence change, closely linking to the variations in UV radiation levels. Most current studies focus on specific countries or regions, lacking a comprehensive global perspective. Moreover, few studies investigated the longitudinal association between UV radiation trends and MM incidence change over multi-decadal timescales. Despite growing recognition of UV radiation as a major carcinogenic factor, it remains unclear whether and how populations with different skin phototypes, social development levels, and historical UV baselines differ in their vulnerability to rising UV radiation. This lack of global evidence hampers targeted public health planning. Understanding such heterogeneity is essential for identifying vulnerable populations and tailoring public health interventions.

Therefore, this study aims to evaluate the impact of changing UV radiation on the incidence of MM at global and regional levels. Using harmonized data from the GBD and ERA5 datasets across 176 countries and 21 regions from 1990 to 2021, we analyzed the temporal trends in population-weighted UV radiation and MM incidence, assessed their associations, and explored the demographic and geographic heterogeneity in risk. By identifying regions and population subgroups most vulnerable to rising UV radiation, this study provides evidence-based insights to support the development of targeted public health interventions in the context of ongoing climate change.

Data and methods

Data sources

Annual malignant skin melanoma (MM) incidence rates for 176 countries from 1990 to 2021 were obtained from The Global Burden of Disease (GBD) study. These MM incidence rates were presented as age-standardized rates, normalized to the GBD world standard population to facilitate cross-country and temporal comparisons. For sex- and age-specific subgroup analyses, we used non-standardized incidence data to examine trends within demographic groups, enabling detailed assessment of vulnerability patterns across populations. Based on the geographical distribution, cultural characteristics, and local conventions, 204 countries/locations were categorized into 21 geographical regions (<https://ghdx.healthdata.org/countries>; accessed on September 18, 2024)^{20,21}. The International Classification of Diseases, Tenth Revision (ICD-10), code for MM is C43.9.

Global monthly mean surface downward UV radiation flux data with a resolution of $0.25^\circ \times 0.25^\circ$ were obtained from the ERA5 dataset for the years 1940 to 2023. ERA5 dataset is a comprehensive global reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset is generated using advanced numerical weather prediction models combined with a vast range of observations from satellites, surface instruments, and upper-air measurements. It provides global meteorological and climatological variables from 1940 to the present, covering the atmospheric, terrestrial and oceanic domains.

The socio-demographic index (SDI) serves as a composite measure of social and economic development at the country level and is derived from measures of income per capita, the educational attainment of the population aged 15 years or older, and the fertility rate of women aged younger than 25 years^{22,23}. The GBD study classifies countries and regions into five levels on the basis of the SDI: low SDI regions, low-middle SDI regions, middle SDI regions, high-middle SDI regions, and high SDI regions. The present study used the SDI scores for 2019 to represent the economic development status of each investigated country.

The population density data utilized in this study was sourced from the History Database of the Global Environment (HYDE) 3.3 dataset, which provides detailed, globally consistent population distribution data²⁴. Country and region boundary shapefiles were obtained from the Natural Earth Dataset, offering precise geographic boundary delineations for national and regional levels.

Statistical methods

First, we analyzed the time series of median and mean global UV radiation from 1940 to 2023. These time series were smoothed using Local Estimated Scatterplot Smoothing (LOESS) curves. LOESS provides a flexible fitting approach that captures local trends and variations in the data, offering a clearer understanding of short-term changes and long-term trends²⁵. We specifically highlighted the time range from 1990 to 2021 within these curves to examine how UV radiation trends within the study period compare to longer-term trends. Additionally, we calculated the annual change rate of UV radiation from 1990 to 2021 by determining the slope of the linear trend for each grid point over the years. This approach allows us to assess whether UV radiation levels have increased or decreased globally and to evaluate the rate of these changes in different regions.

Using shapefiles of national and subnational administrative boundaries along with global population density data, we extracted population-weighted UV radiation values for each country and region from 1990 to 2021. This approach ensures a more accurate representation of human exposure to UV radiation by giving greater weight to more densely populated areas, thereby reflecting the actual distribution of human activity and exposure.

We calculated the absolute changes in population-weighted UV radiation and MM incidence over a 32-year period for 21 GBD regions worldwide from 1990 to 2021. These changes were ranked to assess and compare the degree of variation across regions. To further explore the relationship between UV radiation and MM incidence, we created a heatmap of UV radiation changes for each country and overlaid it with point data representing changes in MM incidence. This visualization aims to identify potential patterns and correlations between UV radiation and MM incidence. Additionally, we constructed scatter plots for UV radiation and MM incidence

from 1990 to 2021. We applied a generalized additive model (GAM) to fit these data points. GAM is used to identify nonlinear associations between UV radiation and MM incidence through smooth splines to obtain a smooth curve and are widely used for association analysis^{26,27}. Natural spline functions are used for exposure-response curve fitting in the GAMs. It allowed us to analyze how changes in UV radiation correlate with trends in MM incidence on an annual basis.

We used UV radiation and MM incidence data from 21 global regions to fit a GAM for each region, using UV radiation as the sole explanatory variable. Relative risk (RR) was calculated to assess the influence of UV radiation on the risk of MM. RR values of more than 1.0 indicated that an increase in UV radiation correlated with an increase in the risk of MM. We also calculated P-values, considering results statistically significant when $P < 0.05$. This allowed us to compare which regions were more sensitive to the impact of UV radiation on MM incidence based on the size and significance of the RR values.

