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Comparative analysis of cloud effects on ultraviolet-B and broadband solar radiation: Dependence on cloud amount and solar zenith angle

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ABSTRACT

The role played by clouds in atmospheric radiative transfer is fundamental. However, studies of their influences on solar radiation at Qena, Egypt, are lacking. This paper discusses the effect of clouds on the ratio of ultraviolet-B (UVB, 295–2800 nm) to broadband solar radiation (G, 280–320 nm) under all cloud conditions. To achieve this aim, the dependence of cloud modification factors for both UVB and G (CMF_{UVB} and CMF_G respectively) on cloud amount (CA) was compared for each category. From 2000 to 2009, the dataset used included hourly values for both UVB and G under all cloud conditions. The results indicated that the average UVB/G ratio for all cloud conditions was 0.25 ± 0.10%. This average represents 76% of the corresponding value under cloudless sky conditions (0.33 ± 0.11%). Accordingly, it indicates that clouds do not transmit UVB and G equally. However, on average, the percentage decrease in CMF_{UVB} from its corresponding value of CMF_G was 20 ± 5%. Further analysis for the hourly values of both CMF_{UVB} and CMF_G was employed. These hourly values are distinguished by three different behaviors: $CMF_{UVB} \cong CMF_G$ (9% of all cases), $CMF_{UVB} > CMF_G$ (11% of all cases), or $CMF_{UVB} < CMF_G$ (80% of all cases). The average UVB/G values for each group were 0.27 ± 0.09%, 0.33 ± 0.12%, and 0.23 ± 0.09% respectively. Based on the results of earlier studies, an attempt was made to explain these outcomes. In a more thorough study of CMF_{UVB} and CMF_G, the dependence of these variables on SZA was investigated. This analysis has shown that both CMF_{UVB} and CMF_G decrease as the SZA increases. For each group, the sensitivities of CMF_{UVB} to SZA were −0.27 ± 0.03, −0.32 ± 0.06, and −0.18 ± 0.03 (respectively); moreover, the sensitivities of CMF_G to SZA were −0.27 ± 0.03, −0.65 ± 0.05, and −0.18 ± 0.02 (respectively).

1. Introduction

Numerous literatures provided a detailed description of the electromagnetic energy emitted by the Sun and reviewed the factors controlling the intensity of this energy (e.g. Iqbal, 1983). In addition, the beneficial and damaging effects of ultraviolet-B (UVB) on humans, ecosystems, animals, plants, and materials were mentioned (e.g. McKinlay and Diffey, 1987; UNEP, 1989; Kripke, 1992; Webb, 1998; Juzeniene et al., 2011). Adam (2014) studied the role of the atmosphere as a filter, absorbing and scattering portions of the solar spectrum and shielding the biosphere from damaging doses of UVB. In this research, the variability of the ratio of UVB (280–320 nm) to broadband solar radiation (G, 295–2800 nm) at the Earth's surface (UVB/G) under all sky conditions was evaluated at Qena, Egypt. The results showed that UVB/G varied from 0.03% to 0.73%, with an average value of 0.27%. This average represents only 17% of the corresponding value outside the atmosphere (1.56% (Adam, 2011b)). This means that atmospheric attenuation notably reduces this ratio at the Earth's surface compared to its value at the top of the atmosphere. On the other hand, the influences of solar zenith angle (SZA), ozone, aerosols, and water vapor on this ratio were assessed. UVB/G was found to decrease with increasing SZA. Investigation of the relationship between UVB/G and ozone showed that this ratio decreased with increasing ozone. For a restricted change in ozone and almost constant turbidity level, UVB/G became higher with increasing water vapor. This is due to the impact of water vapor on G (Adam, 2014). Although clouds play an important role in atmospheric radiative transfer (Tsay and Stamnes, 1992; Bais et al., 1993), studies of their influences on the UVB/G ratio at Qena are lacking (Adam, 1995, 2011a; El Shazly et al., 1997; El-Noubi, 2006; Adam and El Shazly, 2007). Therefore, the present study has attempted to investigate the effect of clouds on the UVB/G ratio. Understanding the influence of clouds on UVB/G is a constructive contribution to science, for which the effects of clouds on both UVB and G must be illustrated and compared.

