ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 23, NO. 5, 2006, 700–710

Long-Term Changes of the Ultraviolet Radiation in China and its Relationship with Total Ozone and Precipitation

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(Received 11 October 2005; revised 19 May 2006)

ABSTRACT

The new version (version 8) TOMS (Total Ozone Mapping Spectrometer) ozone and noontime erythemal ultraviolet (UV) irradiance products are used to analyze their long-term changes in this paper. It is shown that the summer UV irradiance has increased significantly from Central China to the northern and western parts of China, especially in Central China near Chongqing, Shaanxi, and Hubei provinces; whereas the UV irradiance has decreased significantly in the southern part of China, especially in South China. In July, when UV irradiance is at its maximum and hence when the most serious potential damage may happen, the results indicate an increase in the UV irradiance in Central China and the Yangtze River-Huaihe River valley and a decrease in South China and the eastern part of North China. At the same time, the total ozone amount is lower over China in summer with the most serious depletion occurring in Northeast China and Northwest China. It is found that the thinning of the ozone layer is not the main reason for the UV irradiance trend in the eastern and southern parts of China, but that the rainfall and the related cloud variations may dominate the long-term changes of the UV irradiance there. In addition, the future UV irradiance trend in China is also estimated.

Key words: ultraviolet irradiance, total ozone, rainfall variation, linear trend

doi: 10.1007/s00376-006-0700-3

1. Introduction

As a small portion of sunlight, ultraviolet (UV) radiation, on the one hand, initiates the production of vitamin D to build and maintain our bones in small doses; on the other hand, it can have very harmful impacts in large doses (Wayne, 2000). Exposure to UV radiation has been linked to skin cancer, immune system suppression, and cataract formation as well as a number of dermatological and ocular problems. Furthermore, ultraviolet radiation has a variety of effects on plants, animals, and other living things in the biosphere, mostly unfavorable. Since the 1970s, UV radiation has become a topic of increasing concern because of the observed ozone depletion. According to scientific assessment of ozone depletion (WMO, 2003), the ozone holes over the Antarctic and Arctic have increased in both size and duration. More importantly, ozone remains depleted in the midlatitudes of both hemispheres. The thinning of the ozone layer leads to more human UV exposure, especially UV-B (waveband 280–320 nm), which may cause sunburn, snow blindness, eye damage, skin cancer, aging and wrinkling of the skin, and weakening of the immune system, and it may alter plant growth (Hester and Harrison, 2002).

In recent decades, progress has been made in the study of UV radiation distribution and trends in China. For example, Zhou (1986) estimated the UV distribution in China by using an empirical formula based on observed solar radiation energy flux. Bai and Wang (1998) and Bai et al. (2003) pointed out that the UV radiation in Beijing had a decreasing trend in the last 20 years. So far, studies on ozone over China have mainly focused on the ozone over Tibet. Using Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) data, Zou (1996) studied the seasonal variation of ozone over Tibet and noted great ozone deficiencies in summer over the region. This ozone deficiency has also been discussed by Zhou et al. (1995,

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2004), Liu and Li (2001), and Liu et al. (2003). The objective of our study is to extend their studies to examine the distribution and long-term trends of UV irradiance in China with a new version of TOMS ozone and erythemal UV irradiance data, and to find out possible factors affecting the UV trend in China by comparing it with the reanalysis precipitation. In this paper, the datasets used are introduced in section 2. The climatology of the UV irradiance and total ozone in China are analyzed in section 3, and their long-term variability is studied in section 4. In section 5, possible relationships among UV irradiance, total ozone and rainfall in China are discussed. Concluding remarks are presented in section 6.

2. Data

High-quality measurements of UV irradiance may be provided by ground-based instruments, however, owing to the careful instrumental characterization and calibration requisites and the high cost of instrumentation and its maintenance, the deployment of ground-based networks for UV radiation measurements is limited in China (Wu, 2001). Moreover, ground-based observations are generally representative of local atmospheric conditions and not necessarily conditions in the surrounding region. Satellites, however, offer global coverage over extended periods. Furthermore, instrumental errors can be minimized by the use of a single instrument in a satellite measurement. The longest satellite series of UV measurements with a global coverage are provided by the Total Ozone Mapping Spectrometer (TOMS) instrument, which started in 1978 on the Nimbus-7 satellite, and it continues with the Earth Probe. The TOMS Noontime Erythemal UV Irradiance data products are derived from measurements of backscattered radiance using radiative transfer calculations (Herman et al., 1999). They are given for local solar noon, when the Sun is highest in the sky. The data cover the globe except during polar winter time, with a horizontal resolution of $1^\circ \times 1.25^\circ$ (lat×lon). Erythemal UV irradiance is an integration of the UV irradiance at the ground between 280 and 400 nanometers (nm), weighted by the model value of the susceptibility of caucasian skin to sunburn (erythema). It can be taken as an index of the potential biological damage caused by solar irradiation.