We then focused on the regions where MM incidences were most sensitive to UV radiation. By selecting the top four RR values in each of the 21 regions, scatter plots of UV radiation and MM incidence for each of these four regions over the 32-year period were developed. Fitted curves by GAM models were fitted to these plots, and the R^2 values (explained variance) and P-values were utilized to assess the significance of these trends. This approach provided a clear visualization of the relationship between UV radiation and MM incidence in the most sensitive regions. We further analyzed different demographic groups (gender and age) in the regions with the highest RRs. Finally, 49 countries were identified where the MM risks were significant ($RR > 1.0$ and $P < 0.05$).

Results

Global median (Fig. 1A) and mean (Fig. 1B) UV radiation both showed decreasing trends from 1940 to 1980. However, between 1980 and 2023, the global median UV radiation increased significantly, while the mean remained nearly unchanged, with slight increase. From 1990 to 2021, the rise in median UV radiation reflected an overall yearly increase in UV levels across most regions of the world. In contrast, the slight rise in the mean suggested that there were significant regional differences in UV changes, with some areas experiencing notable increases and others seeing significant decreases. This difference arose because the median captured broader trends, while the mean was more affected by extreme values. Additional statistical assessments, including skewness trends and annual probability distributions, are provided in Supplementary Figure S1. Figure 1C showed that the rate of change in UV radiation from 1990 to 2021 varied significantly across different regions of the world. In areas such as Europe, Central Africa, South America, and North America, UV radiation indicated notable increase, with annual rates of change exceeding $0.05 \text{ W/m}^2/\text{year}$. In contrast, UV radiation in the regions like South Asia and Southeast Asia experienced a marked decline. This highlighted distinct regional patterns in UV exposure, with some areas seeing consistent increases while others faced significant decreases.

Figure 2A illustrated the total changes of population-weighted UV radiation for 21 global regions from 1990 to 2021. The regions with the most significant increases in UV radiation included Southern Latin America,

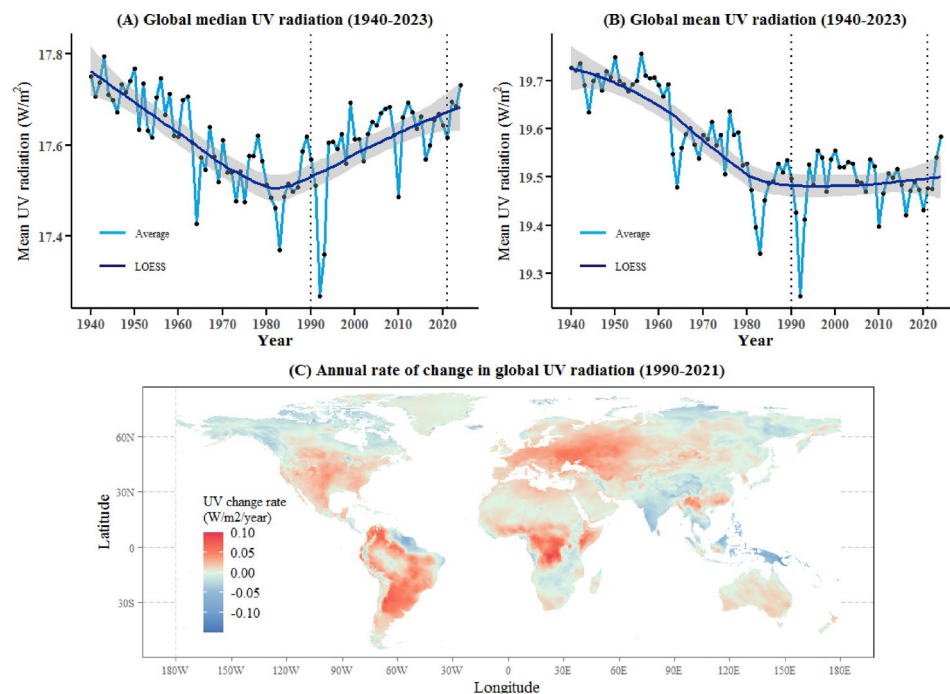


Fig. 1. Global UV radiation trends and spatial distribution: median (1940–2023), mean (1940–2023), and annual change rate (1990–2021). (A) Global median UV radiation from 1940 to 2023 with LOESS smoothing. (B) Global mean UV radiation from 1940 to 2023 with LOESS smoothing. (C) Global UV radiation annual change rate from 1990 to 2021.

