

Long-Term Variability and Empirical Estimation of Daily UVB Doses in Riyadh: Insights from a Decade of Ground-Based Measurements

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Abstract

This study presents a decadal climatology of daily UVB doses at a single ground-based station in Riyadh, central Saudi Arabia, based on ten years (2015-2025) of half-hourly ground-based measurements. Temporal variability, sky-condition influences, and atmospheric controls on surface UVB radiation were examined using empirical modelling and clear-sky residual analysis. Results reveal a pronounced seasonal cycle driven primarily by solar geometry, with summer maxima of $\sim 85 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and winter minima of $35 - 38 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. Annual mean daily UVB doses ranged from 43.84 to $68.11 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and were largely attributable to variations in clear-sky frequency ($\sim 85\%$ of days) and aerosol loading. Overcast conditions suppressed daily UVB doses by $\sim 70\%$ relative to clear skies. Simple linear empirical models based solely on global horizontal irradiance (G) and the cosine of the solar zenith angle ($\cos \text{SZA}$) explained $74\% - 75\%$ of day-to-day variability with near-zero bias and outperformed more complex artificial neural network approaches. Residual analysis after removing the dominant effects of G and SZA demonstrated that secondary factors, particularly PM_{10} and total column ozone, continue to exert measurable influence on clear-sky UVB doses. These findings address an important observational gap in the Arabian Peninsula and provide transparent, physically interpretable tools for estimating daily UVB doses in high-insolation, aerosol-variable desert environments. The models have potential applications in public-health policy, solar-energy assessments, and climate-impact studies.

Keywords

Daily UVB Dose, Clear Sky Residual Analysis, Arid Desert Climate, Aerosol Modulation, Empirical Modeling

1. Introduction

Solar ultraviolet B (UVB) radiation (280 - 315 nm) constitutes a small but biologically and ecologically critical portion of the solar spectrum reaching Earth's surface. Unlike broadband global horizontal irradiance (G , ~290 - 3000 nm), UVB is highly sensitive to atmospheric attenuation by total column ozone (O_3), aerosols, clouds, and solar geometry. Biologically, UVB drives cutaneous vitamin D synthesis yet is also the primary cause of erythema, DNA damage, immunosuppression, nonmelanoma skin cancers, and ocular disorders such as cataracts and photokeratitis [1] [2]. Ecologically, it influences phytoplankton productivity, terrestrial plant physiology, and biogeochemical cycles. In high-insolation regions, excessive exposure poses significant public health challenges. Long-term, detailed ground-based UVB measurements are therefore indispensable for exposure risk assessment, satellite validation, epidemiological modeling, and studies of climate-radiative interactions. Beyond human health and ecology, UVB radiation plays important roles in material degradation (e.g., photodegradation of polymers, paints, and photovoltaic module encapsulants), agricultural productivity through effects on plant growth and stress responses, and assessments of solar energy system durability under intense UV exposure. Surface UVB exhibits pronounced temporal and spatial variability. Analyses from well calibrated networks show that interannual variability typically ranges from 2% - 5% of the mean irradiance, while seasonal cycles are dominated by solar zenith angle (SZA) and day length. For instance, Hicke *et al.* (2008) examined 8 - 11 years of broadband UVB data from eight U.S. stations and reported interannual variability of 2% - 5% of the mean with no clear decadal trend [3]. Similar variability patterns have been documented in Europe, where aerosol and cloud effects often dominate observed trends [4]. Clouds are among the most variable and effective attenuators of UVB. A comprehensive review by Calbó *et al.* [5] demonstrated that UV attenuation under clouds is 15% - 45% weaker than for total solar radiation, owing to enhanced scattering at shorter wavelengths and occasional cloud edge reflections that can produce UVB enhancements of up to 20% even under broken cloud conditions. Overcast skies typically reduce UVB to 30% - 70% of clear sky values, with the exact reduction depending on cloud optical thickness, type, and SZA [5]-[7]. These observations support the use of the clearness index ($KT = G/G_0$) for sky condition classification (clear: $KT \geq 0.65$; partly cloudy: $0.35 \leq KT < 0.65$; overcast: $KT < 0.35$) [8]. Aerosols, particularly mineral dust and urban particulates common in arid environments, further modulate UVB through scattering and absorption. In desert regions, high PM_{10} and $PM_{2.5}$ loadings from dust storms can reduce UVB by

10% - 30% under otherwise clear conditions [9]. Radiation amplification factors (RAF) quantify these sensitivities: a 1% increase in aerosol optical depth typically reduces erythral UV by 0.18% - 0.63%, whereas a 1% decrease in column ozone increases it by 0.67% - 1.74% [10]. Recent studies confirm that dust aerosols play a dominant role in shortwave and UVB attenuation across the Middle East and North Africa (MENA), with severe dust events causing reductions exceeding 300 W m^{-2} [11] [12]. Ground-based measurements remain essential despite satellite products (e.g., OMI, TOMS), which frequently overestimate surface UVB by 20% - 30% in dusty or polluted regions due to incomplete aerosol characterization [13]. High-quality, long-term *in situ* records with rigorous quality control are particularly scarce in the MENA region, where intense solar regimes coincide with extreme aerosol loading and rapid urbanization. Within Saudi Arabia, earlier investigations have documented the country's exceptionally high solar resource and corresponding UV exposure. Al-Dhafiri *et al.* [14] reported 5 years (1983-1987) of hourly UV (290 - 380 nm) and global radiation data for Riyadh, documenting monthly mean UV/G ratios of approximately 2.9% with clear seasonal peaks in June-July [14]. AlAruri *et al.* [15] developed early empirical correlations between global and ultraviolet (290 - 385 nm) radiation in Kuwait and nearby Gulf sites. Recently, Maghrabi *et al.* [16] characterized UVA (315 - 400 nm) over 2015-2020 at the same central Riyadh station, noting strong dust storm suppression and establishing G based models under varying sky conditions. Khalil *et al.* [13] assessed UVB across four other Saudi cities (AlBaha, Abha, Jeddah, Taif) for 2003-2017, confirming pronounced seasonal cycles driven by SZA and KT [13]. The public health context in Saudi Arabia further underscores the societal relevance of precise UVB quantification. Despite abundant solar radiation, vitamin D deficiency remains paradoxically prevalent [17], attributed to cultural sun avoidance behaviours, traditional clothing, and indoor lifestyles. Concurrently, rising skin cancer awareness necessitates reliable UVB exposure estimates to guide photo protection guidelines (AlJasser *et al.*, 2020) [18]. Empirical modelling of UVB from more widely measured broadband G has been pursued globally. Exponential or linear relations (e.g., $\text{UVB} = a \cdot \exp(b \cdot G)$) or multivariable forms incorporating SZA) routinely achieve $R > 0.85$ under all sky conditions, with improved skill when stratified by cloud regime [19]. The present study extends this approach by deriving sky specific models and performing residual analyses to isolate secondary ozone and PM_{10} influences after removing dominant geometric and radiative controls. Such models also support broader applications, including evaluation of UV-induced material degradation in solar energy systems and prediction of ecological impacts in arid ecosystems.

