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Variation characteristics of ultraviolet radiation derived from measurement and reconstruction in Beijing, China

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ABSTRACT

Four years measurements of broadband global solar radiation (R_S) and total ultraviolet (UV) radiation (the sum of UV-A and UV-B) were conducted from 2005 to 2008 in Beijing. These data were used to determine the temporal variability of UV/R_S and its dependence on water vapour content and clearness index. A simple, efficient and empirically derived all-weather model is proposed to estimate UV from R_S. The estimated data were used to analyse the characteristics of long-term variations in UV radiation. Results revealed that annual mean UV was 0.37 ± 0.17 MJ m^{-2} d^{-1}. The highest daily value of UV radiation was measured in May, while the lowest value occurred in December. The monthly mean value of UV/R_s gradually increased from 2.7% in November to 3.7% in August. The annual mean value of UV/R_s was 3.1%.

The annual mean daily UV radiation during 1958–2005 was 0.46 MJ m^{-2} d^{-1}. The interannual variations and long-term patterns of UV radiation derived from reconstructed daily UV values are compatible with changes in measured R_S. Annual mean UV radiation levels decreased from the early 1960s to the late 1990s but began to increase in the late 1990s. Over the latter half of the 20th century, decrease in UV radiation was 0.018 MJ m^{-2} d^{-1} per decade. The decrease trends in long-term annual mean UV radiation of −0.026 MJ m^{-2} d^{-1} per year for 1958–1997 and −0.0024 MJ m^{-2} d^{-1} per year for 1958–2005. The decreasing trend in UV radiation was sharpest in spring and summer but more gradual in autumn and winter.

1. Introduction

Ultraviolet (UV) solar radiation has a significant influence on the environment, human health and the Earth's atmospheric processes (Diffey, 1991, 2004; Slaper and Koskela, 1997; United Nations Environment Programme, 2003; Outer et al., 2005). The amount of UV radiation reaching the Earth's surface comprises only a small fraction of global radiation; about 6–7% of global radiation is in the UV-A (320–400 nm) range and less than 1% is in the UV-B (280–320 nm) range. However, UV radiation plays an important role in many biological and photochemical reactions. In particular, UV radiation plays an important role in the photodegradation of plastics, colorants, paints and artificial and natural fibres as well as the formation and decomposition of photosensitive urban and industrial contaminants (Cañada et al., 2000). UV radiation also has important public health consequences by affecting the development and modification of changes in climate (Bojkov, 1997). In the stratosphere, the absorption of solar UV radiation by ozone counteracts the effect of net infrared radiative cooling caused by increases in CO_2 and H_2O (Cañada et al., 2000). An understanding of changes in long-term, ground-level UV radiation is required to support assessments of UV radiation-induced health and environmental risks (Slaper and Koskela, 1997). Thus, a clear knowledge of UV radiation availability and variations, both temporal and spatial, is important in many research fields.

Despite its anthropogenic importance and impacts, concern about the amount of UV radiation reaching the Earth's surface has only recently developed, primarily as a result of the thinning ozone layer linked to the depletion of stratospheric ozone in the 1980s (Su et al., 2005). UV radiation-measuring networks are extremely scarce, particularly in China.

Numerous factors can influence UV radiation, including cloud characteristics, solar zenith angles, total ozone, aerosol pollution

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and surface albedo. Altitude also has an important effect on UV radiation (Piazena, 1996; Seckmeyer et al., 1997; McKenzie et al., 2001). Several studies have been conducted to quantify the attenuation of UV radiation by clouds (Calbó et al., 2005; Lindfors and Arola, 2008); however, cloud properties have property variations that make it difficult to establish quantitative relationships linking cloud properties to the attenuation of UV radiation. Clouds are known to affect the attenuation of UV radiation differently based on atmospheric location, percent cover, optical thickness, water content and drop size distribution. To determine the cloud-induced attenuation of UV radiation, many studies have reported that it is necessary to know cloud thickness, location, type, microphysical properties and surface albedo (Foyo-Moreno et al., 1999; Nemeth et al., 1996; Díaz et al., 2000). A number of studies have focused on quantative variations in UV radiation and the ratio of UV to global solar radiation (R_s). Additional studies have addressed long-term trends in the variations of UV through reconstructions of past UV radiation based on ground-based and satellite data (Kaurola et al., 2000; Fioletov et al., 2001; Lindfors et al., 2007; Feister et al., 2008). However, only a few studies have investigated long-term trends in UV radiation in Beijing, China, especially for reconstruction of past UV radiation.