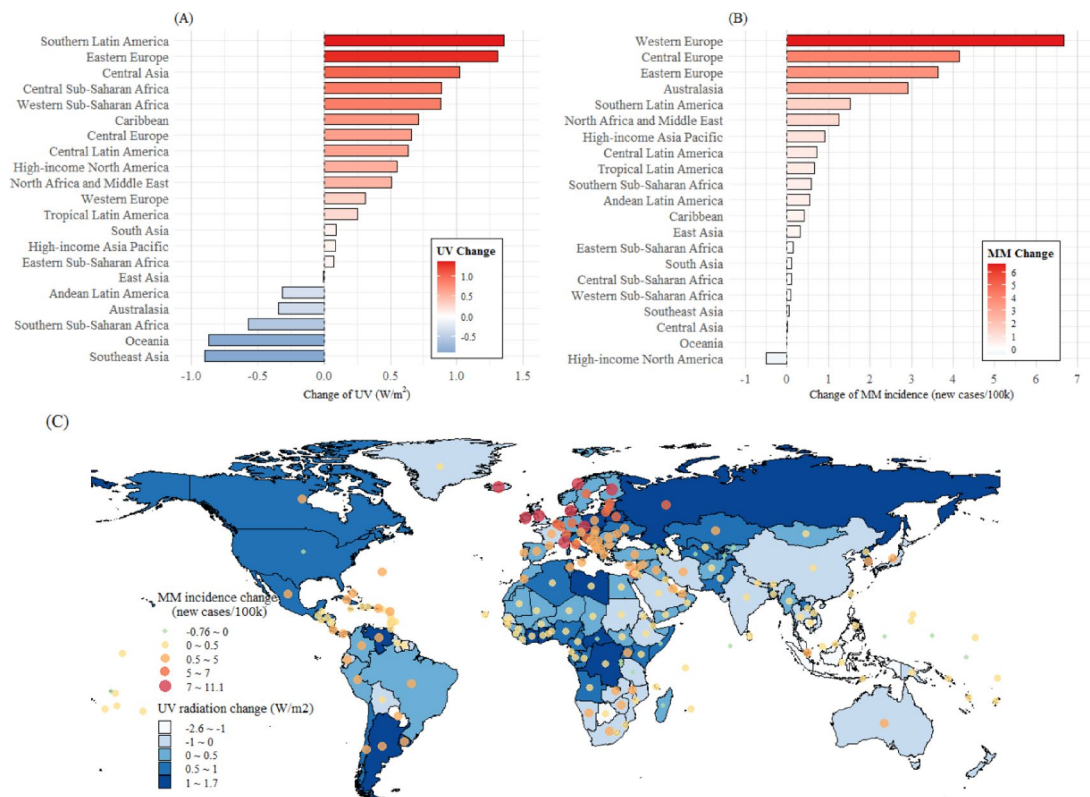


Fig. 2. Regional and global changes in population-weighted UV radiation and MM incidence (1990–2021). **(A)** Total change in population-weighted UV radiation across regions from 1990 to 2021. **(B)** Total change in MM incidence across regions from 1990 to 2021. **(C)** Global distribution of population-weighted UV radiation (with five intervals ranging from -2.6 to 1.7 W/m²) and local MM incidence (color-scaled dots, ranging from -0.76 to 11.1 new cases per 100,000 persons) from 1990 to 2021.

Eastern Europe, and Central Asia, where the average increase ranged from 1.0 to 1.5 W/m² from 1990 to 2021. Central and Western Sub-Saharan Africa, the Caribbean, and Central Europe showed moderate increases between 0.5 and 1.0 W/m² from 1990 to 2021. Southern Sub-Saharan Africa, Oceania, and Southeast Asia saw significant declines in UV radiation, with reductions ranging from -1.0 to 0 W/m² from 1990 to 2021. The increase in MM incidence was most pronounced in Europe, with growth ranging between 3 and 7 new cases per 100,000 people, and Western Europe showing the largest increase at 6.8 new cases per 100,000. Australasia, Southern Latin America, and North Africa and the Middle East experienced moderate increases between 1 and 3 new cases per 100,000. Most other regions saw minimal increases, remaining between 0 and 1 new cases per 100,000. The only region to exhibit a decrease in MM incidence was High-income North America, with a reduction of -0.6 cases per 100,000 (Fig. 2B). It was found that both UV radiation and MM incidence in Eastern Europe increased significantly, with a strong synchronization in their trends. Figure 2C further illustrated the changes in UV radiation and MM incidence for 176 countries from 1990 to 2021. The data showed that MM incidence rose sharply across Europe, which was also characterized by increased UV radiation levels. Similarly, Southern Latin America exhibited synchronized increases in both UV radiation and MM incidence. However, despite substantial increases in UV radiation in Central Africa and North America, the rise in MM incidence in these regions was less pronounced.

Figure 3 reflected that from 1990 to 2021, countries with lower average annual UV radiation levels experienced more significant increases in MM incidence, while those with higher UV radiation saw less pronounced changes. The most substantial rise in MM incidence occurred in regions where annual UV radiation ranged between 10 and 15 W/m², followed by those with UV levels between 15 and 20 W/m². In areas with UV radiation levels between 20 and 25 W/m², the increase in MM incidence was minimal, and for regions with average UV radiation above 25 W/m², there was almost no change in MM incidence over the period. Interestingly, regions with lower UV radiation often corresponded to countries with higher SDI scores, reflecting a higher level of socio-economic development. The most significant increases in MM risk were concentrated in high SDI and high-middle SDI regions, suggesting that the impact of UV radiation on MM incidence was not uniform across all regions globally. Instead, it presented a more pressing environmental health challenge for economically developed regions with relatively lower UV radiation, where the increase in MM incidence was most pronounced.

