Impact of Atmospheric Composition on the Spectral Solar Irradiance and PV efficiency

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The Effect of Atmospheric Variability in Measured Spectral Ultraviolet Radiation in Athens, Greece, During the ASPIRE Campaign

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Abstract. Accurate ultraviolet (UV) radiation monitoring is crucial for health, environmental applications, as well as for optimizing modelling techniques and predictions. However, understanding the interactions between UV radiation and atmospheric components like clouds and aerosols remains complex due to their diverse properties and impacts. Amongst them, ozone, the primary regulator of UV-B irradiance, has shown no significant trends in Athens over 16 years, but the impacts of aerosols and clouds are less established. The present study aims to link the aforementioned aspects under different atmospheric composition cases with solar UV radiation from retrievals gathered during the one-year ASPIRE (Atmospheric parameters affecting SPectral solar IRradiance and solar Energy) campaign in Athens, starting in December 2020. The study integrates ground-based measurements and Radiative Transfer (RT) simulations in order to examine daily datasets and assess the combined effects on UV radiation at ground level, including investigating the enhancement of radiation caused by the presence of clouds, which is explored through a specific case study. The analysis of the case study reveals a higher enhancement in PAR (Photosynthetically Active Radiation) than in UVI (Ultraviolet Index) under broken cloud conditions, while most of the enhancement cases linked to clouds were observed in PAR compared to UV radiation.

1. Introduction

Accurate solar UV radiation monitoring is critical for many human health - related and environmental applications, as well as in optimizing modeling techniques and predictions. Nevertheless, understanding the interactions between UV radiation and some of the key atmospheric components such as clouds and aerosols remains challenging (e.g., Bernhard et al., 2023). For example, while the relationship between total ozone and UV radiation is well established, this is not the case for aerosols and clouds (e.g., Raptis et al., 2018). The diverse nature of these factors (e.g., Logothetis et al., 2020) and their projected changes driven by anthropogenic activities and climate change (e.g., Zerefos et al., 2023), as well as the lack of concurrent observations of both aerosol and cloud properties create the need for further investigation. Dedicated ground-based measurements of the main factors controlling UV radiation levels can provide essential insights and can contribute to reducing the uncertainties and enhance our understanding of the complex interactions affecting UV radiation (Fountoulakis et al., 2020). Subsequently, they can be valuable to estimate future changes in UV radiation under varying atmospheric conditions.

Stratospheric Ozone is amongst the most significant regulators for the levels of the UV-B irradiance that reaches the Earth's surface. Previous studies that exploited ground-based total ozone measurements in the city of Athens did not reveal significant trends over a 16-year period (Eleftheratos et al., 2021), while the decrease of aerosols in recent years (Raptis et al., 2020) and, in turn, the improvement in air quality has resulted in higher UV levels. Furthermore, due to its location, topography and urban structure, Athens is subject to unique meteorological conditions. The combination of local emissions (anthropogenic) and regional dust transport (e.g., Saharan dust) via air masses from Africa (Gerasopoulos et al., 2011) contributes to complex aerosol and cloud behaviour, also in terms of spatial and temporal variability (e.g., Raptis et al., 2020; Amiridis et al., 2024). This makes Athens a particularly interesting area to examine how variability affects radiation and, furthermore, the climate.

In this study, in view of a better understanding of the factors that affect UV, the series of the UV index (UVI) has been reconstructed using ancillary measurements and compared with the measured UVI. Then, we investigate the interactions of aerosols and clouds with solar UV radiation from retrievals gathered during the one-year ASPIRE experimental campaign in Athens, Greece (Eleftheratos et al., 2023).

2. Data and methodology

To investigate the variability in UV with respect to other atmospheric factors we analyzed spectral UV irradiance measured in Athens, Greece, during an intensive campaign, when more ancillary measurements relative to regular operation conditions are available.