The objective of this paper, apart from showing seasonal variations of UV and UV/R_s values, was to develop a simple and efficient parametrization of UV radiation using simultaneous measurements of UV and R_s from Beijing, China. The model is validated using UV and R_s data collected at this site, and extension of the model to other locations is evaluated. Based on this reconstruction method, a long-term data set of UV radiation is developed, and variations in the UV characteristics of Beijing are investigated.

2. Materials and methods

2.1. Site

Beijing Municipality is located on the northwestern border of the North China Plain and is bounded by mountains to the north, east and west. It has a typical East Asian monsoon climate. Stable weather systems prevail in Beijing during autumn and winter, which makes most days clear with north winds bringing dry, cold air into the city. Beijing is also often affected by anticyclonic weather systems in autumn (September–November). In winter (December–February), Siberian anticyclonic circulation patterns frequently pass through Beijing, and cloudless conditions dominate. Atmospheric water vapour begins increasing in spring (March–May). The rainy season begins in June and ends in August, with most rainfall occurring in July.

The study site was located in downtown Beijing (39°56′N, 116°17′E, 75 m a.s.l.), between the Third and Fourth Ring Roads. Domestic dwellings can be found to the north and south of the site with a nearby freeway to the east. The measurement instruments were installed on a flat platform on the roof (at an altitude of about 10 m) of the Institute of Atmospheric Physics, Chinese Academy of Sciences.

2.2. Calibration of solar radiation sensor and quality control of sample data

Values of R_s (305–2800 nm) were measured using CM-11 pyranometers (Kipp & Zonen, Delft, Netherlands) with an accuracy of 2–3%. UV radiation (290–400 nm) was measured using CUV3 radiometers (Kipp & Zonen, Delft, Netherlands) with an accuracy of 5%. All radiation values were recorded at 1-min intervals, and an hourly value was derived by integrating the 1-min values. All CM-11 pyranometers were calibrated using the 'alternate method' (Bruce, 1996). During the process of calibration, we were required to take on-site measurements of global, diffuse and direct sensor voltages in clear and sunny conditions. Diffuse radiation, or radiation that has been scattered by atmospheric constituents (e.g. clouds, particulates and aerosols), was measured using a CM-11 pyranometer. The solar radiation that passes through the atmosphere directly to the earth's surface is called direct radiation and was measured using a pyrheliometer sensor. The pyrheliometer was calibrated against a reference pyranometer, which had been calibrated against a standard pyrheliometer (PMO6) (i.e. an absolute irradiance radiometer (Switzerland)). This absolute irradiance radiometer is calibrated every five years at the World Radiation Center in Davos, Switzerland. The results show that the maximum sensitivity deviations in the CM-11 pyranometers averaged under 0.5%.

Quality control of the UV radiation measurements was based on two main principles: observed UV radiation should be less than the extraterrestrial UV radiation at the same geographical location, and the range of the ratio of UV radiation to R_s should be limited to values between 0.02 and 0.08. Elhadidy et al. (1990) noted that the UV radiation/R_s ratio can be as low as 0.02 on days experiencing high dust levels, while the UV radiation/R_s ratio at the top of atmosphere is 0.08 as derived from integral sun spectral irradiance (Gueymard, 2004). Therefore, the UV radiation/R_s ratio should be between 0.02 and 0.08. Values outside this range were flagged as questionable and excluded from the data set. About 1% of the measurements were eliminated based on these quality control processes. Quality control for R_s was similar to that for UV radiation, and the smallest acceptable value of the ratio of R_s to extraterrestrial global solar radiation was 0.03 (Geiger et al., 2002).

At the start and end of data collection, all measurement sensors were cross -evaluated in Beijing. The maximum deviation of CM-11 sensors averaged 1.5% (the average deviation was 1.2%), and the maximum deviation of CUV3 sensors averaged 2.42% (the average deviation was 1.8%).

The daily global radiation data was derived from the China Meteorological Administration (CMA)/National Meteorological Center for 1961–2005. Before 1990, the instrument used to

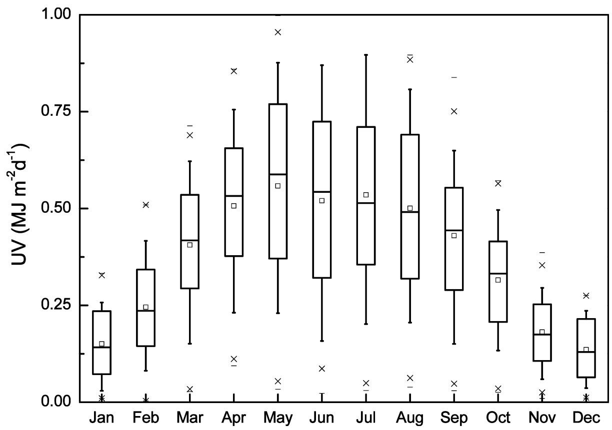

Fig. 1. Variation of UV in Beijing (Error bars correspond to standard deviation).

measure R_s in Beijing was modeled on those used in the former Soviet Union. After 1990, an instrument manufactured in China was used to measure R_s. The pyranometer was calibrated using a multistep method involving calibration of the pyranometers at individual stations against the reference instruments at least once per month, calibration of the reference radiometers against the regional reference instruments, and calibration of the regional reference instruments against the Chinese reference instruments every 2 yr.