In May 2004, a new version (version 8) of the algorithm to convert the backscattered radiance into TOMS products (ozone, erythemal irradiance, reflectivity, aerosols) was released (Wellemeyer et al., 2004), correcting small errors that occurred under extreme conditions in version 7. The new algorithm includes a correction for sun glint and for the effect of aerosols in the troposphere, and it takes advantage of a new climatology for ozone and temperature profiles. Definite improvements are apparent for conditions like high tropospheric aerosol loading, sun glint, persistent snow/ice, and very high solar zenith angles.

For reasons unknown, the optical properties of the front scan mirror of the satellite have undergone continuing changes, therefore data since 2002 are not suitable for trend analysis. In this study, the daily ozone and local noon erythemal UV irradiance data from November 1978 to May 1993 (Nimbus-7) and from August 1996 to December 2001 (Earth Probe) are used. All the data can be obtained from the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center, U. S. A. (http://toms.gsfc.nasa.gov/). The ozone and erythemal UV measurements are in Dobson Units (DU) and milliwatts per square meter (mW m^{-2}), respectively. Monthly means are constructed by averaging daily data over the given month. Summer means are obtained by averaging June, July and August daily data resulting in 19 summer fields.

The monthly mean Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin, 1997) are also used for the period of 1979–2001 in this study. The data are provided through the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostic Center. This dataset has a resolution of $2.5^\circ \times 2.5^\circ$ and covers 88.75°N to 88.75°S and 1.25°E to 358.75°E.

3. The climatology of UV irradiance and total ozone in China

To detect the UV irradiance annual cycle in China, an area-weighted (i.e., cosine of latitude) average is applied in the domain of 20°–50°N and 75°–130°E (figure not shown). The erythemal UV irradiance is high in summer, maximized in July with a value of ~250 mW m^{-2}. The low erythemal UV irradiance occurs in winter, minimized in December with a value of ~80 mW m^{-2}. Therefore, in the annual variation of UV irradiance, the solar cycle is the main influencing factor. The high solar height angle and associated climatological factors lead to the highest UV radiation in July, which may cause the most dangerous biological damage to human beings.

Figure 1 shows the climatological mean fields of erythemal UV irradiance for summer (JJA mean), June, July and August, respectively. All are calculated over a domain including China for the period of 1979 to 2001. The shadings in these figures indicate the standard deviation of individual data. The erythemal UV irradiance has high values in the western

