

NONLINEAR UV RADIATION GRADIENTS REVEAL MICROCLIMATIC CONTROL IN HIGH-ANDEAN ELEVATIONS

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Abstract

Extreme ultraviolet radiation (UVR) remains an underestimated public-health threat in high-Andean environments, where standard ultraviolet index (UVI) scales fail to capture actual exposure risks. This study presents the first high-frequency, year-round characterization of UVI dynamics and their environmental drivers across the altitudinal gradient of Puno, Peru (3810–4134 m a.s.l.). Between July 2024 and July 2025, 140 572 measurements were recorded using a Pasco e789 sensor. Statistical analyses (one-/two-way ANOVA, Tukey, Pearson correlations, PCA) revealed nonlinear UVI–altitude responses, challenging the classical 8–10% increase per 1000 m. The highest UVI reached 43.12 at 3810 m in December 2024 well above global extreme-risk thresholds. Seasonal maxima (UVI > 30) concentrated between November 2024 and March 2025, while winter minima dropped to UVI 5–6. Temperature showed a positive association with UVI ($r = 0.54$), humidity increased UVI at higher elevations ($r = 0.56$), and wind reduced UVI at lower sites ($r = -0.38$). Overall,

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these findings demonstrate strong microclimatic modulation of UVR and underscore the need to adapt international photoprotection guidelines to the chronic extreme-radiation exposure experienced by Andean populations.

Temperature showed a direct correlation with UVI up to $r = 0.54$.

At 4134 m a.s.l., humidity increased UVI with a correlation of $r = 0.56$.

At 3810 m a.s.l., wind reduced UVI showing a correlation of $r = -0.38$.

Key words: ultraviolet radiation, Andean highlands, altitudinal gradient, public health

Introduction. In high-Andean regions, extreme ultraviolet radiation (UVI) levels are primarily driven by altitude, reduced air density, and partial ozone depletion. In the Atacama Altiplano, for instance, UV-B irradiance is approximately 31% higher and UV-A 16% higher than in coastal areas, with UVI values frequently exceeding 11 [1]. Similarly, in the Peruvian Andes (~3300 m), UVI values have reached 18.8 under clear skies and 15.5 under variable conditions, with exceptional peaks close to 28; even thin clouds can intensify irradiance by around 20% [2]. Such findings highlight the relevance of continuous UV monitoring in mountain ecosystems, where environmental factors amplify biological risks. UVI dynamics are also influenced by temperature, wind speed, and aerosol concentrations. Previous high-altitude UV studies have primarily relied on ground-based radiometers, spectroradiometers, and satellite-derived UV products, highlighting the importance of standardized surface monitoring to accurately characterize extreme irradiance conditions in mountain environments [1, 3], and further modulated by desert dust presence [4]. These interactions directly affect human exposure patterns: moderate temperatures often prolong outdoor activity and increase UV risk, while extreme thermal conditions may limit it [5].

Ocular effects are particularly significant in high-Andean environments, where chronic UV exposure is intensified by altitude. Mountain guides working above 3000 m have shown higher risks of cataract (OR = 1.16) and drusen formation (27% vs. 15.6%), risks that can be substantially mitigated by the consistent use of protective goggles (OR ≈ 0.5) [6], however, discrepancies remain, as it may overestimate ground-level values by up to 15% [7]. Global refinements have reduced estimates of reflected radiation to 101.8 W/m² [8].

Extreme UVI has also been recorded worldwide for instance, values exceeding 11 in Nigeria [9] yet the situation is especially critical in the Andes, where 64.8% of Peruvian children present photodermatoses linked to altitude-related exposure [10]. Laboratory and atmospheric studies further reveal the high variability of UV radiation, with fluctuations up to 50% in irradiance and 1000 Rayleighs at shuttle altitudes [11].

ZHANG et al. [12] identified *Pantoea eucrina* KBFS172, a bacterium capable of reducing UV-induced skin injury. Similarly, GARNACHO-SAUCEDO et al. [13] reported that half of cumulative lifetime UV exposure occurs before the age of 20, and BUENDÍA-EISMAN et al. [14] found that educational interventions improved

sun-safe habits by more than fourfold. In the tropical Andes, SUÁREZ SALAS et al. [15] recorded UVI peaks up to 18.8 in Huancayo (3313 m), and CABROL et al. [16] reported an extreme UVI of ≈ 43.3 at 5916 m in the Bolivian Altiplano. ZARATTI et al. [17] emphasized that such extraordinary values surpass current international risk scales, underscoring the need to adapt them for high-Andean conditions.