3. Results and discussion

3.1. *Time series of UV radiation and UV/R_s*

The seasonal variation of four-year-average UV radiation properties from January 2005 to June 2008 is presented in Fig. 1. The minimum monthly average daily UV radiation occurs in the cool, dry season (i.e., the winter period), with an increasing trend of UV radiation in the spring that peaks in May. UV radiation levels decrease gradually following the May peak, falling to minimum levels in winter. The annual mean daily UV radiation for the 4-yr period was 0.37 ± 0.17 MJ m^{-2} d^{-1} with the highest and lowest values being 1.03 and 0.01 MJ m^{-2} d^{-1}, respectively.

Figure 2 shows box plots of the monthly statistics of UV/R_s, water vapour content and clearness index in Beijing. The different symbols represent the monthly mean, maximum and minimum values. Column-integrated water vapour content (based on relative humidity) was derived from an empirical parametric equation developed by Yang and Qiu (2002). There is significant monthly variation in UV/R_s levels. The monthly mean UV/R_s level increases gradually from about 2.7% in November to about 3.7% in August, after which it decreases gradually. This seasonal variation in UV/R_s is influenced by seasonal variations in water vapour content and cloud amount. From spring onwards, the column-integrated water vapour increases, generally reaching its maximum in summer when it is coupled with abundant

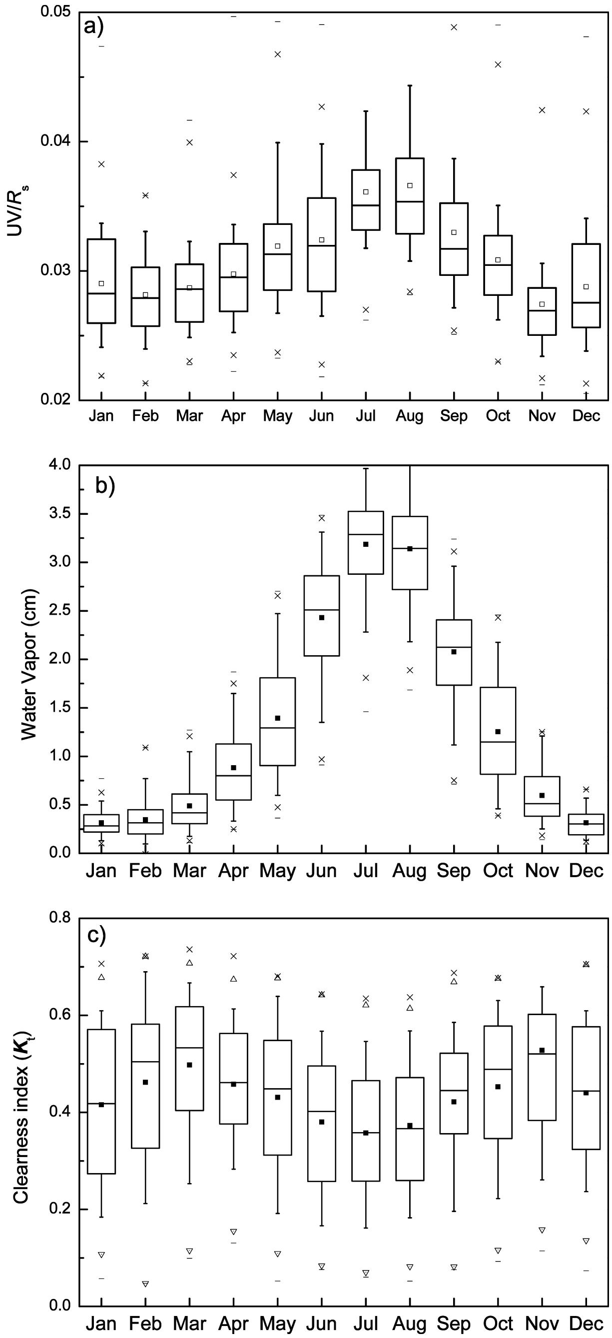

Fig. 2. Box plots of the monthly ratio of ultraviolet radiation to solar radiation (a); water vapour content (b) and clearness index (c). In each box, the central bar is the median and the lower and upper limits are the maximum and minimum, respectively.