This finding underscores the importance of considering not only absolute UV levels, but also baseline exposure and population-specific sensitivity when assessing UV-related health impacts under climate change. To isolate the effects of UV change within stable demographic and cultural contexts, the subsequent within-region

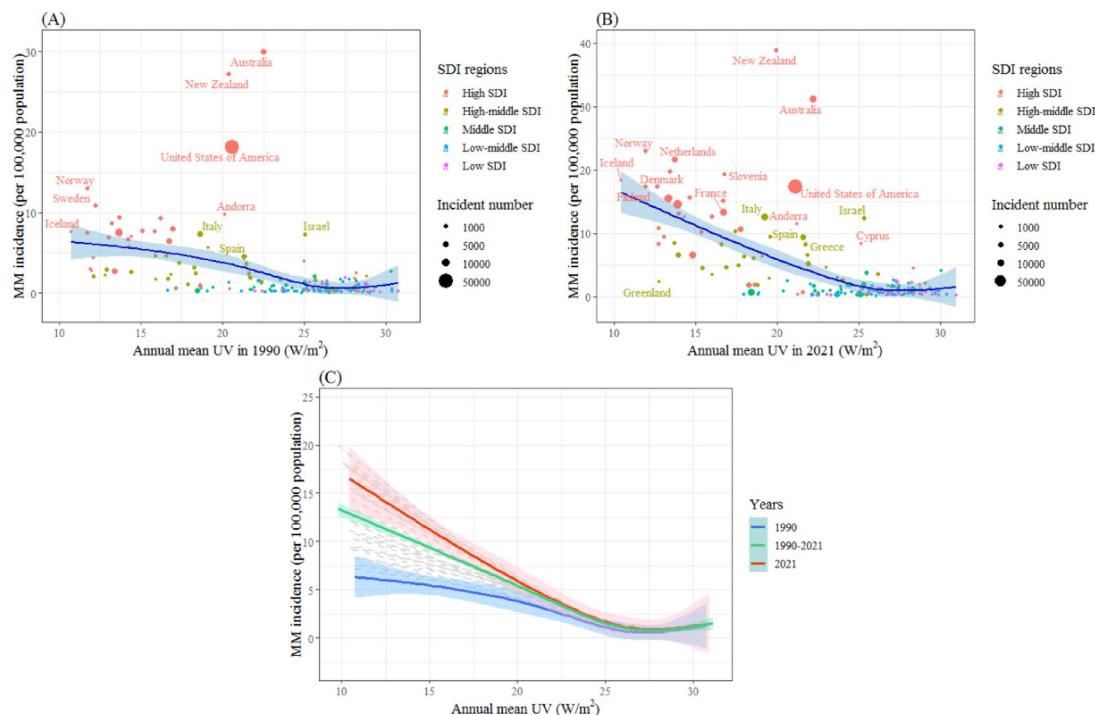


Fig. 3. Comparison of annual mean population-weighted UV radiation and MM incidence rate in 176 countries from 1990 to 2021. **(A)** Scatter plot of annual mean population-weighted UV radiation and MM incidence in 1990, with point size representing incidence numbers and color indicating SDI (Socio-Demographic Index), fitted with a GAM curve. **(B)** Scatter plot for 2021 with similar parameters and GAM fitting. **(C)** Temporal trends comparing annual GAM-fitted curves from 1990 to 2021, with solid lines for 1990, 2021 and 1990–2021, and dashed lines for other years.

longitudinal analyses were performed separately for each country using region-specific MM incidence and UV radiation trends over time.

Figure 4 showed the relative risks (RR) reflecting the impact of UV radiation on MM incidence across 21 global regions. The most significant influence was observed in North Africa and the Middle East, where the RR value was 2.17 (1.69–2.80). This meant that for each unit increase in UV radiation, the risk of developing MM was 2.173 times higher compared to conditions without increased UV exposure. Following this was Eastern Europe, with an RR of 1.77 (1.51–2.07), indicating that UV radiation increased MM risk by 1.77 times in this region. Other notable regions included Central and Western Europe, with RR values of 1.48 (1.26–1.75) and 1.47 (1.22–1.77) respectively. All four regions showed highly significant results, with P-values less than 0.001, marking them as the areas where UV radiation had the strongest impact on MM incidence. In addition, Southern Latin America and Central Sub-Saharan Africa also showed significant effects, with RR values of 1.23 (1.10–1.37) and 1.14 (1.04–1.25), passing the P-value threshold of 0.01. Regions such as Central Latin America, High-income North America, and Tropical Latin America showed moderate impacts, with RR values of 1.33 (1.08–1.65), 1.15 (1.02–1.29), and 1.14 (1.04–1.26), passing the significance test with P-values less than 0.05.

To better understand how the high RR values were derived for North Africa, the Middle East, and Europe, and to more clearly illustrate the strong association between UV radiation and MM incidence in these regions, we fitted GAM curves for the four regions where MM incidence was most sensitive to UV radiation. In Fig. 5, North Africa and the Middle East demonstrated the highest RR values largely because both the regional annual average UV radiation and MM incidence showed a clear, synchronized upward trend from 1990 to 2021. The R^2 value of 0.54 indicated that 54% of the variation in MM incidence could be explained by the increase in UV radiation. Eastern Europe followed a similar pattern, with a very close fit to North Africa and the Middle East, with a 0.6 of R^2 value. Central and Western Europe also showed upward trends in MM incidence corresponding to increases in UV radiation, although the fitting was weaker compared to North Africa and Eastern Europe. The R^2 values for these regions were 0.41 and 0.31, respectively.