Beyond environmental exposure, mitigation efforts have also been explored. MOLINA et al. [18] demonstrated that attached greenhouses in more than 400 Andean homes increased indoor temperatures by 3–5 °C, effectively reducing cold-related health stress. At the same time, TENKATE et al. [19] established a WHO/ILO occupational threshold of $\geq 30 \text{ J/m}^2/\text{day}$ for cataract risk among outdoor workers. Together, these studies reveal the urgent importance of strengthening UV monitoring and prevention strategies in high-altitude regions through an integrated approach that combines architectural design, public health policy, and environmental education.

The study pursued three main objectives: (i) to compare ultraviolet index (UVI) values across five altitudes (3810, 3827, 3908, 3950, and 4134 m a.s.l.) between July 2024 and July 2025; (ii) to evaluate temporal variations in UVI across four standardized time intervals (07:00–09:00, 09:00–11:00, 11:00–13:00, and 13:00–15:00 h); and (iii) to analyze the relationships between UVI and local atmospheric variables (air temperature, relative humidity, and wind speed) in order to determine the relative contribution of microclimatic factors along the altitudinal gradient.

Materials and methods. The study adopted a quantitative, descriptive–comparative, and correlational approach, incorporating multivariate analysis for pattern identification. Measurements were carried out at five altitudes (3810, 3827, 3908, 3950, and 4134 m a.s.l.), corresponding to Puerto Muelle, Plaza de Armas, Cerro Huajsapata, Mirador Villa Paxa, and Ventilla, respectively. Data were recorded across four daily time intervals (07:00–09:00, 09:00–11:00, 11:00–13:00, and 13:00–15:00 h), throughout the period from July 2024 to July 2025. The measured variables included ultraviolet (UV) radiation, air temperature, relative humidity, and wind speed.

Measurement sites were selected in open, unobstructed locations to guarantee direct solar exposure throughout the recording periods. Instruments were installed away from buildings, trees, or topographic obstacles that could generate persistent shading. Temporary shading events were avoided during data acquisition sessions. Site altitude was verified using a portable GPS device prior to each monitoring session.

Ultraviolet radiation and meteorological parameters were recorded using a Pasco e789 wireless meteorological sensor equipped with integrated probes for ultraviolet index (UVI), air temperature (°C), relative humidity (%), and wind speed (m/s). The UV sensor is calibrated to measure erythemally weighted radiation

corresponding to the standard UVI scale. Measurements were programmed at 2–5 second intervals during 20–30-minute recording sessions at each site. Data were acquired through Pasco Capstone software and subsequently exported to spreadsheets for statistical processing. Instrument deployment followed standardized positioning protocols to ensure full-sky exposure and minimize local interference.

Measurements were conducted monthly and continuously for one year, with altitude verified by GPS, yielding a total of 140 572 measurements (35 143 per variable). Although simultaneous real-time measurements at the five altitudes were not logistically feasible, all recordings were conducted within the same pre-defined daily time intervals and under comparable atmospheric conditions. The standardized protocol ensured consistency across sites, allowing reliable comparative analysis of UVI variability along the altitudinal gradient.

For data analysis, one-way and two-way ANOVA were applied to compare UVI across altitudes, months, and time intervals; Tukey's post hoc tests ($p < 0.05$) identified specific differences. Pearson's correlation coefficients quantified relationships between UVI and meteorological variables, while principal component analysis (PCA) reduced data dimensionality and revealed common variation patterns related to altitude, time of day, and seasonality. Records from the Pasco e789 sensor were exported to spreadsheets and processed using INFOSTAT software.

Results and discussion. Comparison of ultraviolet radiation at different altitudes (July 2024 – July 2025). Air temperature exhibited a moderate positive correlation with UVI ($r = 0.31$ – 0.54), consistent with enhanced radiative conditions during warm, low-cloud-cover periods). Relative humidity increased UVI at higher elevations (r up to 0.56), while wind reduced UVI at lower sites (-0.38 to -0.11). These patterns confirm that microclimatic factors modulate UV radiation as strongly as elevation. The PCA indicated that October–December 2024 and February–March 2025 clustered in warm conditions (≈ 20 – 22°C) with maximum irradiance (UVI = 43.12 in December; UVI > 40 in February). June–July 2025 grouped in colder, more humid ($> 60\%$) and windier conditions (up to 3.4 km/h), matching the lowest UVI values (≈ 5 – 6). Overall, the PCA distinguished two regimes: a warm–dry period with extreme UVI and a cold–humid–windy period with reduced irradiance (Fig. 1).