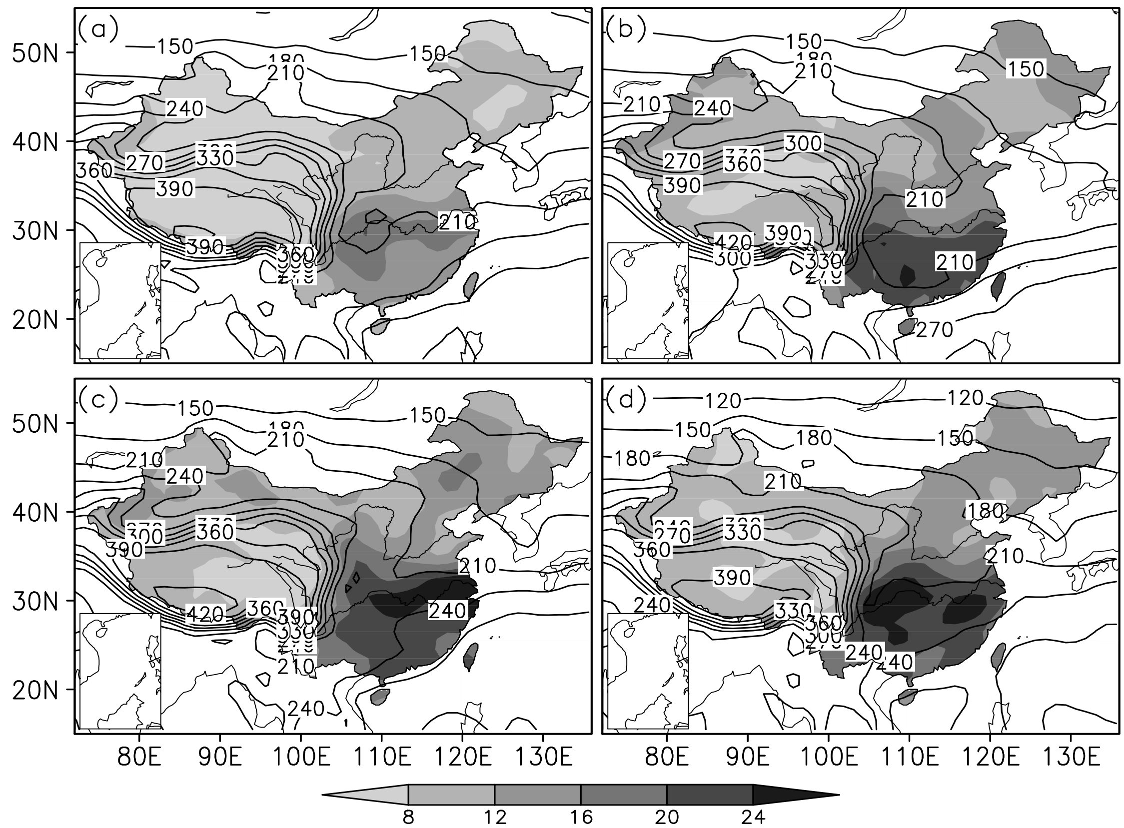

Fig. 1. Climatology of the erythemal UV irradiance for (a) summer (JJA), (b) June, (c) July and (d) August from TOMS averaged from 1979 to 2001. Unit: mW m^{-2}. The contour interval is 30 mW m^{-2}. Shading indicates standard deviation with an interval of 2 mW m^{-2}.

and southern parts of China and low values in the northern and eastern parts of China, with the strongest UV irradiance over Tibet. Due to the high altitude, the sparse air over Tibet can't shield man and animals effectively from UV injury. The highest UV irradiance over Tibet exceeds 420 mW m^{-2} in June and July, which is almost three times the values in Northeast China (around 150 mW m^{-2}). (However, the standard deviations are minimal over Tibet.) Hence, the largest number of cataract victims is found in Tibet. The decrease of UV exposure from south to north is in accordance with the decrease of the solar height angle from south to north. The largest standard deviations in the Yangtze River indicate that the UV has the most obvious interannual variations in the surrounding regions.

The climatological mean fields of total ozone for summer (JJA mean), June, July and August are illustrated in Fig. 2. The distribution patterns are almost opposite to the distribution of UV irradiance. There are low values in the southern and western parts of China and high values in the northern and eastern parts of China, with the lowest values over Tibet. The value of total ozone over Tibet can be as low as 270 DU, which is 20–30 DU lower than that over the eastern part of China at the same latitude. The total ozone over Northwest China is also 10–20 DU lower than that over Northeast China at the same latitude. Our results confirm the existing ozone valley over Tibet in summer and the suggestion of elevated topography inducing the low ozone above it (Zhou et al., 1995, 2004; Zou, 1996). In contrast to the UV irradiance, the standard deviation of the total ozone column increases with latitude, with the largest values occurring in the northern part of China.

4. Long-term changes of UV irradiance in China

Long-term changes of UV irradiance are important because they impact not only people's health and lifestyle but also the national economy. Using linear regression analysis, the trends of TOMS UV irradiance and ozone over China in 1979–2001 are computed. Figure 3 illustrates the linear trends of UV distribution in summer (JJA), June, July and August, respectively.