Since Europe (including Western, Central, and Eastern Europe) demonstrated the most pronounced effect, we thus assess how UV radiation affect MM risk across different gender and age groups in Europe (Fig. 6). The analysis revealed that for both genders and all age groups, UV radiation significantly increased the risk of MM ($RR > 1$; $P < 0.001$). For every $1 W/m^2$ increase in UV radiation, the risk of MM for males rose to 1.89 times (1.73–2.06) compared to conditions without increased UV exposure, and for females, the risk increased to 1.69 times (1.54–1.86). For individuals under the age of 15, there is no associated risk of MM due to UV radiation, as the incidence rate in this age group is consistently zero. For those aged 15 and above, UV radiation significantly raised the MM risk. The higher RR of 1.92 (1.68–2.18) was observed for the age group of 20–24. The

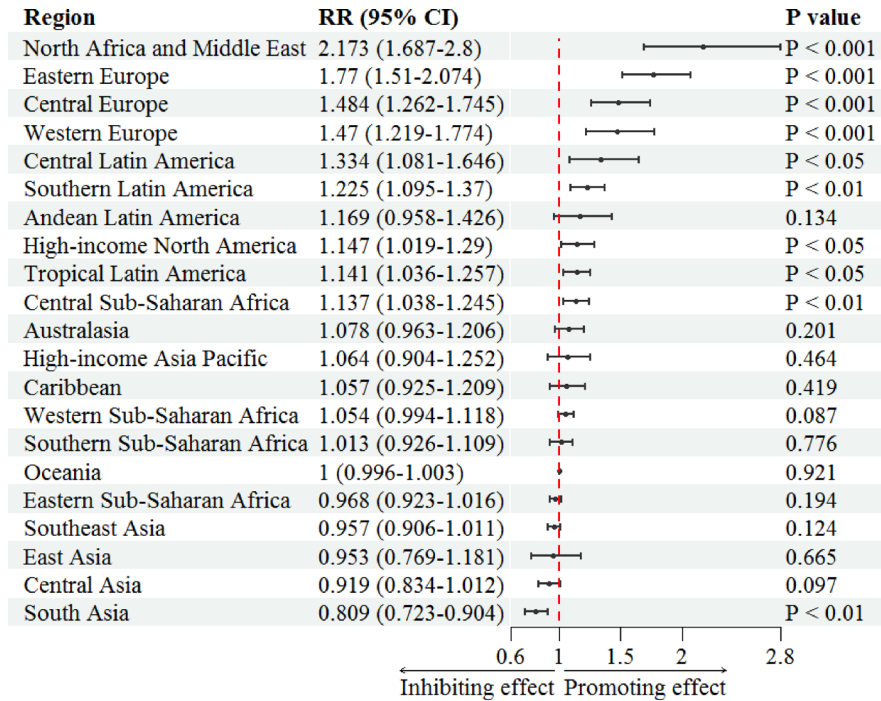


Fig. 4. Forest plot of relative risk (RR) for population-weighted UV radiation and MM incidence across 21 global regions, with 95% confidence intervals and P values.