Altitudinal variability in UVI exhibited nonlinear patterns, where the highest values did not occur at the site with the greatest elevation. This trend is also described by CORDERO et al. [1], who demonstrated that extreme irradiance depends not only on altitude but also on local microclimatic conditions. In the present study, Puerto Muelle (3810 m) and Plaza de Armas (3827 m) recorded the highest averages (UVI = 22.10 – 23.33), whereas Ventilla (4134 m) exhibited the lowest mean value (UVI = 20.14), confirming that altitude alone does not determine radiation intensity. This pattern aligns with findings by Suárez Salas et al. [15] who reported that UVI in the Peruvian Andes is strongly modulated by variable cloudiness, aerosols, and surface reflectance. Likewise, intra-altitudinal

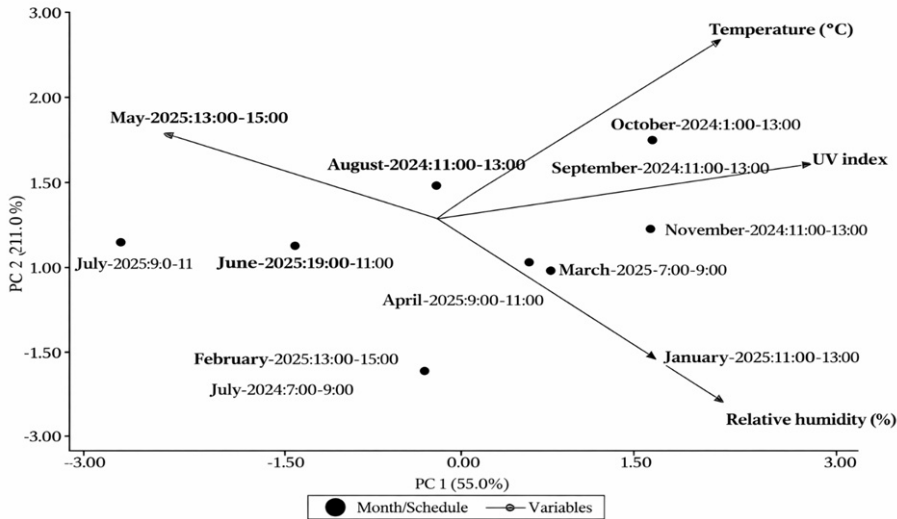


Fig. 1. Principal Component Analysis (PCA) of atmospheric parameters recorded at Puerto Muelle (3810 m a.s.l.), city of Puno, July 2024 – July 2025

differences were consistent with the maximum values reported in the Andean region, where Cabrol et al. [16] documented $UVI > 40$ under clear-sky conditions. Overall, these results demonstrate that altitude influences UVI but is strongly modulated by microclimatic factors that explain the nonlinearity of the gradient observed in Puno.

Evaluated differences in the ultraviolet index across the four-time intervals (07:00–09:00, 09:00–11:00, 11:00–13:00, 13:00–15:00 h). The PCA shows that September, October, and December 2024 (09:00–11:00 h) group with higher temperatures and $UVI > 25–30$. January 2025 aligns with the humidity vector, indicating attenuated irradiance. May–July 2025 aligns with the wind vector (> 3 km/h) and the lowest UVI values ($\approx 5–7$). February 2025 clusters with the UVI vector, confirming intense irradiance. Overall, the PCA differentiates warm, high-radiation months from cold, windy months with reduced UVI (Fig. 2).

The PCA plot shows that the months of September, October, November, and December 2024 (09:00–11:00 h) align with the temperature and UVI vectors, indicating warm conditions and elevated irradiance, consistent with the UVI values $> 25–30$ recorded during this period. In contrast, January 2025 (09:00–11:00 h) is positioned near the relative humidity vector, reflecting greater atmospheric saturation typical of the rainy season. The months of May, June, and July 2025, located close to the wind-speed vector, represent conditions of increased turbulence and lower radiation levels ($UVI \approx 5–7$). March 2025 occupies an intermediate position, with moderate irradiance and a partially humid atmosphere.