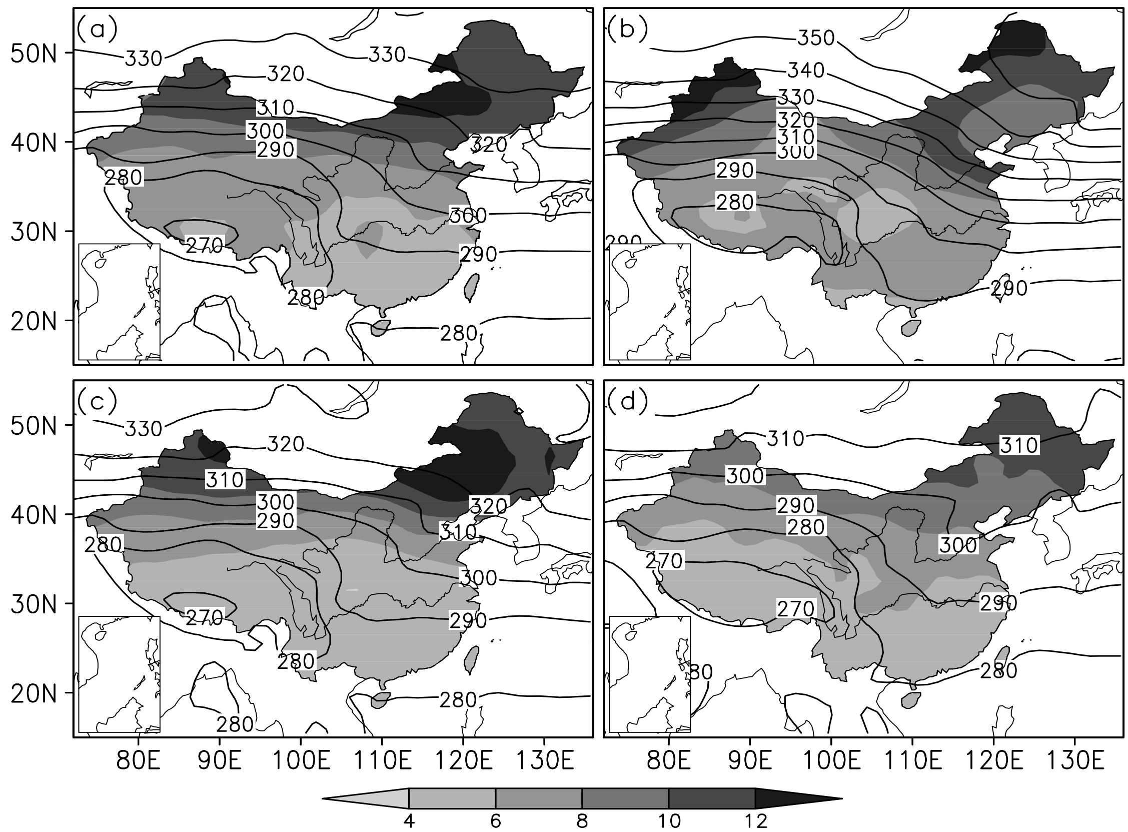

Fig. 2. The same as Fig. 1, but for column total ozone (in Dobson Units). The contour interval is 10 DU, and the shading interval is 1 DU.

In each month and in summer (JJA), the UV irradiance generally increases over the northern part of China and decreases mainly over South China. For the summer average (Fig. 3a), the significant increase mainly appears over the region including Xinjiang and Inner Mongolia. Shaanxi and Hubei provinces also witness a UV increase in the past 20 years with a rate of increase of about 6 mW m^{-2} per decade, which results in an approximate 6% increase of its climatic dose over the whole 23-year period (from 1979 to 2001). A significant UV irradiance decrease is clearly seen south of the Yangtze River with a maximum exceeding −12 mW m^{-2} per decade. This decrease accounts for 11–13% of its climatic dose over the time period studied. In the Yangtze River-Huaihe River valley, the trend of UV irradiance varies in the individual summer months. It decreases in June and August, but increases in July. It is also noted that the summer UV irradiance over the southern part of North China has decreased, which is consistent with the results of previous work (Bai and Wang, 1998; Bai et al., 2003).

When the mei-yu season finishes, East China is controlled by the subtropical high pressure belt. This is the time when the UV radiation reaches its summit and causes the most serious damage. The UV irradiance increases over central China to the Yangtze River-Huaihe River valley (Fig. 3c), which may be a hazard in these populous regions. The positive center among Shaanxi, Sichuan, Chongqing and Hubei provinces has the largest rate of increase of about 13 m W m^{-2} per decade. The total value of increase from 1979 to 2001 is about 30 mW m^{-2}, which amounts to more than 13% of the climatic value in these regions. The increase over the lower reaches of the Yangtze River has a rate of about 11 mW m^{-2} per decade, which amounts to about 25 mW m^{-2} during the 23-year period (about 11% of the climatic value in these areas).