Despite earlier work on UV radiation in Saudi Arabia and the wider MENA region [13]-[16], decadal (≥ 10 -year), high-temporal-resolution broadband UVB datasets with documented quality control, recalibration history, and integrated analysis of sky conditions, aerosols, and ozone remain scarce in the central Arabian Peninsula. The present study addresses this gap with a unique 2015-2025 da-

taset collected at a single detailed station in Riyadh, Saudi Arabia. The main novelty lies in the length and quality of the Riyadh-specific record, the systematic combination of sky-condition stratification, simple physically interpretable empirical models, ANN comparison, and deseasonalised residual analysis of PM₁₀ and ozone under clear skies. These elements provide both a local climatology and practical estimation tools that have not previously been developed for this exact setting.

2. Data and Methodology

2.1. Study Site, Period, and Instrumentation

Riyadh (24.7136°N, 46.6753°E, elevation 612 m a.s.l.) is located in the central Arabian Peninsula. This study uses a ten-year dataset spanning 1 January 2015 to 31 December 2025 (inclusive). Years 2016–2024 are complete. The year 2015 is partial (starts mid-year), and 2025 is also partial. Partial years were excluded from annual-mean calculations but retained for monthly and seasonal statistics when at least 80% of days were available. After quality control, 3542 daily UVB doses were available out of 4018 possible days (88.2% completeness). 312 days (7.8%) were missing and filled by linear interpolation of up to four consecutive half-hourly records. 164 days (4.1%) were removed entirely because they failed physical-plausibility checks or contained >50% missing half-hourly values. A valid-day criterion ($\geq 80\%$ of daytime half-hourly records present and passing quality control) was applied; the reported minimum daily dose of $0.004 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ occurred on a single day with very low solar elevation and was retained after verification. Broadband global horizontal irradiance (G) was measured with a Skye SKS 1110 pyranometer with spectral sensitivity 400–1100 nm. Ultraviolet-B irradiance (280–315 nm) was recorded simultaneously with a Skye SKU 430 radiometer. Both instruments were equipped with cosine-corrected diffusers. Manufacturer specifications indicate negligible cosine errors up to 70° and errors below 5% between 70° and 80° [16] [20]. All sensors underwent initial factory calibration according to National Physical Laboratory (UK) standards. In 2017, both instruments were returned to the manufacturer for recalibration. Post-recalibration assessments indicated an approximate 1% decrease in sensitivity, while overall measurement uncertainty remained below 5%. Monthly PM₁₀ data were obtained from a co-located Met One BAM 1020 beta-attenuation monitor operated at the measurement site, while total column ozone (TOC) was taken from the SBUV Version 8.6 Merged Ozone Data Set (McPeters *et al.*, 2013) [21].

2.2. Data Processing, Quality Control, and Derived Parameters

Raw 1-minute data were aggregated to half-hourly values by numerical integration. Daily UVB dose ($\text{kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) was obtained by summing the half-hourly UVB irradiance values ($\text{W}\cdot\text{m}^{-2}$) over all daytime records with solar elevation $>10^\circ$ and multiplying by 3.6 (conversion factor: $1 \text{ W}\cdot\text{m}^{-2} \times 3600 \text{ s} = 3.6 \text{ kJ}\cdot\text{m}^{-2}$ per hour; half-hourly interval = $1.8 \text{ kJ}\cdot\text{m}^{-2}$). Night-time and low-sun-angle periods were ex-

cluded using standard solar-position algorithms. A comprehensive quality-control protocol aligned with BSRN and WMO standards [22]–[24] was applied. Physical plausibility limits were enforced for G (0 - 1400 $\text{W}\cdot\text{m}^{-2}$), UVB (0 - 20 $\text{W}\cdot\text{m}^{-2}$), temperature (-10°C to 60°C), relative humidity (0% - 100%), and pressure (800 - 1100 hPa). Negative irradiance values were set to missing. Gaps up to four consecutive half-hourly records were filled by linear interpolation, after which physical bounds were reapplied. Solar zenith angle (SZA) was computed as the complement of solar elevation angle. Extraterrestrial irradiance on a horizontal surface (G_0) was determined using the Spencer method, and the clearness index was calculated as $KT = G/G_0$ [25]. Sky conditions were classified as clear ($KT \geq 0.65$), partly cloudy ($0.35 \leq KT < 0.65$), and overcast ($KT < 0.35$).

2.3. Methodology

Linear additive empirical models were fitted by ordinary least-squares regression using daily mean global horizontal irradiance (G) and the cosine of the solar zenith angle ($\cos \text{SZA}$) as the sole predictors. Separate models were developed for the all-sky and clear-sky subsets. Model robustness was evaluated using 5-fold cross-validation together with a temporally independent validation set comprising data from 2024–2025. Performance was quantified using the correlation coefficient (R), root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE) [14]–[16].

To examine whether more complex nonlinear techniques could provide superior predictive skill over the parsimonious linear models, feed-forward multilayer perceptron artificial neural networks (ANNs) were also developed and rigorously compared using identical predictors and the same 80/20 training/testing data partitions. The representative all-sky model (ANN_A_6) contained 6 hidden neurons, while the clear-sky model (ANN_B_10) contained 10 hidden neurons. Networks were trained with the Levenberg-Marquardt algorithm and early stopping (maximum 1000 epochs, validation patience of 10) to prevent overfitting.

Deseasonalised anomalies were subsequently computed by subtracting the long-term monthly mean from each variable. Clear-sky residuals were calculated as observed minus predicted daily UVB doses from the linear model. All statistical associations were evaluated using Pearson correlation coefficients and linear regression at a significance level of $\alpha = 0.05$.

3. Temporal Variability and Atmospheric Controls on Daily UVB Doses in Riyadh

3.1. Variation of Daily UVB Dose during the Study Period

Figure 1 illustrates the daily integrated UVB dose after quality control over the full 2015–2025 decade in Riyadh. The record displays a distinct annual oscillation, with systematically elevated doses during late spring and summer months and markedly lower values in autumn and winter. This seasonal framework is accom-

panied by considerable year-to-year differences, reflecting the combined effects of changing solar geometry and variable atmospheric transmission typical of arid, high-insolation environments in the Arabian Peninsula.