rainfall, and begins to decrease in August. This seasonal cycle is similar to that of UV/R_s. The highest values of K_t (the ratio of R_s to extraterrestrial irradiance) occur in autumn and the lowest values occur in summer; values in spring and winter are intermediate. This seasonal pattern corresponds to the seasonal variation in column-integrated water vapour content. Under humid and cloudy conditions, the absorption of solar radiation in the infrared region is enhanced, whereas absorption in the UV region does not vary significantly. Thus, an increase in the UV/R_s ratio is expected under cloudy skies or humid conditions, and a decrease in UV/R_s levels is predicted under cloudless skies or dry conditions.

3.2. *The dependence of UV radiation on the clearness index*

Most studies use measured values to determine the relationship between UV and R_s and based on this develop UV-estimating models. The range of UV/R_s levels must be recalibrated to account for local climatic and geographical differences as well as atmospheric conditions (Udo, 2000). Our study uses direct-measurement UV data to investigate UV radiation properties under various atmospheric conditions in Beijing.

The clearness index, K_t, is defined as the ratio of the total irradiance to extraterrestrial solar irradiance, both defined on a horizontal surface. The K_t ratio is a general indicator of scattering and absorption processes due to aerosols, gases and clouds that may interrupt the transmission of irradiance through the atmosphere (Liu and Jordan, 1960; Elhadidy et al., 1990).

The 4-year's worth of data used in this study were first divided into two groups: one group for model development, comprised of 50% of all the data (randomly chosen) and another group for validation, comprised of the remainder of the data. Figure 3 depicts hourly UV radiation as a function of the cosine of the solar zenith angle (μ). Different colours represent data with different K_t values. The results show that UV radiation increases almost exponentially with μ for a specified K_t. Long and Ackerman

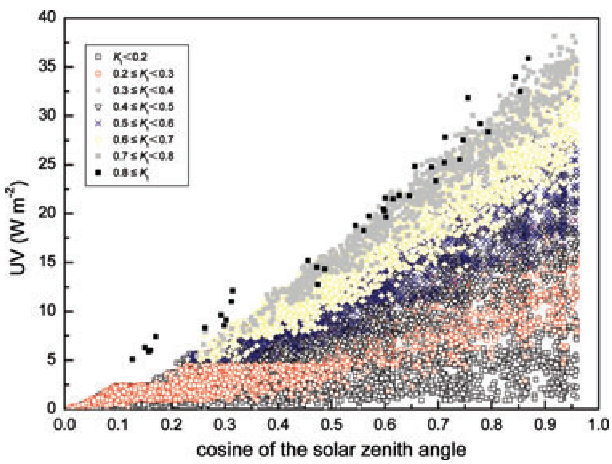

Fig. 3. UV as a function of the cosine of the solar zenith angle. Different clearness index (K_t) values are represented by different colours. The values of UV radiation within a narrow range of clearness index values increases almost exponentially with the cosine of the solar zenith angle.

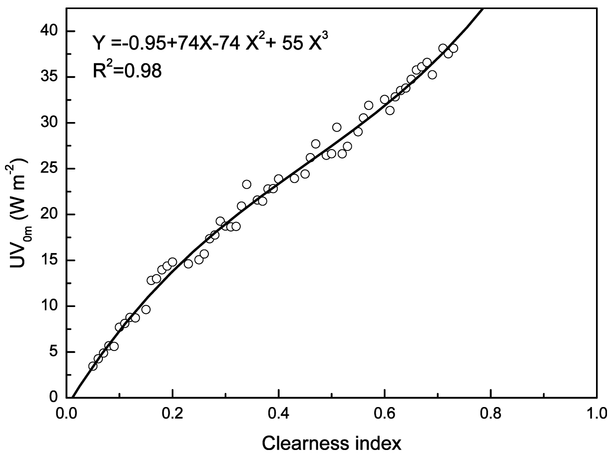

Fig. 4. The parameter UV_{0m} as a function of clearness index (K_t), showing the positive correlation between the two variables. The relationship can be expressed as a cubic polynomial equation.

(2000) used a power law equation to describe the dependence of R_s on clear sky conditions. For a narrow range of K_t values, the relationship between UV radiation and μ can be very well described using the following power law equation:

$$UV = UV_{0m} \times \mu^b, \tag{1}$$

where UV_{0m} is the maximum value of UV radiation per unit of μ.

