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Global, diffuse, direct, and ultraviolet solar irradiance recorded in Malta and atmospheric component influences

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Abstract

Global and diffuse shortwave (SW) and global erythemal (UVER) irradiances were measured in Malta, in the middle of Mediterranean Sea. The effect of solar zenith angle on these irradiances is studied using the measurements and simulations developed with a radiative transfer model. The role of ozone, scattering by gases, and aerosols is analyzed. Results show that ozone and Rayleigh scattering are the main drivers responsible for the behavior of UVER variations with SZA. In the case of global and diffuse irradiance, the role of aerosols is the principal determinant.

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Keywords: Ultraviolet solar radiation; diffuse irradiance; total ozone column; aerosol optical depth; Rayleigh scattering.

1. Introduction

Solar irradiance components at surface level are necessary in numerous solar energy applications as well as in engineering practice. Solar irradiance at Earth surface is affected by scattering and absorption by atmospheric components such as ozone column, aerosol particles, clouds, and precipitable water vapor, with location, altitude, and surface albedo also playing a role. All effects depend on the solar zenith angle (SZA).

Solar radiation through the atmosphere reaching the Earth's surface can be categorized as direct radiation and diffuse radiation. Direct radiation is defined as the solar radiation propagating along the line joining the receiving surface and the sun. Diffuse radiation is the solar radiation scattered by dust,

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molecules and aerosols and has no single direction. The sum of direct and diffuse radiation is referred to as global solar radiation.

$$G = D + B\cos(SZA) \tag{1}$$

where G is the global component on a horizontal surface, D diffuse radiation, and B direct solar beam radiation.

Solar radiation at Earth surface can be classified in different ranges of wavelengths. Total shortwave (SW) radiation is the broadband solar radiation between 280 and 2800 nm. Erythemal ultraviolet (UVER) radiation is defined as the solar irradiance between 280 and 400 nm weighted with the erythemal action spectrum, which indicates the effectiveness of solar radiation to produce sunburn on human skin.

Solar radiation can be scattered by gases due to Rayleigh scattering processes. Rayleigh scattering is stronger for lower wavelengths (~λ-4) and affects UVER radiation more than SW radiation, thereby causing a greater proportion of UVER diffuse radiation. Scattering by particles such as aerosols is due to Mie scattering, which has no strong spectral dependence, unlike Rayleigh processes. Ozone is a gas which has a strong absorption band for wavelengths below 320 nm, UVER radiation thus largely depending on total ozone column (TOC).

Global and direct radiation on a horizontal surface have a clear dependence on SZA since direct beam projection onto a horizontal surface depends on the cosine of SZA. However, dependence on other factors, like ozone and aerosols, varies with SZA. Different behavior between UVER and SW with SZA was reported in [1]. The aim of the current work is to find the physical mean of this reported difference.

The importance and interest of this work is that similar measurement series have not previously been recorded, and there are no similar papers that use solar data from Malta.

The work is structured as follows: Section 2 describes the location and measurements used as well as the method employed. The results are explained in section 3, and the main conclusions are summarized in section 4.

2. Location, measurements, and methodology

The University of Valladolid (Spain) and the University of Malta conducted a solar radiation measuring campaign from May to October 2012. Global and diffuse shortwave (SW; 305-2800nm), and global erythemal ultraviolet (UVER; 280-400 nm) solar irradiance were recorded each ten minutes on the roof of the Institute for Sustainable Energy (University of Malta), located in Marsaxlokk, Malta (35º50'N; 14º33'E; 10 m a.s.l), in the Central Mediterranean Sea. Global and diffuse horizontal irradiance were measured by two well calibrated CM-6B pyranometers and direct SW radiation on horizontal surface was calculated as the global minus diffuse. UVER was recorded by a UVB-1 pyranometer (Yankee Environmental Systems, Inc). The UVB-1 was well calibrated after the campaign in the Spanish Institute for Aerospace Technology (INTA) taking into account the daily total ozone column obtained by satellite retrievals. The calibration process is explained in [2]. Photometric measurements by a Microtops sensor were also recorded in order to evaluate total ozone column (TOC), precipitable water vapor, and AOD_{1020} (aerosol optical depth).