Highly accurate monitoring of the spectral solar UV irradiance has been performed in Athens (37.99° N; 23.78° E; ~ 180 m a.s.l.) since 2003. More precisely, spectral UV measurements are performed in Athens, by a MKIV single monochromator Brewer spectroradiometer with serial number 001 (hereinafter Brewer#001) (Eleftheratos et al., 2021) at the Biomedical Research Foundation of the Academy of Athens (BRFAA). Regular calibrations and systematic quality control/quality assurance ensure the high quality of the used spectra (e.g., Masoom et al., 2023). Apart from UV radiation measurements, total ozone and aerosol optical properties measurements were also conducted at the same site for the under-study period.

2.1 The ASPIRE project

The aim of the ASPIRE project was to investigate interdisciplinary factors influencing solar radiation by examining how atmospheric elements, such as clouds, aerosols, water vapor, total ozone, and trace gases, affect the Spectral Solar Irradiance (SSI) reaching Earth's surface.

As part of the project, a comprehensive experimental campaign took place in Athens from December 2020 to November 2021. During this period, various solar radiation instruments, including high-precision spectroradiometers, photometers, and a sky camera (see Figure1), collected continuous measurements at the afore-mentioned sites.

Figure 1. The instrumentation (left) and the Institutes (right) that collaborated in the frame of the ASPIRE project in Athens, Greece (https://aspire.geol.uoa.gr).

2.2 Methodology

To closer investigate the interactions between aerosols, clouds, and solar UV radiation, we employed synergistic measurements gathered during the ASPIRE campaign, alongside Radiative Transfer Modeling (RTM). The RT simulations were then compared with the respective measured irradiances.

Specifically, to assess the aerosol effect, we compared measured irradiances under cloudless sky conditions with corresponding modeled irradiances, which were simulated assuming an aerosol-free atmosphere. Respectively, to estimate the cloud effect, we compared measured irradiances under all-sky conditions with RT simulations performed for realistic atmospheric aerosol concentration values. The different sky conditions were evaluated based on sun obscuration and cloud coverage information derived from the sky camera data. This comparison was conducted for both, aerosol and cloud effects across four wavelength regions: UV305 (302.5–307.5 nm average), UV320 (317.5–322.5 nm average), Erythemal, and Photosynthetically Active Radiation (PAR; wavelength range: 400–700 nm). The afore-mentioned effects (R) were finally calculated on a monthly basis using the following formula:

$$R = \int IR_{meas} - \int IR_{RTM} \qquad (1)$$

Where *IR* stands for the different irradiances (UV305, UV320, Erythemal and PAR) and *meas* refers to the respective measured irradiances:

- For the aerosol effect: measured under cloud-free conditions
- For the cloud effect: measured under all sky conditions

Finally, *RTM* refers to the simulated irradiances:

- For the aerosol effect: simulated for pristine (aerosol-free and cloud-free) sky
- For the cloud effect: simulated for realistic aerosol load in the atmosphere

A more detailed description of the specifications for the RT simulations is provided in Section 2.3.2, as well as in Masoom et al., 2023.

Finally, a comprehensive analysis of radiation enhancement due to the presence of clouds was conducted. More precisely, the focus was given on cases where clouds were located near the sun but did not obscure the solar disk. These clouds have the potential to enhance the UVI at the surface by redirecting a portion of the diffuse irradiance downward. To identify these enhancement cases, the measured irradiances were compared with the modeled irradiances under cloudless sky conditions, in conjunction with the observed cloud coverage.

2.3 Datasets

In order to analyze the UV variability and, furthermore, assess the impact of various factors that affect the irradiance at 305 nm and 320 nm, the Erythemal and PAR we used both satellite and ground-based measurements as well as RT simulations, as described in the following sections (2.3.1.-2.3.2)

2.3.1 Measurements

The ground-based measurements that were employed in the frame of this study are the following:

- Spectral UV measurements from Brewer#001 were used for the study. Brewer#001 measures in the range 290 – 325 nm. To consider wavelengths longer than 325 nm for the calculation of the UVI the methodology described in Fioletov et al., (2003) was used. The effective spectrum by Webb et al., (2011) was used for the UVI calculation. The average UVI that was measured within ± 30 minutes around the local noon (i.e., the minimum solar zenith angle of the day) is considered to be the average UVI. The irradiances at 305 nm and 320 nm were calculated as the average of the corresponding ± 1.5 nm widths.
- Total ozone from the Brewer#001.
- Level 2.0 (cloud screened and quality-assured; Holben et al., 2006) Aerosol Optical Depth (AOD) at 440 nm from AERONET (Holben et al., 1998) that was measured at the Actinometric Station of the National Observatory of Athens (ATHENS_NOA station) (37.97∘ N, 23.72∘ E; 107 m a.s.l.; ∼4 km from Brewer#001).
- Hemispherical images of the sky from a sky camera that were available during the ASPIRE campaign. The Q24M Mobotix All-Sky Imager (ASI) was installed for observing the cloud conditions having a temporal resolution of 10 s. Such type of ASIs can be employed for performing cloud detection and characterization, providing information about Cloud fraction and sun occlusion. The automatic estimation of total cloud coverage and classification is described in more detail in Kazantzidis et al. (2012) and Tzoumanikas et al. (2016).
- PAR was derived by a high-precision solar spectroradiometer (PSR). PSR is a prototype spectroradiometer, developed and calibrated in the World Radiation Center (WRC, Davos, Switzerland), that is able to provide spectrally resolved global horizontal (GHI) irradiance measurements (in W/m2/nm) in the spectral range 300 - 1020 nm (with a step of 0.7 nm) at 1024 channels (Gröbner and Kouremeti, 2019). The reliability of the measured parameters is maintained through regular calibrations (Gröbner and Kouremeti, 2019; Raptis et al., 2023) and thorough, systematic quality control procedures. The PSR operated at ASNOA during the ASPIRE campaign.

2.3.2 RT Model Simulations

To examine the specific influence of each atmospheric parameter, simulations were conducted for four different solar spectral regions (UV305nm, UV320nm, Erythemal, PAR) using the LibRadtran

RT package version 2.0.5 (Emde et al., 2016; Mayer et al., 2005) for the period of the ASPIRE campaign. The simulations employed the numerical solver DISORT (DIScrete Ordinates Radiative Transfer) (Stamnes et al., 1988; Buras et al., 2011) in a pseudospherical approximation within the uvspec radiative transfer model.

To investigate the interactions of aerosols and clouds with solar UV radiation from retrievals gathered during the one-year ASPIRE campaign, the RT simulations were performed for the time of the corresponding measurements, both for an aerosol-free atmosphere and an atmosphere with realistic values of AOD, Ångström Exponent (AE), and Single Scattering Albedo (SSA) (level 2 direct sun (AOD, AE) and inversion (SSA) products from AERONET) (Giles et al., 2019, Dubovik and King, 2000). Additionally, realistic total ozone values from Brewer measurements were used as inputs in the RT simulations. This methodology for the creation and the evaluation of the simulated UV datasets has been described in detail in Masoom et al. (2023).

3. Results

Monthly ratios between simulated and measured clear-sky (unoccluded solar disk) irradiances were calculated (Equation 1) to investigate aerosol effects, while comparisons including all-sky conditions were analyzed to assess the impact of clouds on the different wavelength regions under study. The respective results are presented in Figure 2.

The monthly aerosol effect corresponds closely to the average AOD at 340 nm, with the most significant impact observed in August (month 8), which coincides with the AOD mean monthly peak, highlighting the importance of seasonal variations in understanding aerosol radiative effect. Regarding the different spectral regions, the highest deviations between them are observed for high AOD values (AOD>0.2) (Figure 2.b).

Regarding the investigation of the cloud effect, the deviation between the simulated and measured irradiances is smaller during the summer period (months 7-8). Furthermore, the highest deviations between the different spectral regions are also observed during the same period (Figure 2.a).

Overall, the analysis of the mean monthly ratios indicates that fluctuations are more pronounced in the case of the cloud effect compared to aerosol effect, as well as the deviations between the different spectral regions.