The relationship between K_t and UV radiation was explored by first binning K_t values in 0.2 increments starting at 0.1. The data points in each bin were then fit using the power law equation. The resulting regression analyses showed that more than 95% of the variance in UV was explained by eq. (1). Figure 4 shows a scatter plot of the maximum value of UV radiation at an observation site per unit of μ (UV_{0m}) as a function of K_t. With this curve, the dependence of UV_{0m} on K_t is regressed as eq. (2).

$$UV_{0m} = 0.95 + 74K_t - 74K_t^2 + 55K_t^3. \tag{2}$$

Although the parameter b from eq. (1) did not exhibit a clear relationship to K_t, the variation of this parameter was very small. Xia et al. (2008) described that when parameter b was set to 1.031, the equation was highly accurate and could be used in Xianghe, located in north China to estimate instantaneous photosynthetic active radiation. Variations in UV radiation are similar to those of photosynthetic active radiation. The climate characteristics of Beijing site is similar as those in Xianghe, so we did not focus on using parameter b and instead used results from Xia et al. (2008). Thus, hourly UV radiation variation was estimated using the following equation:

$$UV = \left(0.95 + 74K_t - 71K_t^2 + 55K_t^3\right) \times \mu^{1.031}. \tag{3}$$

The long-term observed daily values of R_s at the Beijing site were measured by the National Meteorological Center, China Meteorological Administration (CMA). Long-term hourly values of R_s, however, were not possible to obtain. Therefore, to calculate long-term trends in the variation of UV radiation in Beijing, eq. (3) was modified as follows to use daily values of R_s. Historical daily R_s can be used to reconstruct daily UV via eq. (4):

$$UV_{\text{daily}} = \left(8.4 + 3206.8\overline{K_t} - 2210.7\overline{K_t}^2 + 2074.8\overline{K_t}^3\right) \times (\overline{\mu})^{1.031} \times t_{\text{d}}, \quad (4)$$

where UV_{daily} is the daily amount of UV radiation, $\overline{K_t}$ is the ratio of daily R_s to daily extraterrestrial solar irradiance, $\overline{\mu}$ is the average of the cosine of the solar zenith angle from sunrise to sunset and t_{d} is the length of daytime in hour.

3.3. Performance of the estimation equation

Hourly and daily UV radiation predictions were obtained by applying eqs (3) and (4) and comparing these predictions to direct measurements at the Beijing site (Fig. 5). The relative difference between the estimated and measured hourly UV radiation was less than 6.2%, and the mean bias error (MBE) and root mean square error (RMSE) were 0.64 and 1.01 W m^{-2}, respectively. The relative deviation between the estimated and measured daily UV radiation was less than 6.5%, and the MBE and the RMSE were −0.01 and 0.04 MJ m^{-2} d^{-1}, respectively. These results suggest that the model provided acceptable estimates of hourly and daily UV radiation.

Equation (4) was also used to provide UV radiation predictions using two independent data sets collected from Sanya (18°13′N, 109°28′E, 3.0 m a.s.l.) and Lhasa (29°40′N, 91°20′E, 3668 m a.s.l.) in Tibet (Figs. 6 and 7). The climate of Sanya is tropical, while Lhasa is characterized by Qinghai-Tibet Plateau climatic conditions. The detailed climatic characteristics of these two sites have been described by Hu et al. (2007). The relative deviations between the estimates and measured UV radiation

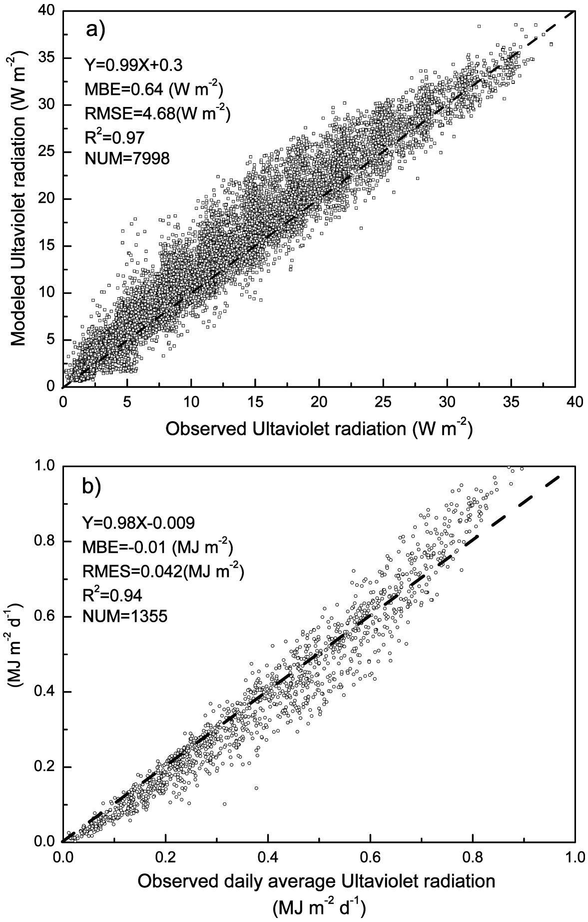

Fig. 5. Scatterplot of measured ultraviolet radiation and the model-predicted values using eq. (3). The daily values are calculated by using eq. (4). The black line represents the 1:1 relationship.

