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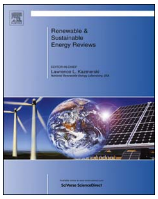

# Ultraviolet radiation over China: Spatial distribution and trends

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## ABSTRACT

An efficient model for estimating Ultraviolet (UV) radiation under various sky conditions was developed based on UV radiation measurements during 2005–2014 from the Chinese Ecosystem Research Network (CERN). The empirical UV estimation model was introduced by analyzing the dependence of UV irradiation on the clearness index ($K_s$, the ratio of the total solar irradiance on a horizontal surface to the extraterrestrial total irradiance on a horizontal surface) and the solar elevation angle under various sky conditions at each typical station. This model provides accurate UV radiation data, with an average root mean square error of 14.31%. We combined this estimation model with a hybrid model to reconstruct the historical dataset of daily UV radiation at 724 routine weather stations of the China Meteorological Administration (CMA) from 1961 to 2014. The hybrid model considered 6 attenuations in the solar radiation transfer process: Rayleigh scattering, aerosol extinction, ozone absorption, water vapor absorption, permanent gas absorption and cloud extinction. The average UV radiation level was 0.49 MJ $m^{-2}$ $d^{-1}$. The spatial distribution and temporal variation of the daily UV radiation in different climate zones were discussed based on the reconstructed historical dataset. Northern China had more UV radiation than southern China, and eastern China had less radiation than western China. The UV radiation on the Qinghai-Tibet Plateau was the greatest (0.66 MJ $m^{-2}$ $d^{-1}$). The UV radiation on the Qinghai-Tibet Plateau increased from 1961 to 1984 and then changed minimally, which did not coincide with the overall trends of the entire country and other regions. In addition, the aerosol optical depth, ozone column concentration, cloud cover and water vapor content attenuated approximately 7.59%, 1.12%, 18.13%, and 6.20%, respectively, of the UV radiation that reached the Earth's surface without the attenuation of the four factors.

## 1. Introduction

Ultraviolet (UV) radiation occurs at wavelengths from 100 nm to 400 nm and is subdivided into three regions: UVA (315–400 nm), UVB (280–315 nm) and UVC (100–280 nm). In this study, UV radiation is defined as radiation with wavelengths from 290 to 400 nm. Although the extraterrestrial ultraviolet solar spectrum contributes only a small fraction (approximately 8.0% at the top of the atmosphere) of the overall solar radiation [1], it has significant influences on ecosystems, environments, human health and the Earth's atmospheric processes [2,3]. UV radiation can inhibit photosynthesis by destroying plant leaves, which subsequently affects the entire ecosystem [4]. UV radiation in the troposphere may accelerate photochemical reactions in the near-surface layer and produce more secondary pollutants. Moreover, it can degrade plastics, colorants, paints and artificial and natural fibers [5]. Excess UV radiation can cause abnormal immune system functioning in the human body, manifested in conditions such as sunburn, skin cancer, and eye cataracts. In the stratosphere, the absorption of solar UV radiation by ozone counteracts the effect of infrared radiation cooling caused by increased carbon dioxide and water vapor [6]. Therefore, precise observation and clear information about UV radiation contribute significantly to many fields, such as agriculture, biological ecosystems, human health and climate systems.

Unfortunately, in situ measured UV radiation data are scarce because UV radiation is not routinely measured worldwide at meteorological observation stations. Moreover, many of these stations have only recently been established, and long-term experimental measurements with spatiotemporal continuity are lacking [7]. China began to

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observe UV radiation in some sporadic locations in the early 1980s, which resulted in a short period of record. Although many characteristics of UV radiation have been obtained, the results are local and not regionally representative. Therefore, high spatial resolution and long historical UV radiation data must be obtained through either empirical/semi-physical methods or satellite inversion algorithms.

To obtain UV radiation data before the use of instrumentation, several authors reconstructed UV radiation series using substitute records, such as solar radiation, sunshine duration ($t_d$), cloud cover, water vapor, ozone and albedo. Fioletov et al. [8] developed a statistical model to extend the UV radiation record over Canada back to the early 1960s. The model estimated UV radiation values based on solar radiation, total ozone, dew point and snow cover. Antót et al. [9] used a simple analytical parameterization to reconstruct past UV index values at Badajoz and Caceres (southwestern Spain) from 1950 to 2000 for cloud-free days. The empirical model included three independent variables: the solar zenith angle, the total ozone column and the clearness index ($K_s$, the ratio of the total solar irradiance on a horizontal surface to the extraterrestrial total irradiance on a horizontal surface). Wang et al. [10] used UV radiation measurements at 38 stations from the Chinese Ecosystem Research Network (CERN) during 2006–2012 to develop a semi-empirical UV estimate model. Combined with the daily global solar radiation ($R_s$) at 115 China Meteorological Administration (CMA) stations [11], long-term UV values during 1961–2012 were reconstructed. However, the observed $R_s$ at CMA stations had serious errors before 1993 due to instrument sensitivity drift and instrument replacement [12], and the spatial resolution of the reconstructed UV radiation was not high. Feister et al. [13] used artificial neural networks to derive solar UV radiation from measured meteorological parameters, such as global radiation, aerosol optical depth (AOD) and atmospheric column ozone, and the solar UV radiation at eight European sites during 1893–2003 was reconstructed.