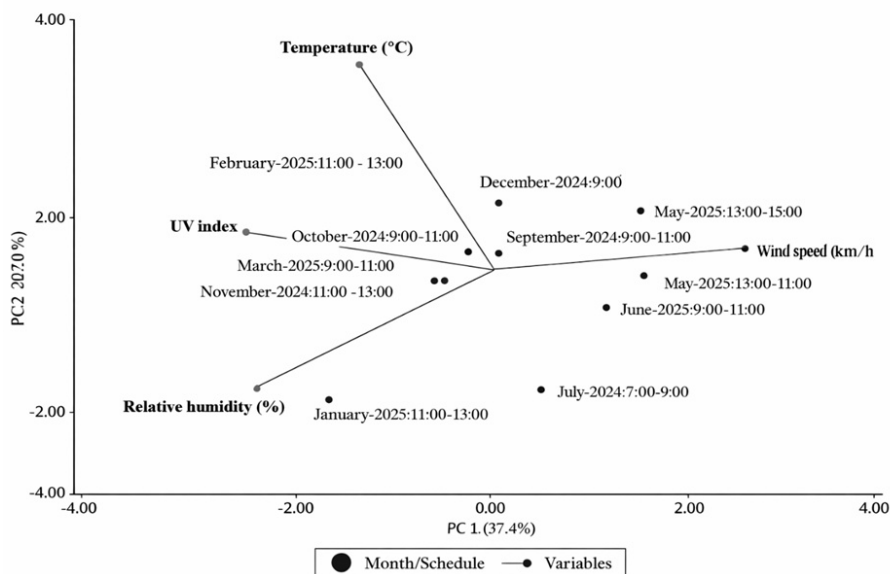


Fig. 2. Principal Component Analysis (PCA) of atmospheric parameters recorded at Plaza de Armas (3827 m a.s.l.), city of Puno, July 2024 – July 2025

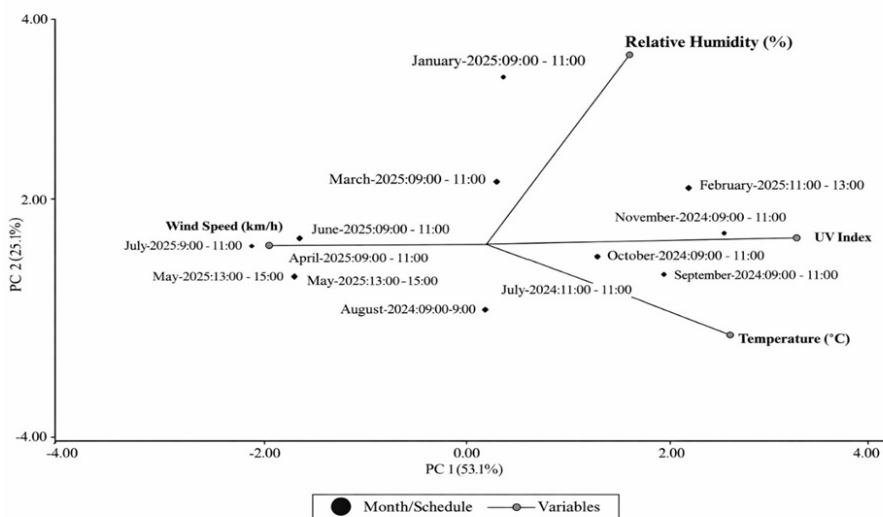


Fig. 3. Principal Component Analysis (PCA) of atmospheric parameters recorded at Huajsapata (3908 m a.s.l.), city of Puno, July 2024 – July 2025

Overall, the PCA clearly distinguishes a warm–dry regime of high irradiance from a humid–windy regime of reduced irradiance (Fig. 3).

Figures 2 and 3 show that the 11:00–13:00 h interval concentrated the highest

irradiance values, consistent with behaviour described for the central Andes, where the daily maximum occurs around midday due to the shorter solar optical path [1]. The months of September–December 2024, aligned with the temperature and UVI vectors across all altitudes, exhibited UVI values > 25 – 30 , consistent with the radiative peaks documented by [2] for clear morning conditions.

In contrast, the 07:00–09:00 h and 13:00–15:00 h intervals showed moderate to low irradiance, particularly during January–March 2025, reflecting the modulation effect of cloudiness described by CALBÓ et al. [20] as one of the main factors attenuating UV transmission. Moreover, February and March mornings exhibited occasional irradiance increases consistent with the “cloud enhancement” phenomenon reported by [15] in high-Andean environments.

Afternoon intervals (13:00–15:00 h), associated with increased turbulence and stronger winds during May–July 2025, displayed the lowest values ($\text{UVI} \approx 5$ – 7). This behaviour agrees with reductions in irradiance documented by MAGHRABI et al. [3], who demonstrated that higher wind speeds disperse aerosols and decrease incident radiation.