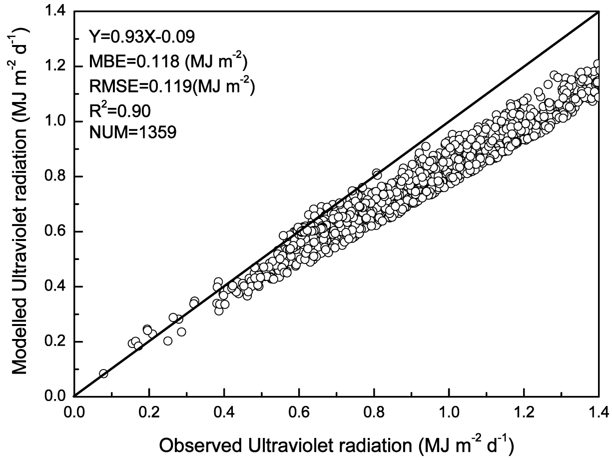

Fig. 6. Scatterplot of measured daily ultraviolet radiation and the model-predicted values using eq. (4) in Lhasa site. The black line represents the 1:1 relationship.

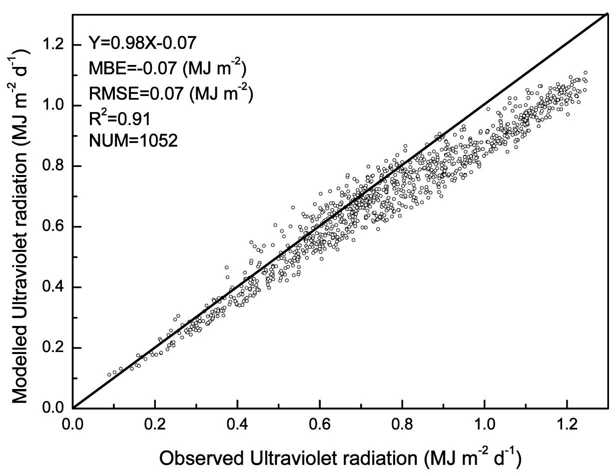

Fig. 7. Same as Fig. 5 but for Sanya site.

were less than 15% for the two sites. The MBE and RMSE were −0.07 and 0.07 MJ m^{-2} d^{-1}, respectively, for Sanya and about 0.118 and 0.119 MJ m^{-2} d^{-1}, respectively, for Lhasa. MBE predictors and regression parameters (*a* and *b*) calculated by fitting data at both sites show model underestimates and weaknesses. The proportion of the difference that arose from systematic errors was only about 7.5% for the Sanya site and 13.3% for Lhasa. These results suggest that the model provides acceptable estimates of UV radiation at locations other than Beijing, where the relationship was developed.

One advantage of this method is that it uses the same empirical functions of the cosine of the solar zenith angle, the length of daytime, and the daily R_s levels at all locations. From the transferability of the model to other locations, we note that a weakness of the method is that it is based purely on an empirical statistical model that does not account for ozone absorption and albedo. Zerefos (2002) points out that enhancements in UV-B under clear skies are directly related to the corresponding total ozone changes but enhancements in UV-A are not. In this study, we focus primarily on total UV radiation and ignore the effects of ozone absorption on UV radiation. Surface albedo must be specified within a radius of 30 km around a measurement site to avoid errors greater than 3% (Degünther et al., 1998). The Beijing observations were made in downtown Beijing, where the variability of albedo is small (0.14 in spring and summer, 0.12 in autumn) (Wang et al., 2008). Based on the low variability of albedo at the Beijing site, the effects of seasonal variation of albedo on UV radiation are ignored in this study. The empirical statistical model should in future be modified to include ozone and long-term albedo variation effects in order to improve accuracy of reconstruction and apply this model to other sites. However, the model parameters may also depend on local climatic factors, which vary geographically, and such factors are beyond the scope of this study.