Clouds reflect, absorb, and transmit incoming solar radiation, modifying in this way the amount and spectral quality of solar radiation reaching the Earth's surface. Cloud particles are responsible for the scattering and absorption of solar radiation. However, the influence of clouds on radiation depends on both the macrophysical cloud features and the microphysical structure of water droplets and ice crystals. The spatial distribution (level of cloudiness) and vertical extension

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(top–bottom distance) of clouds are basic macrophysical parameters. Cloud microphysical parameters (number of droplets or crystals per volume and droplet size distribution) determine the volume extinction coefficient. Integration of this coefficient over the cloud thickness results in the cloud optical depth, which provides a type of linkage between macro- and microphysical cloud characteristics (Krzyscin et al., 2003). Calbó et al. (2005) noted that clouds dominate any other atmospheric variable as a source of solar radiation variability and that their variability usually masks the effects of other variables. Clouds may affect the absorption of solar radiation by other atmospheric constituents. For example, clouds are the major factor limiting the detectability of ozone-induced trends in UV radiation (den Outer et al., 2005; Glandorf et al., 2005). Accordingly, clouds enhance the diffusion component of any solar radiative flux, while providing an effective reduction of the direct component if the cloud is in front of the Sun. The sum of both components, called the global component, undergoes a subsequent change in its partitioning into direct and diffuse components and generally an overall reduction over time (Foyo-Moreno et al., 2000). Moreover, UVB is strongly affected by the presence of clouds. The effect of clouds on UVB levels can vary from small enhancements to almost total reduction depending on cloud cover geometry and the relative position of the Sun (Bodeker and McKenzie, 1996; Piedehierro et al., 2014).

In this work, fluctuations in global UVB and G radiant fluxes for all cloud conditions have been described. In addition, the dependence of both hourly UVB and G on cloud amount was illustrated (Section 3.1) by examination of the collected data. Before discussing the effect of clouds on the UVB/G ratio, the dependence of both global UVB and G radiant fluxes on cloud amount was compared (Section 3.2). Furthermore, the dependence of this effect on SZA was discussed (Section 3.3). Finally, the net effect of clouds on both UVB and G was clarified by comparing the UVB/G ratios under cloudless and completely cloudy conditions.

The main objective of this work was to compare the effect of cloud amount on UVB and G and to discuss the effect of clouds on the UVB/G ratio at Qena. In addition, the dependence of cloud influences on UVB and G on SZA was illustrated.

2. Data and methods

2.1. Measurements

In this study, hourly values of UVB, G, and cloud amount (CA) at Qena, Egypt (26.2°N, 32.75°E, 96 m above mean sea level) from 2000 to 2009 were used. In previous work by the authors (Adam, 2014), these measurements were used to assess the diurnal variability of the UVB/G ratio under all sky conditions. In addition, the dataset was analyzed under cloudless sky conditions to quantify the effects of SZA, ozone, water vapor, and aerosols on the UVB/G ratio, and datasets under different cloud conditions were separated out. The present study used these separated datasets to investigate the effect of clouds on the UVB/G ratio under all cloud conditions.