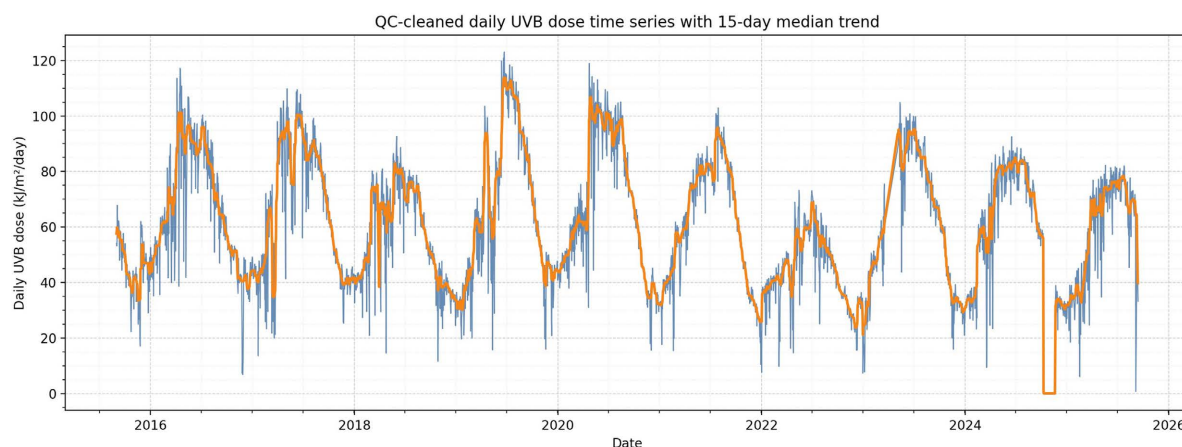


Figure 1. Temporal variation of daily UVB dose during the study period.

Across 3542 valid daily observations, the mean daily UVB dose was $59.93 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ (median $58.22 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, standard deviation $23.30 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$). Variability was substantial, with a coefficient of variation of 38.88%. The distribution exhibited mild positive skewness (0.107). The full range extended from $0.004 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ to a peak of $123.04 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$.

Monthly means increased progressively from $37.66 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in January to maxima of $84.96 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in June and $84.23 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in July, then declined toward minima in November ($34.94 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) and December ($35.82 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$). Annual mean daily UVB doses ranged from $43.84 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in 2022 to $68.11 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in 2020.

3.2. Variations in UVB Doses under Different Classified Sky Conditions

To better understand the drivers of temporal variability, daily UVB doses were stratified according to sky conditions using the clearness index (KT). **Figure 2** shows box plots of QC- daily UVB dose for all-sky, clear, partly cloudy, and overcast categories. A clear gradient emerges, with UVB decreasing progressively from clear to overcast skies, while the all-sky distribution reflects the combined influence of all conditions.

Clear-sky days accounted for 84.9% of the record (3007 days) with a mean of $63.65 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. Partly cloudy days comprised 13.1% (465 days) with a mean of $41.96 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. Overcast conditions represented only 2.0% of days (70 days total) with a mean of $19.24 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, corresponding to approximately 30% of the clear-sky mean. Results for overcast conditions should be interpreted cautiously because of the small sample size (only 70 days overall and a single overcast day in summer).

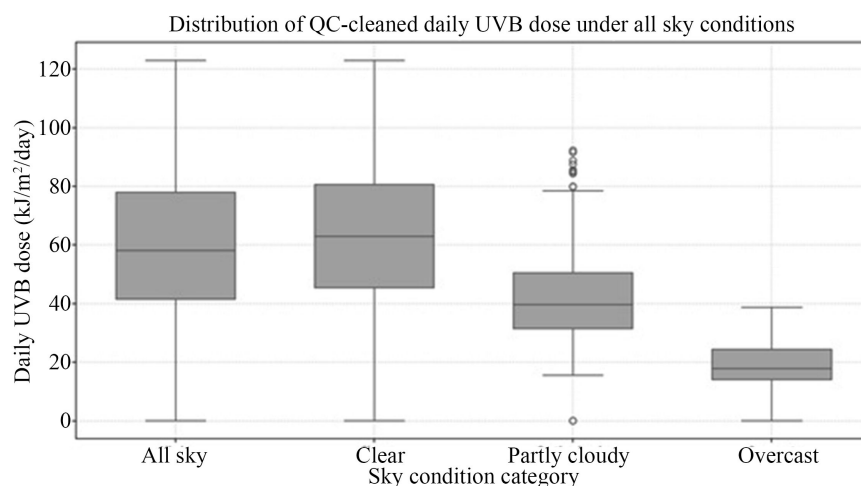


Figure 2. Box plot of the daily UVB dose under all sky, clear, partly cloudy, and overcast conditions.

The statistical dispersion within each category further illustrates this pattern. Absolute standard deviations decreased from clear skies ($22.39 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) to partly cloudy ($14.85 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) and overcast conditions ($8.66 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$). However, the coefficient of variation was highest under overcast skies (45.01%), compared with 38.88% (all-sky), 35.17% (clear), and 35.40% (partly cloudy). This indicates that, although overcast days delivered the lowest absolute doses, they exhibited the greatest relative variability—likely due to large differences in cloud optical thickness and microphysical properties among events.

3.3. Monthly and Seasonal Variations of UVB Doses

Monthly and seasonal stratification of the daily UVB dose provides deeper insight into the interplay between astronomical forcing and atmospheric modulation across sky regimes (Figure 3 and Figure 4).

All categories exhibited a pronounced annual cycle characterised by low values in winter, progressive increases through spring, peak levels in summer, and subsequent declines in autumn. Under all-sky conditions, monthly standard deviations were relatively small during winter but increased substantially in the transitional months of spring and autumn. Seasonal means under clear skies were highest in summer ($83.48 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$), followed by spring ($73.17 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$), autumn ($52.16 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$), and winter ($42.09 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$). Partly cloudy conditions followed the same broad seasonal progression but with consistently lower mean values, while overcast conditions produced the lowest UVB doses throughout the year. Autumn displayed the highest relative variability under both all-sky and clear-sky conditions (coefficients of variation of 38.07% and 35.06%, respectively).

Analysis of monthly extremes showed that many of the highest monthly means occurred in 2016, 2019, and 2020, whereas 2022 accounted for a large proportion of the lowest monthly means. The same pattern was evident at the seasonal scale, with the highest winter and spring means recorded in 2016 and the highest sum-

mer and autumn means in 2019. Substantial year-to-year differences persisted even when the analysis was restricted to clear-sky days.