3.4. *Long-term trends in ultraviolet radiation in Beijing*

The precision of reconstructed UV is mainly dependent on the measurement accuracy of R_s. Errors in the historical R_s measurements probably do not exceed 5%. Shi et al. (2008) established a set of quality assessment (QA) algorithms and used them to test the quality of daily measurements of R_s, direct radiation, and diffuse radiation measurements in China from 1958 to 2005. For global daily irradiation, the percentage of erroneous and suspected data was 3.07%. In this study, the QA algorithms established by Shi et al. (2008) are used to test daily R_s. The long-term UV dataset is then reconstructed based on data that passed the QA tests. The reconstructed data is reliable for analysis of the long-term variability of UV radiation.

Long-term UV radiation data are reconstructed from data from the Beijing observation station, which is located in the southwest Fourth Ring Road of Beijing. R_s observations collected from 1958 to 2005 by the National Meteorological Center (CMA) are used in this study.

A time series of annual average UV radiation in Beijing is shown in Fig. 8a. Seasonal average time series for spring (represented by April), summer (represented by July), autumn (represented by October) and winter (represented by January) are shown in Figs. 8b–e, respectively. Annual mean UV radiation levels decreased from the early 1960s to late 1990s but began to increase in the late 1990s. The annual mean daily UV radiation over 1958–2005 was 0.46 MJ m^{-2} at the Beijing station. Over the latter half of the 20th century, decreases in UV radiation of 0.018 MJ m^{-2} d^{-1} per decade were measured. We measured trends in long-term annual mean UV radiation of −0.026 MJ m^{-2} d^{-1} per year for 1958–1997 and −0.0024 MJ m^{-2} d^{-1} per year for 1958–2005. These results are consistent with results from the R_s analyses (−0.78 W m^{-2} per year for 1961–1990 and −0.45 W m^{-2} per year for 1961–2000) (Che et al., 2005). This consistent temporal variation in UV radiation suggests that increased aerosol loadings were at least partially responsible for the decreasing trend in UV radiation. A decrease in cloud amount over China for the period 1951–2000 has indeed been documented (Kaiser, 1998, 2000), so it seems reasonable to attribute the decline in UV radiation to increasing aerosol emissions. Large quantities of fossil fuels were burned during the rapid economic development of China over the past several decades, causing an increase in anthropogenic aerosol loadings. These aerosol particles can both absorb and scatter solar radiation in the atmosphere, and as discussed below, they have likely contributed to the decrease in UV radiation. After the mid-20th century, annual mean levels of UV radiation increased slightly, supporting reports of improved air quality by the Beijing Environmental Bulletin. Specifically, since 1999, a gradual decrease in the annual average concentrations of sulphur dioxide (SO_2) and carbon monoxide (CO) has been observed, as well as declines in the number of hours of ozone (O_3) concentrations exceeding Chinese ambient air quality standards and in the annual average concentrations of particulate matter of diameter less than 10 μm (PM10) (Beijing Municipal Environmental Protection Bureau, http://www.bjepb.gov.cn/). The decreasing trend of UV radiation was sharpest in spring and summer with more gradual decreases observed in autumn and winter. This seasonal difference was probably due to high relative humidity and temperature in the summer that favoured the formation of secondary sulphates, which scatter solar radiation (Chang et al., 2009). In addition, the sharp decrease of UV radiation in spring may have been linked to sand and dust storms that can also contribute significantly to UV radiation reductions in Beijing (Mahowald et al., 2007). The seasonal variation in UV radiation may also be dependent on seasonal variations in the amount of cloud cover. These questions merit further investigations in future studies.