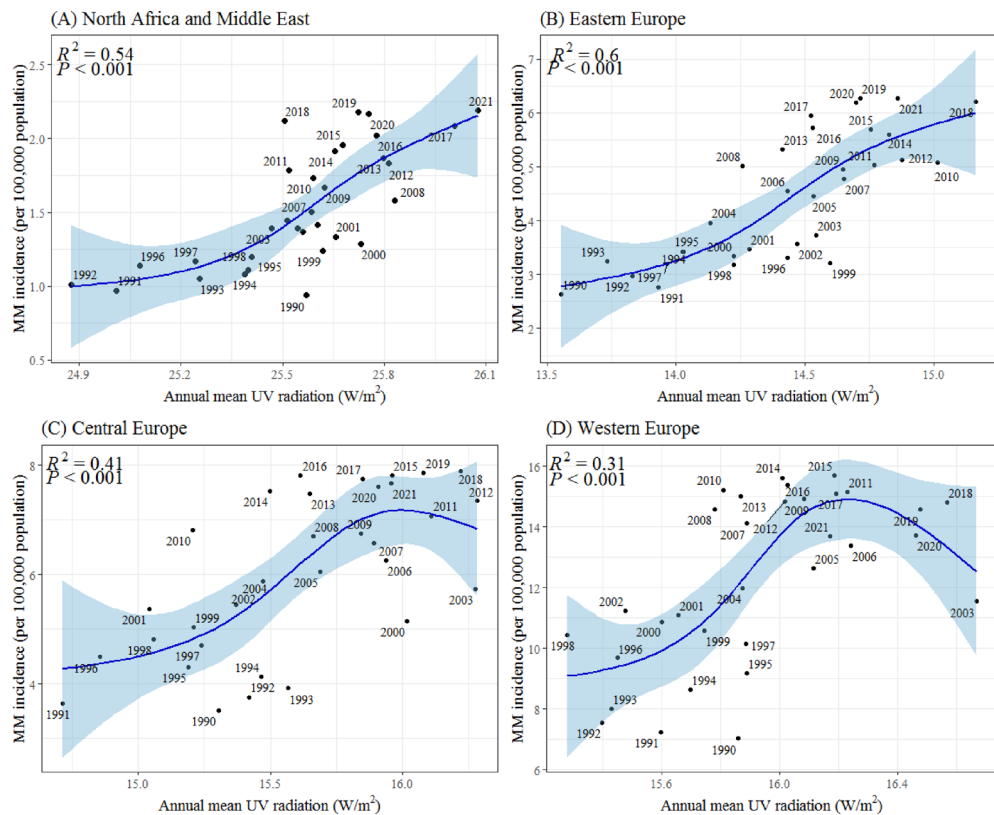


Fig. 5. Relationship between the annual mean population-weighted UV radiation and MM incidence from 1990 to 2021 in the four regions with the highest RR values: (A) North Africa and Middle East, (B) Eastern Europe, (C) Central Europe, and (D) Western Europe.

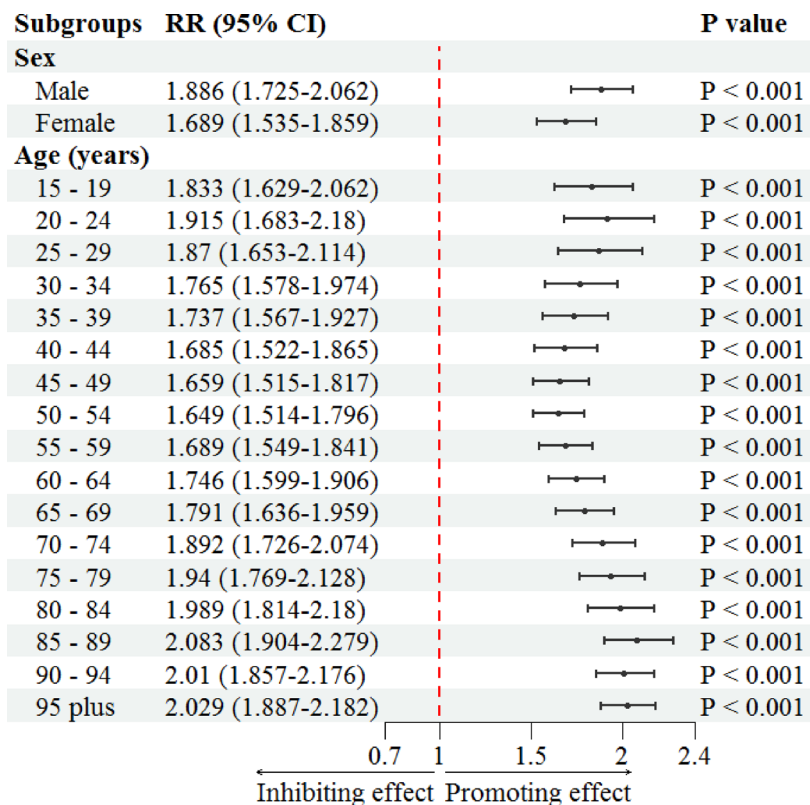


Fig. 6. Forest plot of relative risk (RR) for population-weighted UV radiation and MM incidence across age and sex subgroups in Europe (Eastern Europe; Central Europe; Western Europe) from 1990 to 2021, with 95% confidence intervals and P values.

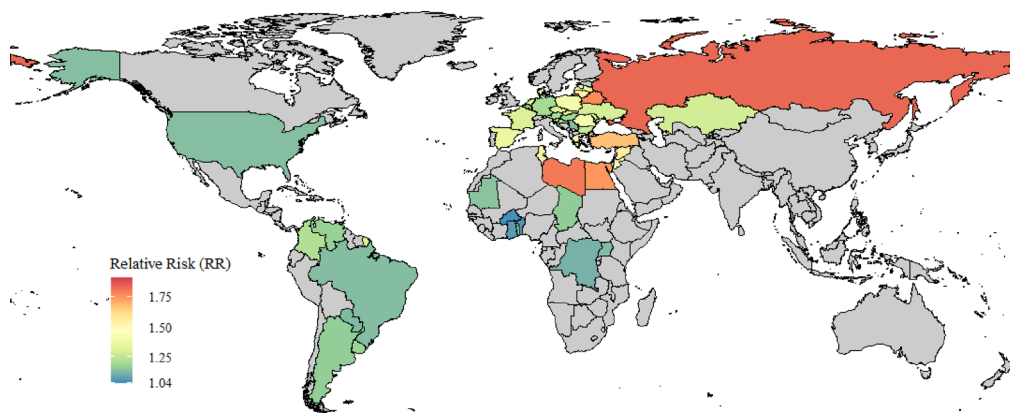


Fig. 7. Global distribution of countries with significant UV-induced increase in MM incidence (1990–2021): RR values for 49 countries with P values < 0.05 and relative risk > 1.

RR decreased for the 50–54 age group, with a value of 1.65 (1.51–1.80). However, beyond age 54, the effect of UV radiation on MM risk strengthened, with RR values climbing steadily with age, peaking in individuals aged 85 and above (mean RR = 2.04 [1.88–2.21]). This suggested that increased UV radiation posed a greater MM risk for males, young adults aged 20–24, and individuals over 85 years old.