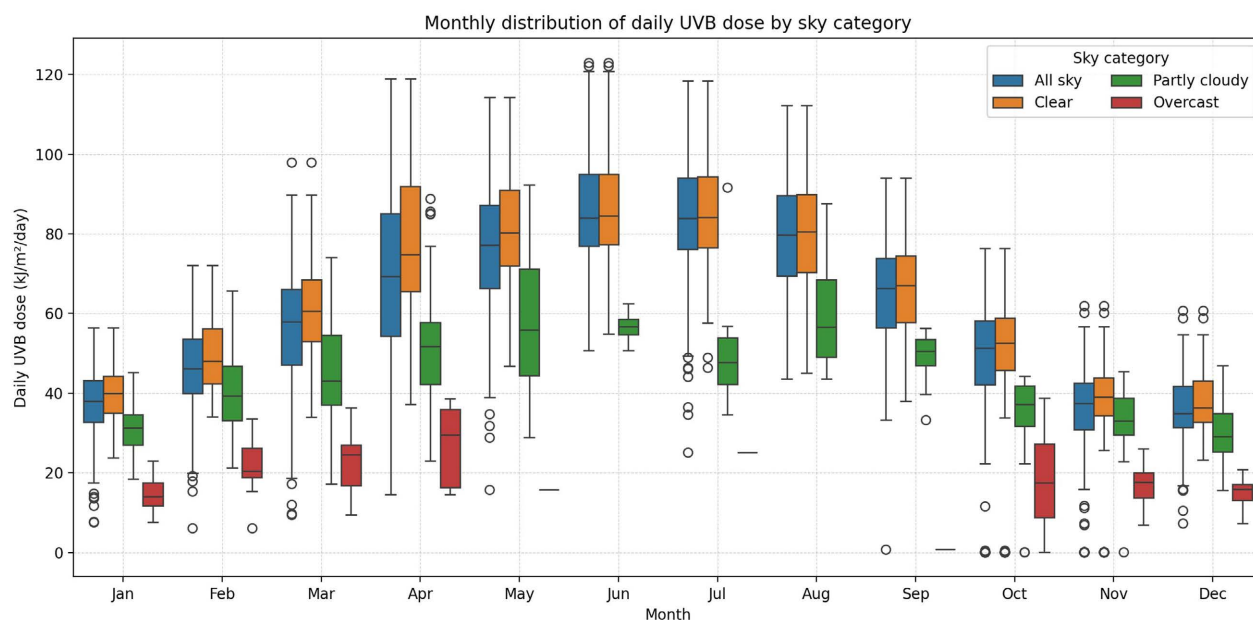


Figure 3. Monthly box plots of the daily UVB dose under all sky, clear, partly cloudy, and overcast conditions.

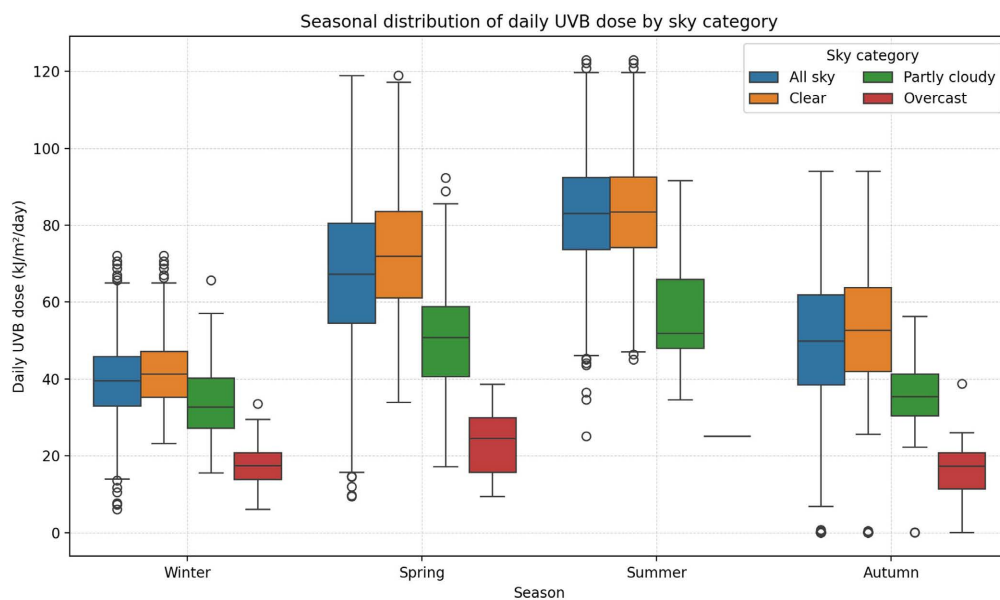


Figure 4. Seasonal box plots of the daily UVB dose under all sky, clear, partly cloudy, and overcast conditions.

Comparable pronounced seasonal cycles with summer maxima and winter minima have been reported in other arid regions. In the United Arab Emirates, Islam *et al.* [26] documented strong annual oscillations in UV radiation, with peak values in summer months driven primarily by solar elevation. Similar patterns were observed in Kuwait, where seasonal UVB variability was largely governed by changes in solar geometry and day length, with secondary modulation by local

atmospheric conditions [15].

3.4. Development of Simple Empirical Models for Daily UVB Dose

Accurate estimation of daily UVB dose from more readily available broadband measurements is essential for gap-filling, historical reconstruction, public-health applications, and solar-energy assessments in regions with limited direct UVB observations. In the present study, simple empirical models were developed to capture the dominant physical controls on surface UVB radiation in the arid desert environment of Riyadh—primarily solar geometry and broadband global horizontal irradiance (G)—while maintaining physical transparency and operational simplicity.

Figure 5 shows relationships between daily UVB dose and key predictors (daily mean G , $\cos(\text{SZA})$, RH, and T) under different sky conditions.

