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Analysis of ultraviolet radiation in Central China from observation and estimation

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ABSTRACT

Measurements of UV (ultraviolet) and global solar radiation in Central China during 2006–2012 were first reported to investigate the UV radiation variability in different time scales and its UV fraction under different sky conditions. Both UV irradiation and UV fraction showed similar features that peaked in values at noon during summer (July) and reached their lowest in winter (January) with annual mean values being about 0.49 MJ m^{-2} d^{-1} and 4.35%, respectively. It was also discovered that there were inverse relationships between UV fractions and clearness indexes at all sky conditions; clouds, water vapor and seasonality were main factors causing the daily variations of UV irradiations. The maximum UV irradiances decreased by 51.14% (33.49%) in overcast days when compared to clear days in summer (winter). By analyzing the dependence of UV irradiances on cosine of solar zenith angle and clearness index, an efficient all-sky model has been developed for estimating UV values in Central China, which has also been tested at Sanjiang and Lhasa and produced satisfied estimations. UV dataset from 1961 to 2011 in Central China was then reconstructed and annual mean daily UV irradiation was about 0.488 MJ m^{-2} d^{-1}. There was a significant decreasing trend (−0.018 MJ m^{-2} d^{-1} per decade) during the last 50 years, the decreases were sharpest in summer (−0.027 MJ m^{-2} d^{-1} per decade) with smallest decreases being observed in autumn (−0.001 MJ m^{-2} d^{-1} per decade). Meanwhile, it was also revealed that UV energy began to increase since 1990s (0.003 MJ m^{-2} d^{-1} per year).

1. Introduction

Solar UV (ultraviolet) radiation is divided into three ranges: UV-A (315–400 nm), UV-B (290–315 nm) and UV-C (100–290 nm) [1,2]. Although UV radiation near the surface constitutes only a small fraction of global solar radiation (G) [3], it has received considerable attention in recent years because of its photochemical effects on the biosphere and its close relationship with stratospheric ozone creation and dissociation [4,5]. UV radiation disrupts proteins, causes sunburn, skin cancer, eye cataract and other deleterious effects in many biological systems [6,7]. Meanwhile, ultraviolet radiation can be used in cleaning processes of photodecomposition of organic residues, dye, natural and synthetic fibers [8,9]. Thus, a detailed knowledge of availability and its variation, both temporal and spatial, is of great significance not only due to the effects produced on human beings, but also in plants, biochemical cycles and aquatic ecosystems [10,11].

Generally, the UV levels reaching the earth's surface are modified by the atmospheric constituents (ozone and aerosols), astronomical parameters (zenith angles), meteorological conditions (cloudiness) and characteristics of the surface (altitude and albedo) [12,13]. The magnitude of the attenuation is the combined effects of above parameters during the irradiative processes, so it is difficult to determine the role of each variable under different sky conditions [1,14]. Therefore, it is essential to have as many measurements as possible on a continuous basis to make a detailed study of the climate variability of UV radiation reaching the surface in long-term trends [15]. Unfortunately, one of the difficulties is the poor spatial and temporal coverage of the UV observations due to the high cost of the instrumentation and great difficulty in maintaining the

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sensors [16,17]. The number of UV observation stations is limited in the world up to now, not to mention that in China [17,18]. Irradiative transfer models were alternatives by considering the scattering and absorption processes in the radiation path through the atmosphere [19–21]. They require detailed knowledge of atmospheric parameters, for example, cloud properties, aerosol optical depth, ozone amount and water vapor, which increase the difficulty of the model application [11,21]. Another widely adopted method is estimating the UV radiation from global radiation measurement by considering UV/G (F_{UV}) as an empirical constant [22]. However, the accuracy of this method varies with locations and sky conditions, which indicates that this parameter model should be recalibrated to account for local conditions before application [23–25].

Although lots of studies have attempted to estimate UV radiation in the world [6,24,26], many models have been restricted to clear-sky conditions [21,27,28]. Even with a number of scientists focused on the effects of aerosol, clouds, and ozone amounts, we could not have a clear understanding of how UV radiation was affected under various sky conditions in China [29,30]. Norsang et al. [31] documented measurements and modeling of UV radiation in Lhasa, Tibet, there was few studies regarding UV characteristics in Central China. Meanwhile, fewer studies focused on reconstructing historical data to reveal the long-term changes of UV and their causing factors in Central China, we have no ideas of how UV evolved during the past 50 years [32,33]. With increasing requirements for understanding about energy situation and global climate change, more knowledge of UV radiation distribution is still needed [34], which necessitate UV studies from analyzing its characteristics with direct measured data and then developing all-sky models which can work well under various sky conditions in Central China.