In order to remove the effect of clouds, full cloud-free days were selected using a visual criterion, which gave a total of 47 cloud-free days in the campaign. In the present work, we only used data measured on cloud-free days, with an SZA below 85º for global (SW) and UVER, and an SZA below 80º for diffuse SW (SW_{dif}) and direct SW (SW_{dir}) on a horizontal surface. The effect of Sun-Earth distance was neglected, using a normalization of data to 1 A.U. as in [1].

Some UVER and SW irradiance simulations under cloud-free conditions were performed using the UVSPEC/LibRadtran model [3]. Inputs for this model were aerosol optical depth at 500 nm, the

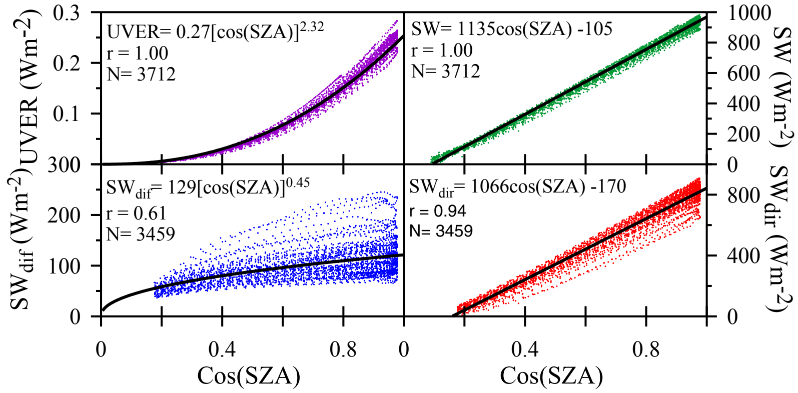

Fig. 1. Global UVER (violet) and SW (green) irradiance and diffuse (blue) and direct (red) SW irradiance measurements on horizontal surface as a function of solar zenith angle cosine. The black line represents the linear or power fit, r is the correlation coefficient, and N is the number of data

Angström exponent, α, total ozone column, and surface albedo, all calculated from measurements and remote sensing satellite information. SW and UVER irradiance were calculated from 5º to 85º in SZA bins of 5º. Bins of 1º and 89º are also included.

3. Results

The normalized SW (global), SW_{dif} (diffuse), SW_{dir} (direct), and UVER horizontal irradiance under cloud-free conditions are represented as a function of the cosine of SZA in Fig. 1. As expected, global UVER and SW (shortwave) show different behavior. UVER fits as a power function and SW fits as a linear behavior, their fits being similar to those obtained by [1]. Direct irradiance on a horizontal surface represented in Fig. 1 shows a linear behavior except for high SZA values. The lowest values for each SZA are due to the presence of a high aerosol load. The linear behavior indicates that the atmosphere transmittance for SW irradiance does not present strong variations with SZA since the direct component follows a cosine law.

However, diffuse irradiance shows a different function with SZA, similar to a power function, the highest values being due to high aerosol load episodes. The diffuse component is much lower than the direct component in SW irradiance, and the diffuse variation with SZA is low. Thus, global SW irradiance has the same linear behavior as direct SW with the SZA cosine.

The power behavior in global UVER might be caused by the diffuse component, which is high in the UV range. However, diffuse UVER measurements are not available, and therefore simulations using a radiative transfer model were employed, as indicated in section 2.

In order to explain the results, simulations of UVER global, diffuse, direct, and solar global, diffuse, and direct irradiances were performed using the previously evaluated input variables, and varying the solar zenith angle.

Fig. 2 shows global, direct, and diffuse UVER and SW simulated irradiance results for the input conditions explained above. It can be seen that global UVER in Fig. 2 has the same power behavior as in Fig. 1

Direct and diffuse UVER irradiance also have this power function shape. Therefore, the sum of the two gives a power shape in the global irradiance. Fig 2 includes the components of SW irradiance, which are similar to those observed in Fig. 1.