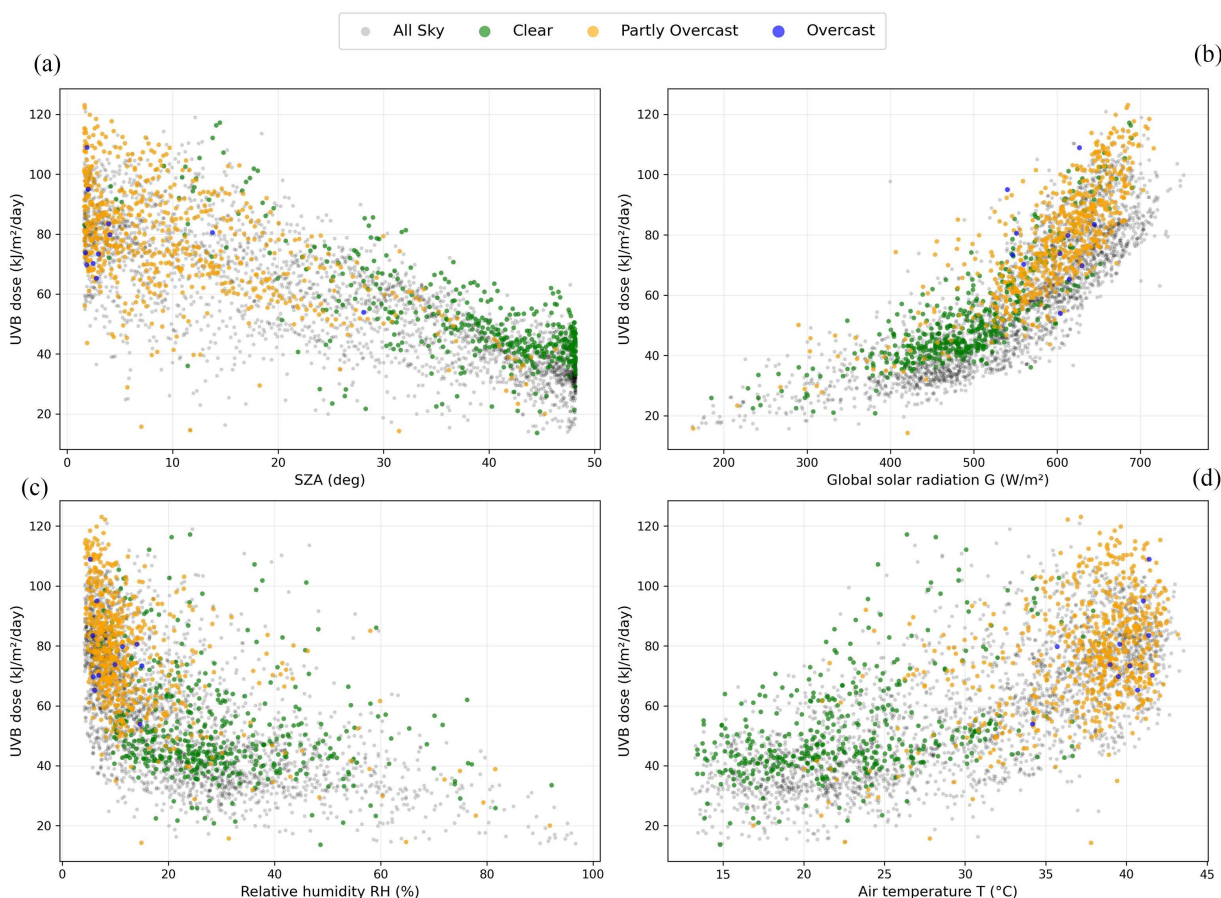


Figure 5. Relationships between daily UVB dose and (a) SZA, (b) G , (c) RH, and (d) T , under all sky, clear, partly cloudy, and overcast conditions during the study period.

Although relationships were examined across all sky regimes, model development focused on all-sky and clear-sky conditions. A linear additive structure was selected for its superior physical transparency, as it explicitly separates the contributions of solar geometry and broadband radiation from overall atmospheric atten-

uation. Separate linear regressions were fitted using only two predictors: daily mean global horizontal irradiance (G) and the cosine of the solar zenith angle ($\cos(\text{SZA})$).

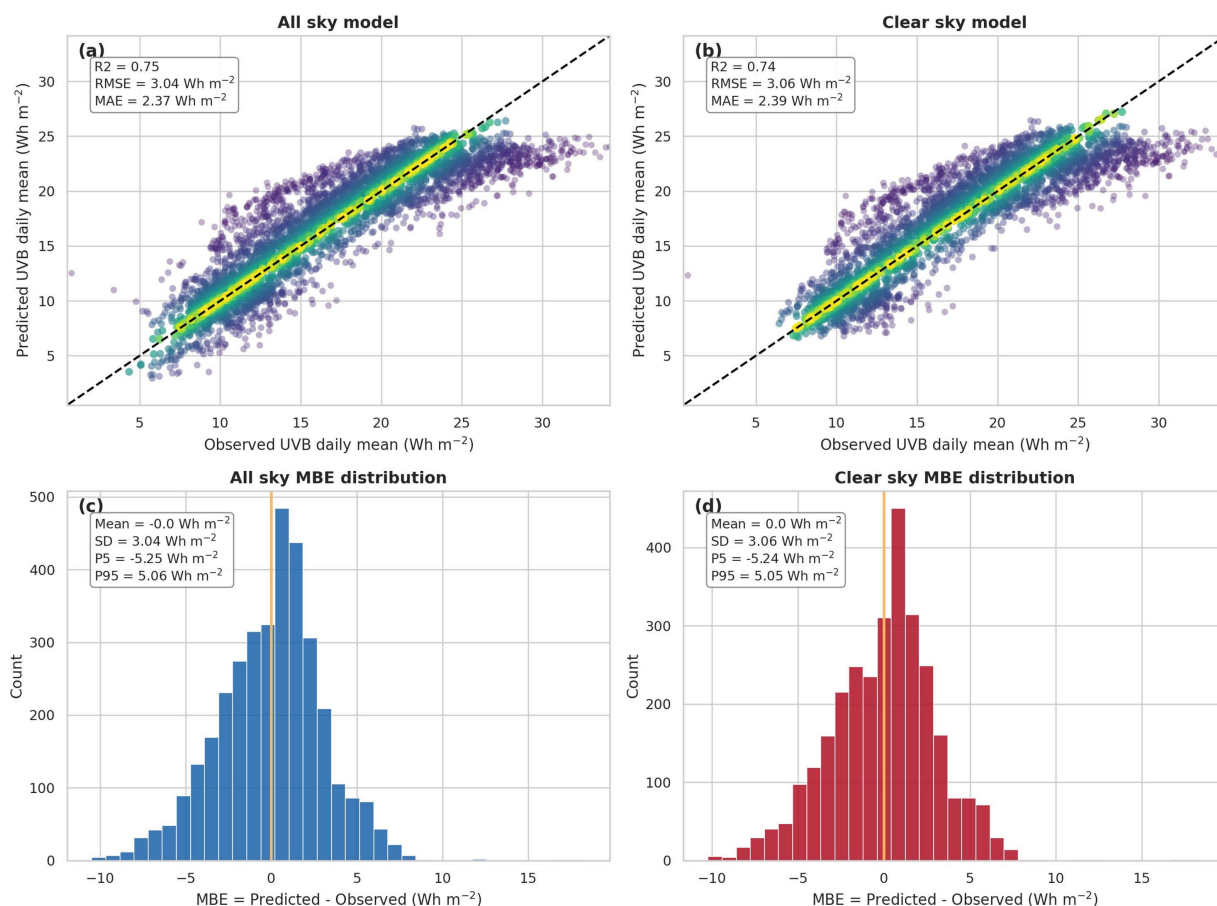


Figure 6. Observed versus predicted daily UVB for the all sky model (a) and clear sky model (b), together with the corresponding MBE histograms in (c) and (d). The dashed lines represent the 1:1 line.