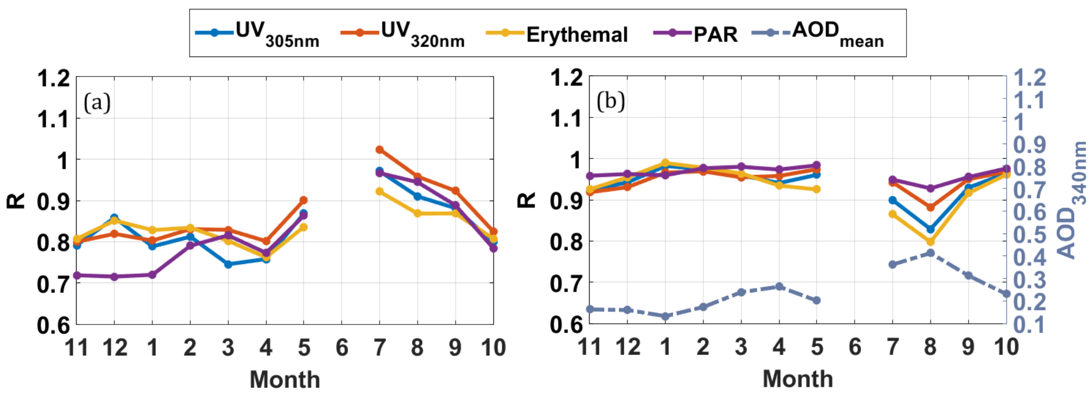

Figure 2. Monthly (a) cloud and (b) aerosol effect. The dashed line on figure 6 (b) denotes the mean monthly AOD at 340 nm. Period of analysis: December 2020 to November 2021.

As a next step, we investigated the impact of aerosols based on the optical depth (Figure 3) under cloudless conditions and over several spectral regions (UV at 305 nm, UV at 320 nm, UVI, and PAR). The agreement between simulated and measured irradiances was overall strong at low AOD (given at 340nm) and denoted an inverse relationship with increasing AOD. Although similar overall trends were observed in the different spectral regions, the results revealed that PAR was the least affected by aerosol load while the greater attenuation of UV radiation can be attributed to the more significant effects of Rayleigh scattering at shorter wavelengths. Since the AE is greater than zero, AOD decreases with increasing wavelength. Thus, irradiance at 305 nm and the UV index (which is more sensitive to 307–308 nm) decrease more rapidly with increasing AOD. For the dominant aerosol types in Athens (e.g., dust, smoke, sea salt, and sulfuric aerosols), the SSA is either relatively invariant with wavelength (in the UV and visible regions) or increases with wavelength. This leads to stronger absorption at shorter wavelengths, enhancing the observed wavelength-dependent sensitivity to aerosol effects.

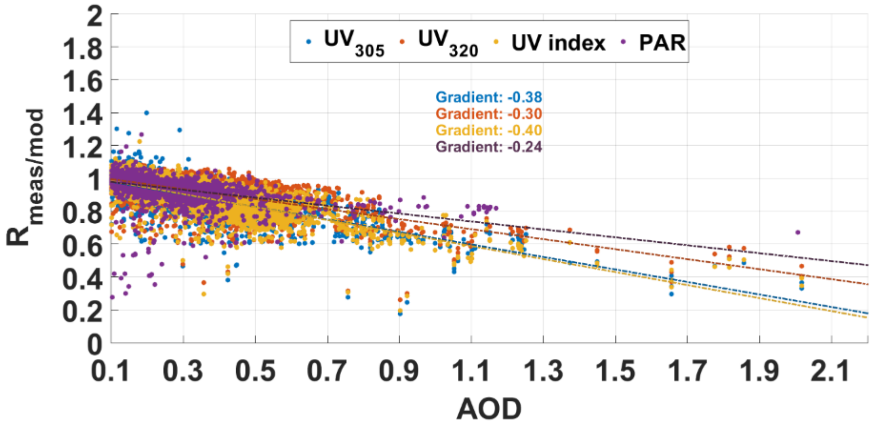

Figure 3. Effect of aerosols on the different spectral ranges of solar irradiance (UV at 305 nm, UV at 320 nm, UVI, and PAR) under cloud-free conditions. Period of analysis: December 2020 to November 2021.

Finally, we examined in more detail the enhancement of radiation due to the presence of clouds. We considered cases where clouds were present around the sun but the sun was not obscured (the solar disk was not covered). Such clouds can enhance the UVI at the surface, by redirecting part of the diffuse irradiance to the surface.