In Fig. 7, a detailed analysis was conducted on the RR of UV radiation impact on MM incidence across individual countries to provide more accurate results compared to broader regional trends. Out of 176 countries, 49 were found to have RR values with statistical significance ($P < 0.05$), indicating a strong correlation between the increased UV radiations and rising MM incidence in these countries. These 49 countries were primarily concentrated in Europe (24 countries), the Middle East and North Africa (7 countries), Latin America (7 countries), the United States in North America, and 10 countries from other regions. Among these, European countries generally showed the highest RR values, with Eastern Europe leading. Notable countries included

Russia (RR: 1.83 [1.50–2.22]), Belarus (RR: 1.76 [1.38–2.24]), Turkey (RR: 1.67 [1.21–2.30]), Lithuania (RR: 1.54 [1.24–1.89]), and Greece (RR: 1.41 [1.14–1.75]). In the Middle East and North Africa, countries with high RR values included Libya (RR: 1.79 [1.48–2.17]), Egypt (RR: 1.74 [1.32–2.29]), Syria (RR: 1.55 [1.09–2.19]), and Israel (RR: 1.44 [1.11–1.87]). In Latin America, the countries with the highest RR values were Colombia (RR: 1.22 [1.10–1.36]), Uruguay (RR: 1.18 [1.06–1.31]), and Venezuela (RR: 1.17 [1.01–1.36]). In contrast, countries in North America, Central Africa, and West Africa generally showed lower RR values. More detailed RR values for these 49 countries can be found in Table S1 of the appendix.

Discussion

The results of current study provide clear evidence of a strong association between increasing UV radiation levels and the rising incidence of MM in 49 out of 176 countries globally, spanning from 1990 to 2021. Among the regions most affected, North Africa, the Middle East, and Europe show the most significant impacts on MM risk. Notably, countries like Cabo Verde, Russia, Libya, Belarus and Egypt exhibit high RR values, underscoring the particular vulnerability of populations in these areas. In Europe, UV radiation is found to elevate MM risk across genders and all age groups over 15, with the highest susceptibility observed in males and aged over 85. Further, in countries such as Denmark and Germany, over 90% of MM cases from 2012 to 2016 are attributable to UV exposure, highlighting the critical role of UV in MM incidence²⁸.

Over the past 30 years, certain regions have experienced marked increases in UV radiation. While the Montreal Protocol has contributed to stabilizing global average UV levels from 1990 to 2021¹³, the rise in median UV radiation indicates a significant upward trend. For example, Eastern Europe, historically a region with relatively low baseline UV levels, has seen an increase of 1.3 W/m². Our analysis reveals a robust correlation between this rise in UV radiation and MM incidence rates, highlighted by high R² values for Eastern Europe and the Middle East. The goal of this study was to identify regions with the most substantial UV radiation increases and assess the sensitivity of their MM incidence. By using RR values, the regional comparisons provide a clearer understanding than global comparisons, as they take into account societal and environmental factors that remain relatively stable within each region.

As shown in Fig. 3, regions with lower average UV radiation experienced greater increases in MM incidence from 1990 to 2021, suggesting a potential environmental vulnerability shaped by long-term adaptation. Populations in historically low-UV regions, often characterized by lighter skin phototypes and less behavioral protection against UV, may exhibit heightened sensitivity to even modest increases in UV exposure. In contrast, those in chronically high-UV regions may possess stronger biological and cultural adaptations that mitigate the impact of similar UV changes. It reflects a typical pattern of environmental adaptation vulnerability, paralleling the observation that populations in cold climates are more vulnerable to heatwaves, or that arid regions are more prone to flash flooding after sudden rainfall events. This finding underscores the importance of considering not only absolute UV levels, but also baseline exposure and population-specific sensitivity when assessing UV-related health impacts under climate change. To isolate the effects of UV change within stable demographic and cultural contexts, our subsequent analyses (Figs. 4, 5, 6 and 7) were performed separately for each country using region-specific MM incidence and UV radiation trends over time. This within-region longitudinal approach helps control for cross-national confounding factors such as ethnicity, skin type distribution, and behavioral norms, thereby enhancing the causal interpretability of the observed association between UV increase and MM risk.

The findings in the current study emphasize a particular vulnerability in fair-skinned populations within Eastern Europe, where MM susceptibility is notably high. Despite this, awareness and prevention efforts have largely concentrated in the United States and Western Europe¹¹, while regions such as Eastern Europe and the Middle East, which are more sensitive to rising UV levels, receive less attention. This gap represents a significant public health challenge and highlights the need for more focused epidemiological study and prevention initiatives in these under-addressed regions.

Skin damage from sun exposure is accumulated throughout a person's life. Previous studies suggest that by the age of 26, individuals have typically received most of their lifetime sun damage, although the effects may not yet be apparent. This accumulated damage can later lead to skin cancer, with factors in older age acting as triggers²⁹. Studies have demonstrated that melanoma is common even in patients under 30 years of age, especially in young women^{6,30,31}. This is consistent with our findings that increased UV radiation significantly promotes melanoma in people aged 20–24 years. Skin cancer commonly appears in individuals in their 50–60 s, and the incidence and mortality rates of melanoma particularly increase sharply after the age of 60. Our findings similarly indicate that the role of UV radiation in inducing melanoma gradually rises in Europeans over the age of 50. Moreover, melanoma often presents at a younger age compared to other cancers. The median age of melanoma diagnosis is only 57 years, whereas other cancers, such as colorectal cancer (68 years), lung cancer (70 years), and prostate cancer (71 years), typically occur later^{32,33}.