One model was derived from all valid observations (all-sky), and the other was restricted to the clear-sky subset. The resulting equations are:

$$\text{All-sky model: UVB} = -18.99 + 0.0355 \times G - 18.68 \times \cos(\text{SZA})$$

$$\text{Clear-sky model: UVB} = -21.08 + 0.0416 \times G - 17.05 \times \cos(\text{SZA})$$

These coefficients are physically consistent with radiative-transfer principles. The positive coefficients for G reflect the direct association between broadband solar energy reaching the surface and UVB transmission, while the negative coefficients for $\cos(\text{SZA})$ capture the reduction in optical path length and increased UVB transmission as the sun approaches zenith. Attempts were made to add more variables (RH and T) to further improve the performance of the models, but only marginal changes occurred. Although multiplicative (power-law) formulations were also tested and occasionally yielded marginally better statistical performance, the linear additive models were preferred for their superior physical interpretability and ease of application.

Statistical performance was strong and nearly identical for both models. The

all-sky regression yielded $R^2 = 0.75$, $RMSE = 3.04 \text{ Wh}\cdot\text{m}^{-2}$, and $MAE = 2.38 \text{ Wh}\cdot\text{m}^{-2}$. The clear-sky regression produced $R^2 = 0.74$, $RMSE = 3.06 \text{ Wh}\cdot\text{m}^{-2}$, and $MAE = 2.39 \text{ Wh}\cdot\text{m}^{-2}$. **Figure 6** presents observed-versus-predicted daily UVB doses for the all-sky (panel a) and clear-sky (panel b) models, along with the corresponding mean bias error (MBE) histograms (panels c and d). The dashed 1:1 line indicates perfect agreement. Model bias was quantified as $MBE = \text{Predicted UVB} - \text{Observed UVB}$. For both models, the mean MBE was essentially $0.00 \text{ Wh}\cdot\text{m}^{-2}$, indicating that predictions are unbiased on average.

3.5. ANN Methodology and Procedure with Results Included

To determine whether nonlinear machine-learning techniques could outperform the simple linear models, feed-forward multilayer perceptron artificial neural networks (ANNs) were developed and rigorously compared against the linear benchmark using identical train-test data partitions [e.g., 16]. The ANN architectures were trained on the same two predictors as the linear models: daily mean G and $\cos(\text{SZA})$. For the all-sky dataset, 2770 samples were used for training and 693 for testing. For the clear-sky subset, 2382 samples were used for training and 596 for

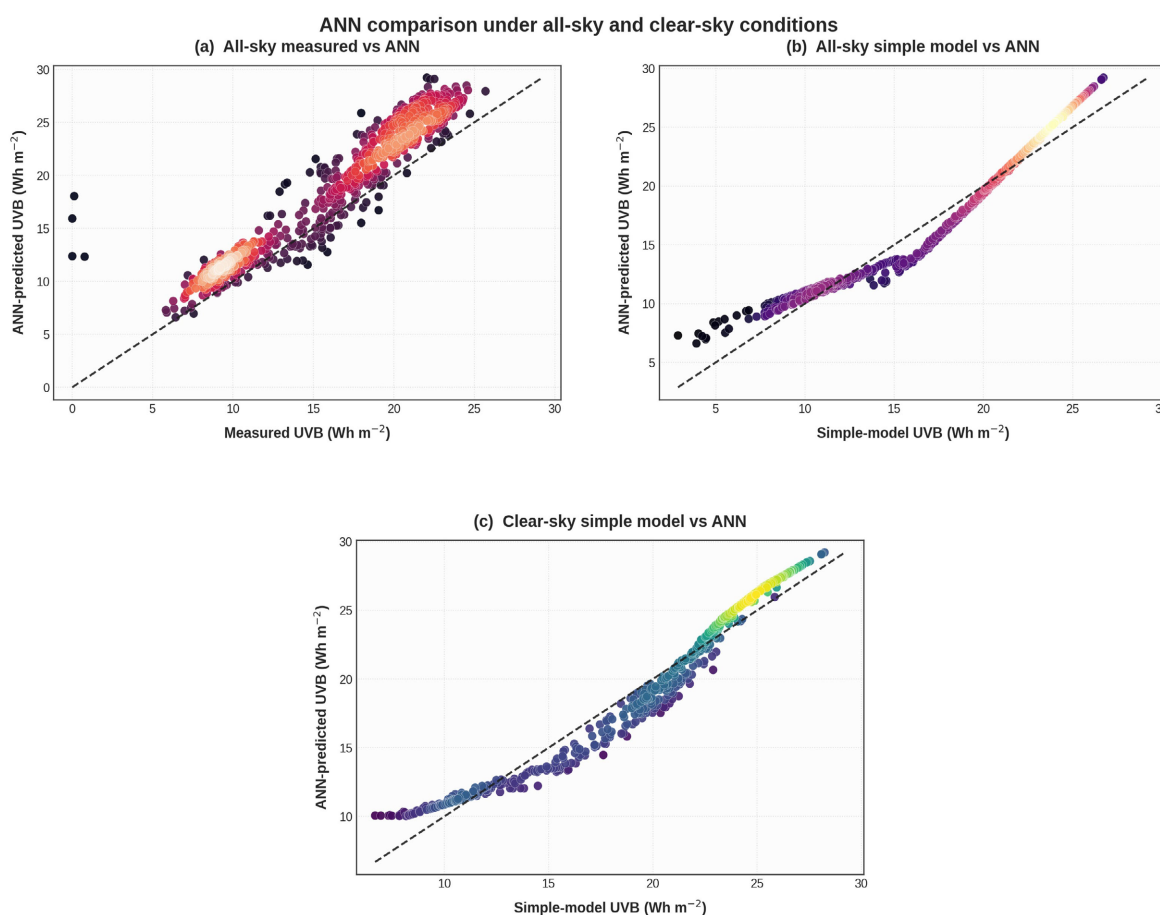


Figure 7. Comparison of observed versus predicted daily UVB dose for the artificial neural network (ANN) and linear models. (a) All-sky ANN predictions versus observations, (b) all-sky linear model predictions versus ANN outputs, and (c) clear-sky linear model predictions versus clear-sky ANN outputs. The dashed line represents the 1:1 line of perfect agreement.

testing. Among the tested configurations, ANN_A_6 was selected as the representative all-sky model and ANN_B_10 as the representative clear-sky model.

