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ScienceDirect

Solar Energy 121 (2015) 131–138

SOLAR ENERGY

www.elsevier.com/locate/solener

Global, diffuse, beam and ultraviolet solar irradiance recorded in Malta and atmospheric component influences under cloudless skies

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Received 13 January 2015; received in revised form 6 April 2015; accepted 27 April 2015
Available online 27 June 2015

Abstract

Global (G) and diffuse (G_d) shortwave and global erythemal (UVER) horizontal irradiances and atmospheric components like, total ozone column, water vapour column, aerosol optical depth were measured in Malta, at the Institute for Sustainable Energy in the south-eastern village of Marsaxlokk, 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.

Horizontal global and beam (G_b) irradiances show a linear relation with zenith solar angle cosine. The role of ozone, scattering by gases, and aerosols is analysed. Simulation model results show that total ozone column, aerosol optical depth and Rayleigh scattering are the main drivers responsible for the behaviour of UVER variations with solar zenith angle (SZA). In the case of global and diffuse shortwave irradiance, the effect of aerosols is the principal determinant.

Keywords: Erythemal ultraviolet solar irradiance; Shortwave global, beam and diffuse solar irradiance; Total ozone column; Aerosol optical depth

1. Introduction

Shortwave 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 total ozone column, aerosol particles, clouds, and precipitable water vapour, location, altitude, surface albedo and astronomical factors also affect solar irradiance and as consequence all effects depend on the solar zenith angle (SZA) (Bilbao et al., 2014a).

Solar radiation at Earth's surface can be classified in different ranges of wavelengths. Thermal radiation encompasses the wavelength range (0.2–1000 μm) (Iqbal, 1983). The ultraviolet interval (UV) ranges from 0.2 to 0.4 μm; the visible spectrum ranges within (0.39–0.77 μm) and the infrared (IR) portion of thermal radiation is generally divided into two parts: near IR (0.77–25 μm) and far IR (25–1000 μm). Another subdivision of thermal radiation is shortwave and longwave. In solar energy terminology, the major portion of solar radiation is considered to be within the shortwave, the limit put variably from 3 to 4 μm.

Ultraviolet (UV) waveband is the portion of solar radiation with the shortest wavelengths reaching the Earth's

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http://dx.doi.org/10.1016/j.solener.2015.04.048
0038-092X/

atmosphere. UV range is divided into three sub-intervals: UV-C (200–280 nm), UV-B (280–315 nm) and UV-A (315–400 nm), but only UV-B and UV-A reach the surface (Vanicek et al., 2000). UV radiation is involved in different chemical and biological processes and UV radiation affects human health (both short-term deterministic effects, such as erythema or sunburn, and long-term deterministic/stochastic effects such as photoaging/skin cancer), damages aquatic life, affects plants, affects conservation and durability of materials, in addition to impacting global energy balance and climate change (WMO, 2010; WHO, 2002).

The erythemal action spectrum gives the effectiveness of the wavelengths to produce the erythema (McKinlay and Diffey, 1987; Diffey, 1991), and the UV solar radiation (UVB + UVA) weighted by this spectrum is named the ultraviolet erythemal radiation (UVER), (Madronich and Flocke, 1997). Gases and particles due to absorption and scattering processes affect UV radiation transmitted across the Earth's atmosphere. Several authors (McKenzie et al., 1991; De Miguel et al., 2011b; Román et al., 2012) reported a strong relationship between the decrease in UVER levels and the increase of the total ozone column (TOC) due to the strong ozone absorption in the UV-B waveband.

But, not all effects are harmful, the synthesis of vitamin D is one of the beneficial effects of UV (Webb, 2006; Fioletov et al., 2009) and the corresponding action spectrum is used to quantify these effects (Webb et al., 2011).

Solar radiation can be scattered by gases due to Rayleigh scattering processes. Rayleigh scattering is stronger for lower wavelengths ($\sim\lambda^{-4}$) 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) (Mateos et al., 2010; Román et al., 2014c).

One of the most relevant variables that affect shortwave and UV solar radiation is the solar zenith angle. This variable determines the optical path of solar rays from the top of the atmosphere until they reach the Earth's surface. In recent years different researchers have worked in improving and understanding the behaviour of the UV through the atmosphere and the variables that affect it. Authors like Dubrovsky (2000) analysed solar UV in two stations and observed that UV is affected by the solar zenith angle, the path length of the direct solar beams through the Earth's atmosphere, clouds, ozone, aerosols and surface albedo; a statistical model relating clear-sky UV-B irradiance with solar zenith angle, total ozone, and day of the year was proposed; the root–mean square error of the model varied with the zenith angle from 8% to 14%. Koepke et al. (2002) explained and analysed the variability of UV solar radiation due to atmospheric components which effects depend on solar zenith angle, wavelength of the solar radiation and receiver geometry of the system. Some authors proposed a solar mathematical model to represent the UV solar radiation taken into account the solar elevation, optical air mass and cloudiness (through the global shortwave clearness index, which is defined as the ratio of the shortwave global solar radiation to the extraterrestrial one, both values on a horizontal surface) (Foyo-Moreno et al., 1999).

The relationship between UV and global solar radiation and cloudiness was studied by Bilbao et al. (2011c) and authors concluded that solar elevation represented by the optical air mass was the main influence factor and the results were compared with the obtained in several cities. Mateos et al. (2010) showed the different atmospheric components that influence on solar UV radiation; authors developed different models that link hourly UV total radiation (295–385 nm) with solar elevation, UV and shortwave global clearness indices and solar global radiation; two models for clearness skies and 5 models for all sky conditions were proposed and validated. The effects of atmospheric components on solar UVER, global, diffuse and beam irradiances were quantified under cloud-free conditions at different solar zenith angles (Bilbao et al., 2014a) and it was found that the aerosol effect on UVER is stronger than on global horizontal solar irradiance.

For instance, the effect of ozone on diffuse solar radiation has been reported recently for 54 models by Badescu et al. (2013a), various different inputs are used and the study provides detailed quantitative results for the accuracy of each model. Also, the effect of ozone on global solar radiation has been reported for the same models in Romania by Badescu et al. (2013b) and the influence of uncertainty is shown.

Sensitivity of global and beam irradiance to aerosol has been studied by Gueymard (2012), therefore different sensitivity index were defined and the results show that solar beam normal irradiance, DNI, is more sensitive to aerosols than global solar irradiance.

In the Mediterranean Sea, Meloni et al. (2003) studied the influence of aerosols in UV at Lampedusa, Italy. Di Sarra et al. (2002) studied the combined effects of ozone and aerosol in a region characterised by large aerosol variability that is mostly due to strong influence of dust transport events originating from the Sahara; authors observed that aerosol and ozone were negatively correlated, the attenuation of the UV per unit aerosol optical depth depended on solar zenith angle and ranged between 30 and 54% and ozone effects depended on wavelength.

It can be deduced that aerosols have a big impact on UV solar radiation by scattering and absorption but it is known that few measurements and evaluations have been carried out in the place. Due to the effect of atmospheric compounds have on solar irradiance and to evaluate solar UVER irradiance levels, a measurement campaign was developed at Marsaxlokk, Malta. In addition, the geographical position of the measurement station, in the centre Mediterranean Sea, is affected by dust mineral aerosols