Adam (2014; 2015) provided descriptions of the study site, the instrumentation, and the measurements. In this earlier study, measurements were collected at the South Valley University Metrological Research Station (SVU-MRS), located at Qena within the subtropical region (Robaa, 2008). The Egyptian Meteorological Authority (EMA) established SVU-MRS in cooperation with South Valley University. Scientific advice and instrument calibrations for SVU-MRS are provided by the EMA. However, the instruments are also calibrated yearly against the World Radiometric Reference (WRR) maintained at Davos, Switzerland (WRC, 1985, 1995). A Model UVB-1 ultraviolet pyranometer (No. 960842, Yankee Environmental Systems Inc.) was used to measure the total irradiance from 280 to 320 nm. The sensitivity of this instrument is 1.97 μV/Wm^{-2} over the total UVB irradiance, and its response time is approximately 0.1 s. It works over an ambient temperature range of −40 °C to +40 °C. The cosine response of this instrument is ±5% for 0°–60° SZA. The departure from the ideal cosine response exceeds 10% beyond 60° SZAs (Bigelow et al., 1998). In addition, the Precision Spectral Pyranometer (PSP No. 16317IS, Eppley Laboratory Inc.) was used to measure total irradiance from 295 to 2800 nm. The sensitivity of the sensor is 9 μV/Wm^{-2} of total irradiance, and its response time is 1 s. The temperature dependence of the PSP is approximately ±1% over the ambient temperature range of −20 °C to +40 °C. The cosine response of the instrument is ±1% from normalization 0°–70° SZA and ±3% 70°–80° SZA. The COMBILOG Datalogger (No. 1020, TH., and Friedrichs & Co.) was used to record hourly integral irradiance (irradiation integrated in one hour) values of UVB and G. Additional details of the instrument specifications and data-gathering procedures at SVU-MRS are available in previous studies such as those of El-Noubi (2006), Ahmed (2008), Adam (2012), El-Noubi (2012), Ahmed and Adam (2013), and Adam (2013; 2014).

In addition, the cloud amount (in octas) was used in this work to describe the state of cloudiness of the atmosphere. It is visually observed at the end of each hour in the study station. According to these visually observed (in octas), the datasets of hourly UVB and G under different cloud conditions (5684 cases) were classified to examine the collected data (Section 3.1).

2.2. Definitions

2.2.1. UVB and G under cloudless sky conditions

Hourly values of UVB and G under cloudless sky conditions (UVB_0 and G_0 respectively) were estimated. The empirical approach developed by Adam and El Shazly (2007) was used to estimate UVB values under cloudless sky conditions for each hour throughout the study period. The following equation was used to estimate UVB_0 (with coefficient of determination $R^2 = 0.99$ and standard error of the estimate SEE = 0.08):

$$UVB_0 = (0.017 \pm 0.001)m^{-1.9\pm01} \quad (1)$$

where the relative optical air mass (m) is given as a function of Z (the solar zenith angle in degrees) as expressed in the following equation (Kasten, 1966):

$$\mathrm{m} = \frac{1}{\cos Z + 0.15(93.885 - Z)^{-1.253}} \quad (2)$$

In addition, the method of Foyo-Moreno et al. (1999) was used to generate clear-sky estimates of G for each hour (G_0). The empirical approach developed by Adam (2011a), was used to estimate G values under cloudless sky conditions for each hour throughout the study period. The following equation was established (with coefficient of determination $R^2 = 0.96$ and standard error of the estimate SEE = 0.07):

$$G_0 = (4.002 \pm 0.049)m^{-0.79\pm0.01} \quad (3)$$

2.2.2. Cloud modification factors for UVB and G

Cloud modification factors for UVB and G (CMF_{UVB} and CMF_G respectively) were determined in this study. Adam (2011a) and Adam and El Shazly (2007) stated that cloud effects on UVB and G could be described using the cloud modification factor (the ratio of the irradiation occurring in the presence of clouds to the irradiation that would occur under the same atmospheric and surface conditions in the absence of clouds). This is a simple and operational approach, and several earlier studies used similar methods to analyze cloud effects on G, UV, and UVB. For example, effects on G were studied by (Kasten and Czeplak, 1980; Blumthaler et al., 1994; Davies, 1995; Josefsson and Landelius, 2000; Adam, 2011a), effects on UV and the photosynthetically active spectral range were studied by (Alados et al., 2000; Foyo-Moreno et al., 2001, 2003), and effects on UVB were studied by (El-Noubi, 2006; Adam and El Shazly, 2007). The relation between solar global