Figure 7 presents the comparison. Panel (a) compares all-sky ANN predictions with observations and reveals moderate alignment with the 1:1 line accompanied by substantial dispersion. Panel (b) shows the relationship between all-sky linear predictions and ANN outputs, highlighting overall correspondence but with systematic deviations that do not improve accuracy. Panel (c) displays a similar pattern for the clear-sky case, with noticeable scatter confirming that the ANN reproduces the general trend of the linear model without providing superior predictive skill.

Under all-sky conditions, the linear model clearly outperformed the ANN ($R^2 = 0.64$, $RMSE = 3.21 \text{ Wh}\cdot\text{m}^{-2}$, $MAE = 2.67 \text{ Wh}\cdot\text{m}^{-2}$, and $MBE = 2.52 \text{ Wh}\cdot\text{m}^{-2}$). The ANN reduced the explained variance by 0.07 and increased both RMSE and MAE while showing a stronger positive bias. A similar pattern was observed under clear-sky conditions ($R^2 = 0.548$, $RMSE = 3.458 \text{ Wh}\cdot\text{m}^{-2}$, $MAE = 2.873 \text{ Wh}\cdot\text{m}^{-2}$, and $MBE = 2.782 \text{ Wh}\cdot\text{m}^{-2}$). Even in the more stable radiative environment of clear skies, the ANN failed to surpass the simpler linear formulation and exhibited higher error metrics and bias.

4. Discussion

This study provides the first decadal climatology of daily UVB doses in central Saudi Arabia using ten years of high-quality, half-hourly ground-based measurements in Riyadh. The results reveal a pronounced seasonal cycle driven primarily by solar geometry, substantial interannual variability linked to changes in clear-sky frequency and aerosol loading, strong suppression of UVB under overcast conditions, and robust simple linear empirical models based on global horizontal irradiance (G) and $\cos(\text{SZA})$. Residual analysis under clear skies further demonstrates that secondary atmospheric factors continue to modulate UVB even after the dominant effects of solar geometry and broadband radiation are removed. The seasonal cycle, with summer maxima of $\sim 85 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in June–July and winter minima of $35 - 38 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, is governed predominantly by astronomical factors. Higher solar elevation angles and shorter optical air mass in summer reduce atmospheric path length, thereby decreasing attenuation by ozone, Rayleigh scattering, and aerosols, while longer winter paths enhance attenuation. This astronomical control persists across all sky categories but is expressed most clearly under clear skies, consistent with observations in other arid regions where solar zenith angle and day length constitute the primary drivers [13] [26] [27]. Clouds and aerosols mainly modulate the magnitude of the received dose rather than the underlying seasonal envelope. Interannual variability is pronounced, with annual mean daily UVB doses ranging from $43.84 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in 2022 to $68.11 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ in 2020. High-UVB years were associated with clear-sky fractions exceeding 83% and reduced aerosol loading during peak solar months, whereas low-UVB years showed increased cloudiness and dust activity. Even in years maintaining high clear-sky frequency ($\sim 88\%$ in 2024), doses remained below average, indicating

that non-cloud factors, particularly aerosol burden, play a significant role. This variability exceeds the 2% - 5% typically reported in mid-latitude networks [3] [4] and is amplified in the MENA region by frequent dust events and fluctuations in atmospheric transparency [11] [12]. Sky-condition stratification using the clearness index highlights the strong attenuating effect of clouds. Clear skies dominate the record (~85% of days) and deliver the highest doses (mean $63.65 \text{ kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$), while overcast conditions suppress UVB to approximately 30% of clear-sky values (~70% reduction). This attenuation is weaker than for total solar radiation owing to enhanced scattering at shorter wavelengths and occasional cloud-edge enhancements [5]. The observed gradient is consistent with reports from arid environments in Egypt and the Negev Desert [26] [27] and earlier Saudi studies [13]. The prevalence of clear skies is characteristic of high-insolation desert climates, yet occasional dust storms and cloud episodes drive the observed interannual extremes [9]. The simple linear empirical models using only G and $\cos(\text{SZA})$ explain 74% - 75% of day-to-day variability with near-zero mean bias under both all-sky and clear-sky conditions. Attempts to incorporate additional variables (RH and T) produced only marginal improvements, confirming that G and solar geometry capture the dominant controls. The linear additive structure was preferred over multiplicative formulations for its superior physical interpretability, as it clearly separates geometric and radiative contributions from atmospheric attenuation effects. These models achieve skill comparable to more complex approaches reported elsewhere while offering greater simplicity and transparency, making them particularly suitable for operational use in aerosol-variable arid environments. An important question addressed in this work is how secondary atmospheric factors influence surface UVB under clear-sky conditions once the dominant effects of solar zenith angle and global horizontal irradiance are removed. To investigate this, residuals were calculated as observed minus predicted UVB using the clear-sky linear model. Monthly PM_{10} data were obtained from ground-based beta attenuation monitors (BAM 1020, Met One Instruments) operated at the measurement site, while total column ozone (TOC) values were derived from the SBUV Version 8.6 Merged Ozone Data Sets [21] (e.g., Maghrabi *et al.* [20] for more details). Deseasonalized anomaly analysis was then applied to isolate genuine departures from the climatological seasonal cycle (Figure 8).

The analysis reveals that ozone exhibits the expected negative relationship with UVB residuals, consistent with its strong absorption cross-section below 320 nm. In contrast, PM_{10} anomalies show a positive relationship with UVB residuals. In this arid environment, elevated coarse mineral dust often coincides with drier atmospheric conditions that reduce water-vapor absorption and limit thin-cloud formation, thereby acting as a proxy for enhanced UVB transmission rather than direct attenuation. This positive residual relationship contrasts with the typical negative (anti-correlated) raw relationship reported in the same region, where UVB decreases with increasing PM_{10} due to scattering and absorption [20] [28]. The reversal after removing SZA and G effects highlights the value of anomaly