Men are more likely to develop melanoma due to UV radiation exposure than women³⁴, but inconsistent results have also been reported in previous studies. Females aged 20–24 years are more likely to be diagnosed with MM than males³⁵; however, as age increases, males become much more likely to develop melanoma (aged greater than 65 years)³⁶. Population-based studies indicate notable gender differences in melanoma awareness and detection practices. Recent studies have suggested that some of this disparity may be explained by relatively higher sun exposure and lower knowledge/awareness of skin cancer and compliance with sun protection measures in men^{37,38}.

This study has several limitations. First, the GBD dataset only includes national-level MM incidence data at high administrative levels, lacking more detailed data at the provincial, state, or regional levels. This limitation may result in an oversight of intra-national differences in MM incidence rates, potentially averaging out or obscuring regions with higher MM risk within a country. Moreover, although GBD data are modeled

to account for reporting differences, limited surveillance in earlier years or lower-income countries may still influence incidence estimates. Additionally, heightened public awareness or targeted screening programs in certain countries may lead to detection bias. However, we observed that the most pronounced increases in MM incidence occurred in high-income countries with long-standing registry systems, suggesting that these trends are more likely reflective of true increases in disease burden rather than reporting artifacts. While UV radiation is a significant driver of MM incidence, the increase in MM cases is still influenced by multiple factors. These include variations in human behavior, lifestyle choices, occupational exposure, sun protection measures, and socio-economic conditions across different regions. While these factors may influence certain regional findings, they do not diminish the significance of the observed association between UV radiation and MM incidence. Moreover, not all regions face the same environmental health challenges regarding the impact of UV radiation on MM incidence in this study. The results in this study emphasize the strong association between UV radiation and MM incidence in certain regions, such as Europe and the Middle East, but these results and recommendations may not be directly applicable to other lower-risk areas. In addition, although we incorporated long-term UV data (1955–2023) to contextualize recent changes, this study did not fully explore the environmental mechanisms behind long-term UV variability. A more in-depth analysis of historical UV distributional shifts and their climatic drivers will be addressed in future work. We also acknowledge that solar cycle-related fluctuations may introduce short-term variability in UV exposure; however, their limited temporal scale is unlikely to alter the long-term trends emphasized in this study. Furthermore, we did not include a fixed time lag between UV exposure and MM incidence due to inter-population variability in latency periods, we recognize this as a key area for refinement in future studies using lagged modeling frameworks. Lastly, although ERA5-based UV radiation estimates used in this study account for atmospheric parameters such as clouds and aerosols, we did not explicitly separate the individual contributions of these factors. Future research is needed to disentangle and quantify these contributing mechanisms across regions.

Conclusion

Our study highlights the strong association between increasing UV radiation and the rising incidence of malignant skin melanoma (MM) across 176 countries, providing a comprehensive global and regional analysis of UV radiation on MM risk. From 1990 to 2021, there was a general increase in global UV radiation, with significant regional disparities. The overlap between regions with significant increases in UV radiation and those with rising MM incidence was particularly notable in Eastern Europe. In North Africa, the Middle East and Europe, the increase in UV radiation has the most significant impact on MM risk, characterized by a clear synchronized rise in both UV levels and incidence. The more detailed subgroup analysis focusing on Europe reveals that UV radiation significantly raises MM risk across all genders and age 15-over groups, especially for males and individuals aged over 85. Out of the 176 countries studied, 49 exhibited statistically significant RR values, with most of these concentrated in Europe and the Middle East. Countries like Cabo Verde, Russia, Libya, Belarus, Egypt have the top five of high RR values. This research underscores the urgent need for public health initiatives and policy interventions aimed at mitigating UV exposure and reducing melanoma risk, particularly in the most affected regions.

Data availability

ERA5 data are publicly available at <https://cds.climate.copernicus.eu/cdsapp#!/home>. GBD data is available at <https://www.healthdata.org/research-analysis/gbd>. The geographic information system data for country boundaries from the Natural Earth Dataset are available at <https://www.naturalearthdata.com/>. The historical and current population distribution data are available from the HYDE 3.3 database at <https://landuse.sites.uu.nl/datasets/>.

Received: 10 February 2025; Accepted: 3 October 2025

Published online: 10 November 2025

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Acknowledgements

Acknowledgements Computing resources were supported by the Supercomputing Center of Lanzhou University.

Author contributions

Y.M. designed and carried out the research; F.F. carried out the research and result analysis; Y.Z. and Z.W. assembled and analyzed data; R.Z. collected and assembled data; S.Y. collected data; F.F. and Y.M. wrote and revised the manuscript. All authors reviewed the manuscript.

Funding

This work was supported by grants from the National Natural Science Foundation of China (grant nos: 42375177, 41975141) and Natural Science Foundation of Gansu (Grant No. 23JRRA1079) and the Fundamental Research Funds for the Central Universities (Grant Nos. lzujbky-2024-it36).

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-23066-z>.

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