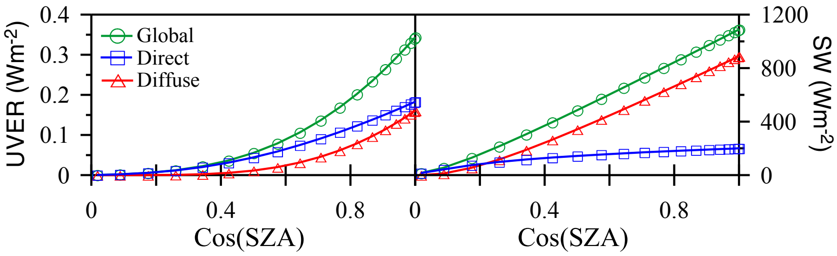

Fig. 2. Simulated global, direct and diffuse UVER (left) and SW (right) irradiance on a horizontal surface as a function of solar zenith angle cosine.

In order to explain the behavior of diffuse and direct (and then global) UVER irradiance, the same simulations as in Fig 2 were re-run, changing certain atmospheric conditions. Fig 3 includes global, diffuse, and direct UVER irradiance under a TOC-free atmosphere (No Ozone), an atmosphere without Rayleigh scattering (No Rayleigh), an atmosphere without either TOC or Rayleigh scattering (No Ozone; No Rayleigh), and under an atmosphere without TOC, Rayleigh, or aerosols (No Ozone; No Rayleigh; No Aerosols).

When ozone is null, direct UVER irradiance displays a power shape, although the diffuse, which is higher than the direct, shows a linear behavior. The sum of diffuse and direct gives a slight power shape to the global UVER due to the direct component.

In the case of "No Rayleigh", both diffuse and direct UVER show a power behavior, which might be due to a variation in the ozone optical depth with the SZA, which gives a strong power shape in the global component.

When neglecting the effect of ozone and Rayleigh, global, direct, and diffuse UVER irradiance are similar to those observed in SW irradiance: direct is linear, and diffuse, which is lower than direct, varies slightly.

Also it can be observed in Fig. 3 (left)that, the variation of diffuse UVER is due to the presence of aerosol, since in the final panel; and in the case of (No Ozone; No Rayleigh; No Aerosol), Fig. 3 (right) the diffuse tends to null values for all possible SZAs.

4. Conclusions

Measurements of solar UVER and SW (global and diffuse) irradiance were recorded in Malta. The data measured under cloud-free conditions were selected and represented against the SZA cosine. A power behavior was found in UVER, and a linear behavior in SW irradiance. The behavior of the variation of direct UVER irradiance with SZA is mainly due to ozone and the effect of Rayleigh scattering. Diffuse UVER variation with SZA is controlled by ozone, giving a power function shape behavior. In the case of diffuse SW irradiance, it varies due to the presence of aerosols.

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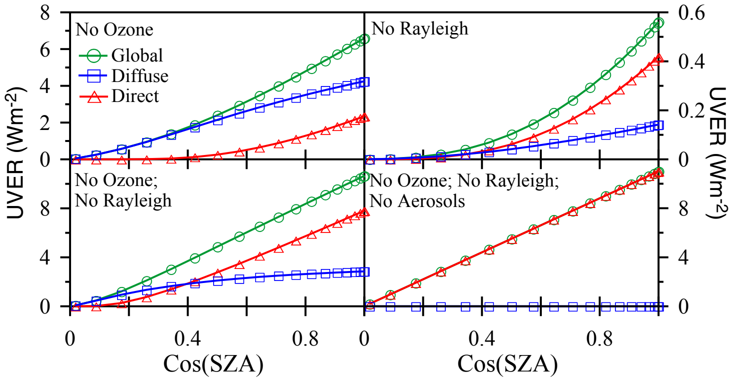

Fig. 3. Simulated global, direct, and diffuse UVER irradiance on a horizontal surface under different atmospheric conditions as a function of solar zenith angle cosine.

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