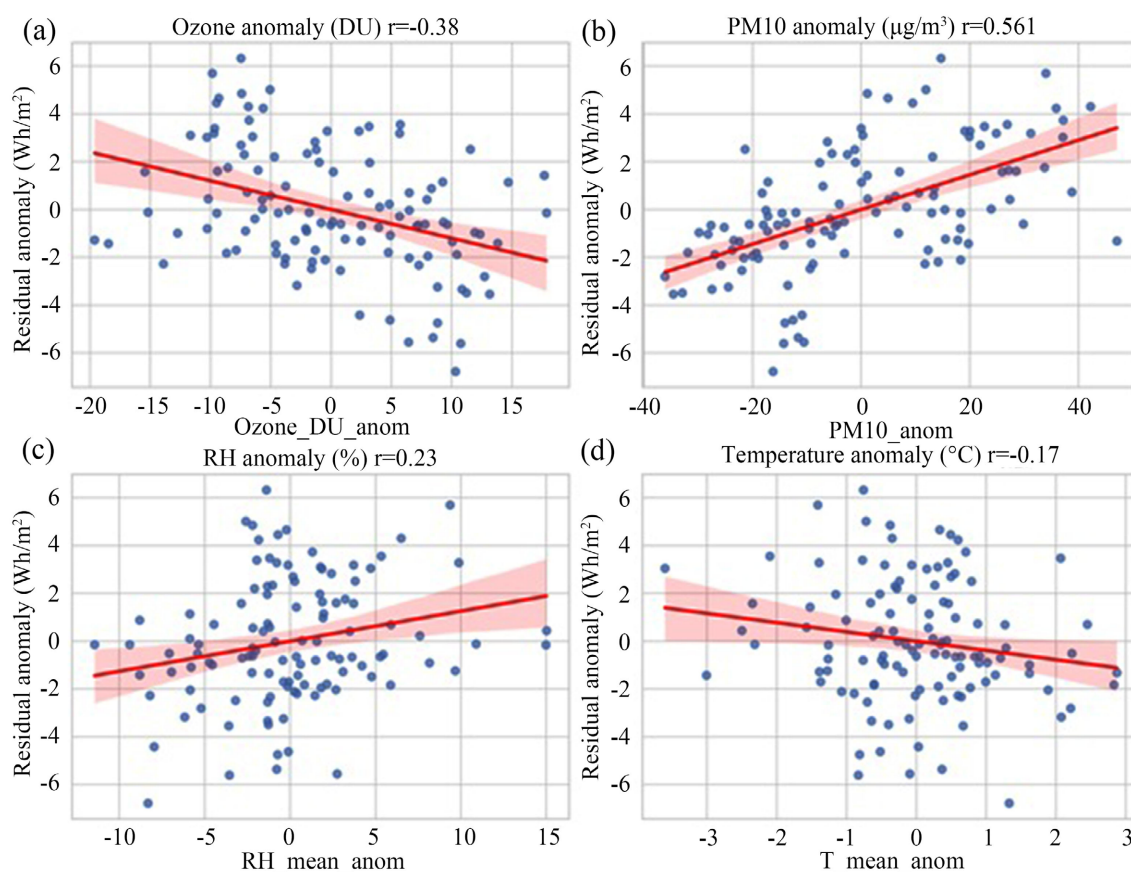


Figure 8. Scatter plots showing the cleaned deseasonalized monthly anomaly relationships between UVB residual anomaly and (a) ozone anomaly, (b) PM₁₀ anomaly, (c) relative humidity (RH) anomaly, and (d) temperature (T) anomaly.

analysis in disentangling proxy effects from direct attenuation. Relative humidity shows a modest positive association with UVB residuals, likely reflecting reduced dust mobilization and lower coarse-particle loading under higher RH conditions. Temperature has limited independent explanatory power once G is accounted for, as its primary influence is already captured through broadband radiation. These findings confirm that, even under predominantly clear skies ($\sim 85\%$ of days), aerosols (represented by PM₁₀), ozone, and to a lesser extent RH remain important modulators of surface UVB. The deseasonalized approach strengthens statistical confidence by removing shared seasonal structure and aligns with residual analyses in other arid and mid-latitude regions [4] [20] [29]. The high summer UVB levels and marked interannual variability have direct public-health relevance for Saudi Arabia, where vitamin D deficiency remains prevalent despite abundant sunshine, largely due to cultural sun-avoidance behaviours and indoor lifestyles (Alshahrani & Aljohani, 2013) [17]. The findings can inform targeted photoprotection guidelines and supplementation strategies, especially during low-UVB years, and support skin-cancer risk mapping (AlJasser *et al.*, 2020) [18]. For solar-energy applications, the strong clear-sky dominance and aerosol modulation are relevant for assessing UV-induced degradation of photovoltaic materials. The developed models provide transparent, practical tools for historical reconstruction

and resource assessments in data-limited arid settings. Limitations of the study include its single-station design and the empirical nature of the models, which do not incorporate real-time aerosol optical depth. Future research should extend the observational record to examine long-term trends, integrate direct AOD and ground-based ozone measurements for refined residual analysis, and develop erythemal or vitamin D-weighted UV indices.

5. Conclusions

The present study provides a decadal climatology of daily UVB doses for central Saudi Arabia based on ten years of half-hourly ground-based measurements at a single station in Riyadh. By integrating quality control following BSRN/WMO standards, clearness-index sky-condition classification, physically transparent empirical modelling, artificial neural network comparison, and clear-sky residual analysis, the work delivers new insights into the dominant and secondary controls on surface UVB radiation in a high-insolation, aerosol-variable desert environment.

The simple linear models based solely on global horizontal irradiance (G) and the cosine of the solar zenith angle ($\cos \text{SZA}$) achieve good predictive skill ($R^2 = 0.74 - 0.75$) with negligible bias and outperform more complex nonlinear ANN approaches. Residual analysis demonstrates that, even under predominantly clear skies, PM_{10} and total column ozone exert measurable influences on UVB variability. These findings help fill an important observational gap in the Arabian Peninsula and provide practical, transparent tools for estimating daily UVB doses in data-limited arid regions. The results have potential relevance for public-health policy, solar-energy yield assessments, and studies of UV-induced material degradation in desert environments.

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Abdullrahman Maghrabi, Latifa Shaber, Abdulah Aldosari, Mohammed Altilasi, and Ghada Khouqeer. The first draft of the manuscript was written by Abdullrahman Maghrabi, and all authors commented on it for its improvement. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Table of Abbreviations

Abbreviation	Full Term
ANN	Artificial Neural Network
BSRN	Baseline Surface Radiation Network
G	Global horizontal irradiance
KT	Cleanness index
MAE	Mean absolute error
MBE	Mean bias error
PM ₁₀	Particulate matter ≤ 10 μm
RMSE	Root mean square error
SZA	Solar zenith angle
TOC	Total column ozone
UVB	Ultraviolet-B radiation
WMO	World Meteorological Organization