Other studies have attempted to reconstruct UV radiation using radiation transfer models that consider the absorption and scattering processes in the radiation transmission path, such as LibRadtran, SBDART and SMART [14–16]. It is essential for all UV radiation transfer models to account for the effect of clouds. As cloud optical data sets are scarce and pyranometer measurements of global solar radiation contain valuable information about the influence of clouds on the amount of solar radiation received at the Earth's surface, many researchers simulated UV radiation under clear sky conditions and then used the measured solar radiation to correct the cloud extinction. Román et al. [14] used a radiative transfer model (UVSPEC/LibRadtran) to simulate UV radiation at 9 stations on the Iberian Peninsula from 1950 to 2011 under cloudless conditions. The model required inputs such as the AOD, Ångström exponent, aerosol single scattering albedo, water vapor column, surface albedo and total ozone column, and the output was modified by a cloud modification factor obtained from an empirical equation. However, the monthly values of AOD, surface albedo and water vapor column were used in the radiative transfer model, and changes in these variables were not considered. Zhang et al. [16] used a radiative transfer model (SMARTS) to reconstruct daily UV radiation at nine observation stations in China. First, the daily UV radiation under cloudless-sky conditions was simulated using the SMARTS radiative transfer model. Then, the daily cloud modification factors (the ratio of daily observations to simulations of UV radiation) were calculated using empirical relationships. UV radiation could only be reconstructed at a limited number of stations because of input data limitations for the radiative transfer models.

In summary, we lack a clear understanding of how UV radiation has evolved and the effects of correlative factors on the UV radiation trends during the past 54 years (1961–2014) at the national scale in China. CERN is a nationwide solar radiation network for simultaneously measuring UV radiation, solar radiation and routine meteorological parameters. The network has been updated since August 2004 following the criteria of the Baseline Surface Radiation Network [17]. The observations from this network can be used to estimate UV radiation at the national scale.

The objectives of this study are as follows: (1) Analyze the variation characteristics of UV radiation and the UV fraction by measuring UV radiation and Rs; (2) Introduce simple, efficient all-sky experiential models to investigate the dependence of UV radiation on the solar elevation angle, clearness index and sunshine duration in 8 different climate zones and introduce a hybrid model [18,19] to estimate global solar radiation at 724 CMA stations; (3) Investigate the spatial characteristics and temporal trends of UV radiation in China from 1961 to 2014 based on the dataset reconstructed at the CMA stations; (4) Quantitatively analyze the effects of AOD, ozone, clouds and water vapor on UV radiation attenuation.

## 2. Materials and methods

### 2.1. Site description and data collection

The CERN network was established to measure solar radiation to investigate the radiation budget and its spatial and temporal variation properties in China. This network consists of 39 stations marked by five-pointed star symbols in Fig. 1. These stations are distributed across almost all typical ecosystems in China, including agricultural, forest, grassland, desert, marshland, lake, marine and urban ecosystems. CM-11 pyranometers with an accuracy of 3% (Kipp and Zonen, Delft,

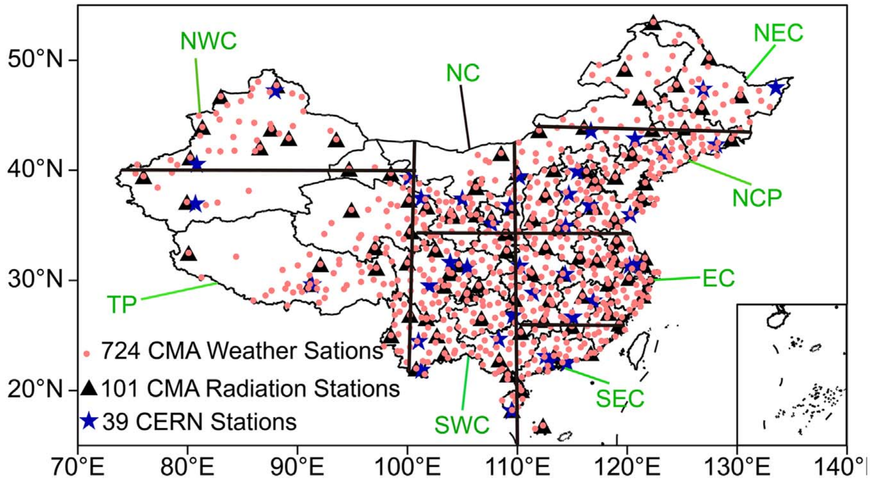

**Fig. 1.** Spatial distribution of the 101 radiation stations and 724 weather stations of the CMA and the 39 CERN stations.