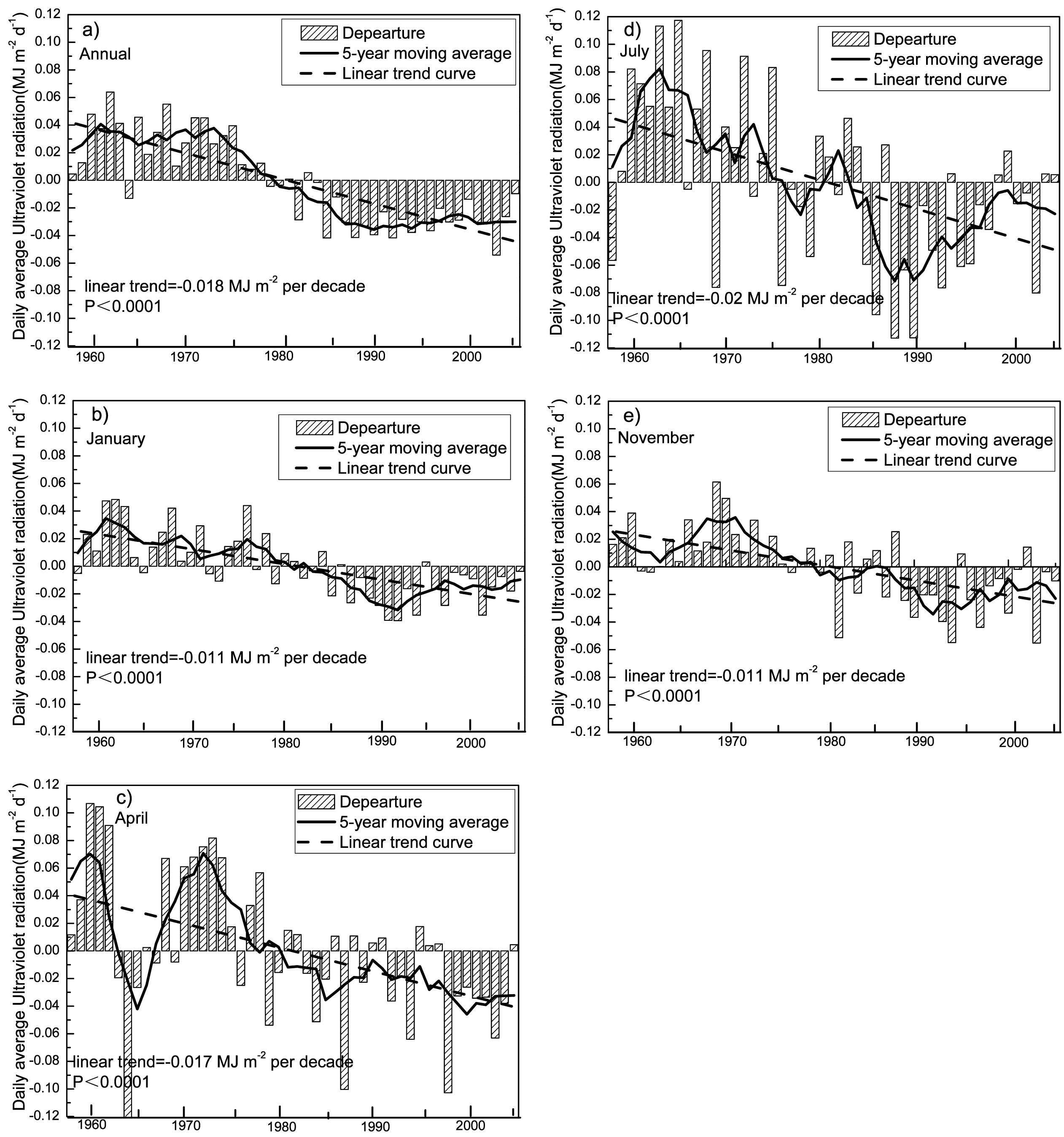

Fig. 8. Time series of annual departures of ultraviolet radiation for 1958–2005.

4. Conclusions

Temporal variations in UV radiation over Beijing were determined using UV radiation and R_s data collected in Beijing from January 2005 to June 2008. Seasonal variations in UV radiation were investigated and a simple, all-weather empirical model was established to estimate UV radiation based on R_s. The UV radiation levels increased gradually in spring, reaching a peak in summer, and then gradually declined to their lowest levels in winter. The annual mean daily UV radiation was 0.37 ± 0.17 MJ m^{-2} d^{-1}, and the highest and lowest daily UV radiation levels were 1.03 and 0.01 MJ m^{-2} d^{-1}, respectively. The highest daily values of UV radiation occurred in May, and the lowest values were measured in December. The monthly mean daily UV/R_s value gradually increased from 2.7% in November to 3.7% in August, after which it gradually decreased. The annual mean daily UV/R_s value was 3.1%.

The all-weather empirical model was established using measurements at Beijing and validated with data from two other stations with different climate conditions. The validation results indicated that this model could quickly and accurately estimate UV radiation from R_s. The interannual variations and long-term patterns of UV radiation derived from reconstructed daily UV values are compatible with changes in measured input data. The annual mean daily UV radiation from 1958 to 2005 was 0.46 MJ m^{-2} d^{-1}. Over the latter half of the 20th century, there have been significant decreases in UV radiation (0.018 MJ m^{-2} d^{-1} per decade). The decreasing trend in UV radiation was sharpest in spring and summer and more gradual in autumn and winter. Although there is some evidence that air quality conditions have improved over the past decade, the consistent temporal variations in UV radiation and R_s suggest that increased aerosol loadings were at least partially responsible for the decreasing trend.

These results improve our basic understanding of UV radiation and the climate of Beijing. Additionally, they have the potential to improve estimation of UV radiation from R_s observations on a larger scale. The model developed here may prove a particularly powerful tool for ecosystem process modelling designed to predict the growth and productivity of various ecosystems.

5. Acknowledgements

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