A more detailed investigation into the number of enhancement cases revealed fewer instances where enhancement exceeded 20%, while the number of cases observed in PAR was significantly higher at both higher and lower enhancement levels compared to UVI. Furthermore, the data indicated that more cases of enhancement were recorded during the winter months, attributed to the higher frequency of cloudy conditions.

Figure 4. Clouds near the sun on 18/02/2021.

We investigated a case in which clouds were present close to the sun but the sun remained unobscured (see Figure 4). In such cases, the direct solar radiation reaching the ground undergoes minimal or negligible attenuation due to the lack of obstructing clouds. However, diffuse and, consequently, total irradiance levels are enhanced due to multiple scattering interactions with surrounding cloud droplets. As illustrated in Figure 5 (green line), the measured radiation can exceed the typical values that are expected under clear-sky conditions (blue line), resulting in pronounced peaks. The results revealed an enhancement up to ~40% in the case of PAR, while in the case of UVI, the respective enhancement was approximately 20%. The slight time delay observed between the two measurements can be attributed to the small spatial separation between the two measurement sites (approximately 4 km).

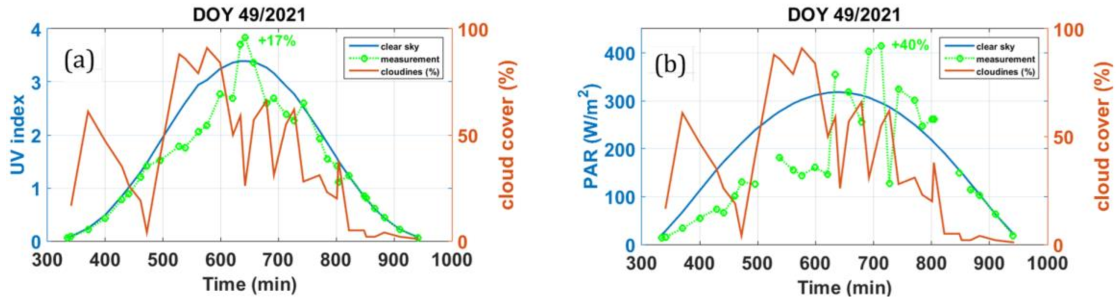

Figure 5. Daily timeseries of cloud coverage (orange line), measured (a) UV index and (b) PAR (green lines) and the corresponding simulated irradiances for clear-sky conditions (blue lines) for 18/02/2021.

4. Conclusions

The results presented in this study mark an initial step toward understanding the complex dynamics between aerosols, clouds and UV radiation, in complicated environments such as that of Athens. Both clouds and aerosols significantly affect the Earth's energy balance, with direct implications for solar energy production and climate modeling. Accurately quantifying and understanding these interactions can significantly contribute to improving our understanding of regional and global climate predictions as well as future applications.

Aerosols exhibit pronounced effects on solar irradiance due to their optical properties, including scattering and absorption, which vary with wavelength. This study revealed that this distinct spectral signature is characterized by stronger attenuation at shorter UV wavelengths, highlighting their spectral dependence. Additionally, the strongest aerosol effect was observed in August, which aligns with the seasonal AOD peak. These findings underline the importance of understanding aerosol radiative forcing, its seasonal and spectral variability, and its implications for ecosystems, climate dynamics, and solar energy applications.

Clouds can occasionally enhance solar irradiance due to scattering and multiple reflections. The case study presented in this work, revealed that broken cloud conditions led to significant radiation enhancements reaching approximately 40% for PAR and 17% for UVI, underlining the cloud distinct spectral modification. The increased and pronounced cloud-related enhancement events that were observed in PAR compared to UV denoted that clouds modulate these spectral regions differently. These findings underscore the complexity of cloud-aerosol-radiation interactions and their dependency on cloud properties. Incorporating cloud type, thickness, and dynamics into future models could yield more precise predictions of their impact on solar irradiance and energy.

To confirm the observed spectral dependence of aerosol attenuation and comprehensively capture seasonal variations, analysis of longer-term datasets is essential. Further analysis incorporating additional key parameters would provide further valuable insights into these complex interactions. Furthermore, investigating a larger number of enhancement events could help estimate their frequency, significance, and energy impact over extended time scales.

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