In recent years, a few studies began to estimate UV radiation using some observed and computed variables, for example, the sky brightness and clearness index, which are seen as general indicators for absorption and scattering processes of all atmospheric compositions [35,36]. This may provide new thoughts in UV modeling with high accuracy. The objective of this study is not only to analyze the UV radiation variability at different time scales and its relation to G under different sky conditions using 7-year observed radiation data (2006–2012), but also to develop an efficient all-sky UV model by studying the dependence of UV on clearness index and solar zenith angle in order to reconstruct the hourly and daily UV radiation from 1961 to 2011. The proposed models were also validated at two other sites in China with distinctly different climates. At the same time, the variation characteristics of UV datasets were investigated and analyzed for the first time in Central China.

2. Sites and measurements

2.1. Sites and instruments

The observation site WHU (Wuhan University) is located at LIESMARS (State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing), Wuhan University, Wuhan (Hubei province) in Central China, where Yangtze River and Han River flow across the main city (Fig. 1) [33,37]. This region experiences a typical North subtropical humid monsoon climate with an annual average temperature about 15.7–17.5 °C and an annual average rainfall 1050–2000 mm (Table 1). Water vapor begins to increase in spring (March–May). In summer (from June to August), warm and humid air from the Western Pacific brings large amounts of rainfall [37]. Meanwhile, Siberian anticyclones often bring cold and dry northwest air currents in winter (from December to February) [38]. It is worth to note that industrial activities such as cement processing, coal combustion and smelting have caused severe air pollution, haze conditions appear frequently in recent years [38,39].

A series of atmospheric observation equipments has been installed at the top of a building (about 30 m above sea level) in WHU for years. CM-21 pyranometer was adopted for G observation with experimental error being around 3%; UV radiation (290–400 nm) was measured using CUV3 radiometers with an accuracy of about 5% [40]; PAR (photosynthetically active radiation) was observed using PAR_LITE with a relative error below 4% estimated by the manufacturer; the direct and diffuse radiation can also be obtained by CH-1 direct radiometer and CM-11 radiometer respectively. Above instruments were all manufactured by Kipp & Zonen, Delft, Netherlands and calibrated against a reference pyranometer, which had been calibrated against a standard pyrheliometer [29]. All instruments were calibrated at the beginning and end of the experiment [38], which has been described in detail by Hu et al. [43]. Liquid water path and integrated water vapor can be obtained from the Low Humidity and Temperature Profiler. Meanwhile, aerosol optical parameters and water vapor content can be measured or retrieved from Sun photometer CE318 and our newly developed LIDAR system. Routine maintenances were conducted to guarantee that all radiation equipments were horizontally positioned and operating regularly [38,41]. All meteorological and radiation data have been recorded at 1-min interval, the daily and 6-min means were then used to minimize the deviation caused by instruments response difference.

Apart from data from WHU, the daily G data were obtained from National Meteorological Center of China; daily mean values of UV and G from SJ (Sanjiang) and LS (Lhasa) station in China during 2007–2010 provided by CERN (Chinese Ecosystem Research Network) were also used here for further accuracy assessment of the newly developed all-sky UV model. The locations for both sites have also been shown in Fig. 1 and Table 1, SJ is characterized by temperate humid and semi-humid continental monsoon climate in Northeast China; annual rainfall is about 500–650 mm and an annual evaporation being 550–650 mm [42]. LS site is located in a region of plateau temperate semi-arid monsoon climate with frosty winters and mild summers. The region enjoys nearly 3000 h of sunlight per year and is thus called “sunlit city”. The coldest month is January with average temperature being $-1.6\,^{\circ}$C and the warmest month is June about 16.0 °C [43].

2.2. Data analysis

Due to a complete range of solar angles and climate conditions were included in the dataset (2006–2012), the G and UV data should be examined for inconsistencies to eliminate errors associated with shadowband misalignments and other questionable observations. Considering the cosine response problem, the analysis in this study has been limited to cases that solar elevation angle h was higher than 5° [28]. QC (quality control) for G was based on that G should be smaller than extraterrestrial G_0 in the same geographical location and G also should be larger than the minimum values in continuous overcast conditions [44]. Then QC for UV was mainly based on two principles: each measured UV should be less than UV_0 at the top of atmosphere in the same geographical coordinates; UV/G (F_{UV}) must be in the range of 0.02–0.08, otherwise it was considered as a questionable observation [45]. The extraterrestrial G_0 can be obtained from:

$$G_0 = 24/\pi \times S_0 L_0 \times [(\pi/180)\gamma(\sin\delta\sin\phi) + (\cos\delta\cos\phi\sin\gamma)] \quad (1)$$

where S_0 is about 1367 W/m^2, L_0 represents correction factor of the Earth’s orbit, δ is solar declination, γ is sunrise hour angle, and φ is for geographical latitude. Details of above calculation were described in Ref. [46].