Correlation analysis between ultraviolet index and atmospheric variables (air temperature, relative humidity and wind speed). The PCA shows that February 2025 (11:00–13:00 h) projects in the direction of the UVI vector, indicating conditions of elevated irradiance, consistent with the reported UVI values > 30 for that month. The months of September, October, and November 2024 (07:00–09:00/09:00–11:00 h) are associated with the temperature vector, reflecting warm conditions that favour high morning radiation levels. In contrast, January 2025 (07:00–09:00 h) is positioned near the relative humidity vector, indicating greater atmospheric saturation typical of the rainy season. The months of May, June, and July 2025 (11:00–14:00 h) align with the wind-speed vector, indicating increased turbulence and reductions in UV transmission. Overall, the PCA distinguishes a warm–dry regime of high irradiance during spring–summer from a humid–windy regime of moderate irradiance during autumn–winter (Fig. 4).

The five PCA plots collectively confirm the combined influence of temperature, humidity, and wind on UVI variability throughout the year. The alignment of dry-season months (September–December 2024; February–March 2025) with the temperature and UVI vectors supports the positive correlation reported in this study ($r = 0.31$ – 0.54), consistent with the thermal–radiative relationship described by [1]. The recurrent positioning of January and February near the relative humidity vector coincides with the radiative attenuation observed during the rainy season, in agreement with the modulating effect of dense cloud cover described by [20].

Furthermore, the months of May–July, grouped near the wind-speed vector, reflect the reduction in irradiance caused by atmospheric turbulence ($\text{UVI} \approx 5$ – 7), an effect documented by [3] for arid and high-mountain regions. The presence of February–March 2025 in the direction of the UVI vector confirms episodes of

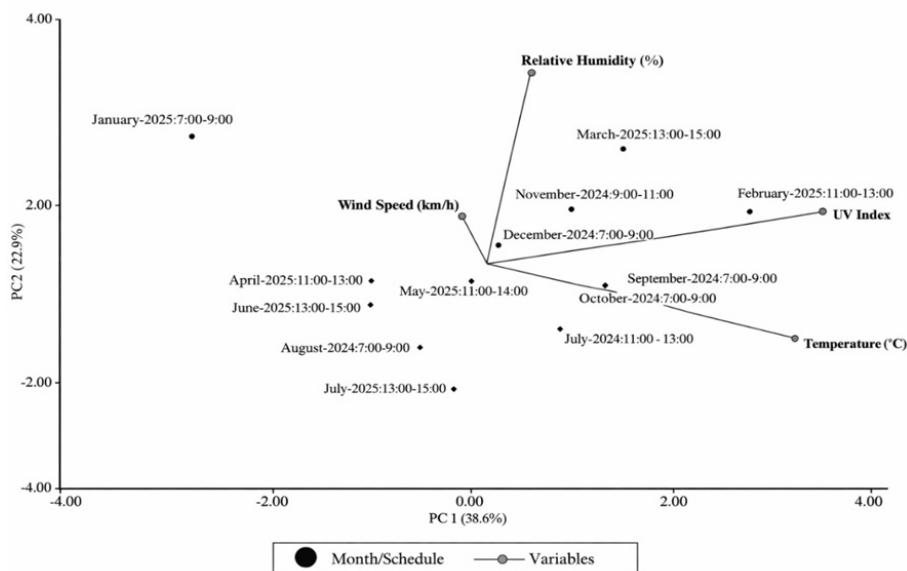


Fig. 4. Principal Component Analysis (PCA) of atmospheric parameters recorded at Ventilla (4134 m a.s.l.), city of Puno, July 2024 – July 2025

intense irradiance even under variable humidity also reported by [15] and [16].

Finally, the distinction between a warm–dry high-irradiance regime and a cold humid windy low irradiance regime is consistent with the atmospheric conceptualization proposed by [17], who emphasized that radiation in the Andes is modulated primarily by microclimatic interactions rather than altitude alone.

Conclusions. a) UVI did not increase with elevation. The highest site (Ventilla, 4134 m) showed the lowest mean (UVI = 20.14), while lower sites at 3810–3827 m recorded higher means (UVI = 22.10–23.33). Altitudinal differences of only 24–324 m produced up to 15% variation in UVI.

b) The 11:00–13:00 h interval showed the highest irradiance, reaching UVI > 30 and peaking at UVI = 43.12 in December 2024. Early morning and late afternoon values dropped to UVI ≈ 5–7, especially in May–July 2025.

c) Temperature showed a positive correlation with UVI ($r = 0.31$ – 0.54), matching peaks of UVI > 25–30. High humidity (> 60%) and strong winds (> 3 km/h) coincided with the lowest values (UVI ≈ 5–7), indicating up to 75% reduction in irradiance under these conditions.

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