5. Relation among UV irradiance, total ozone and rainfall changes in China

The linear trend of total ozone variation in China presented in Fig. 4 shows a uniform decrease in each summer month and in the summer mean. This is consistent with the global ozone depletion caused by Ozone Depletion Substances (WMO, 2003). The ozone depletion is much larger in the northern and western

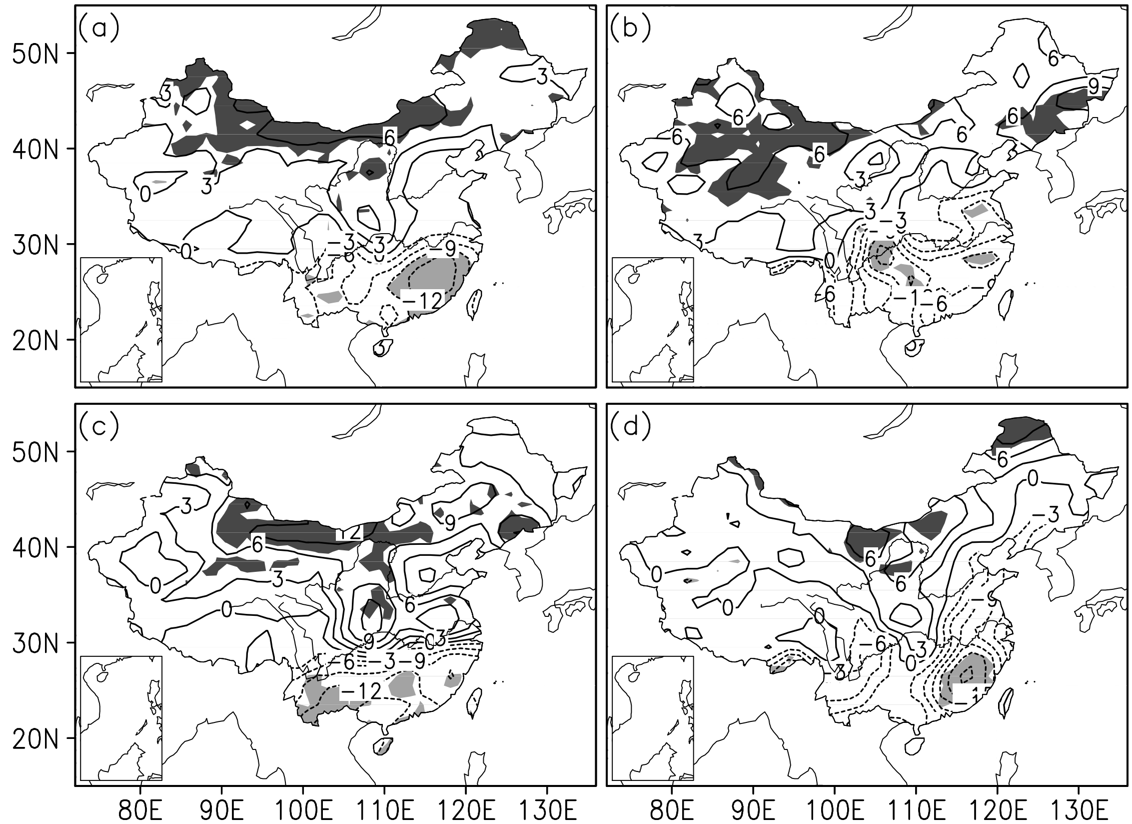

Fig. 3. Linear trend of erythemal UV irradiance for (a) summer (JJA), (b) June, (c) July, and (d) August from TOMS in 1979–2001. Unit: mW m^{-2} per decade. The regions exceeding the 95% significance level are shaded.

parts of China, especially in Northeast and Northwest China where the depletion rate exceeds 10 DU per decade (accumulating to 25 DU over the 23 years from 1979 to 2001, ∼7% of the climatic value). The ozone depletion in South China is expected to result in an increase in UV irradiance there; however, Fig. 3 presents a decrease in the UV irradiance. This suggests that other factors besides the ozone may dominate the changes in UV irradiance there.

Many studies have indicated that UV irradiance reaching the earth surface is influenced by various factors including total ozone amount, aerosol, dust, sulfur dioxide, and especially cloud (e.g., Herman et al., 1999; Wang et al., 1999; Frederick and Snell, 1990; Den Outer et al., 2005, Calbó et al., 2005). Frederick and Snell (1990) showed that dense cloud could attenuate the UV irradiance reaching the earth's surface by up to 90%. The calculation by Den Outer et al. (2005) suggested that on average cloud can reduce the UV irradiance to 68% of its original clear-sky amount. Since cloud is closely related to the precipitation and long-term precipitation data are available, the trend of precipitation is analyzed in this paper.

Figure 5 presents the linear trend of summer precipitation rate according to CMAP data. As shown in Fig. 5a, the precipitation rate has increased in the past two decades in the southern part of China. In particular, in South China and Southeast China, the rate of increase surpasses 1.4 mm d^{-1} per decade. In contrast, the precipitation rate has decreased in central China among Shaanxi, Sichuan and Hubei provinces where the rate of decrease is about 0.6 mm d^{-1} per decade. The pattern varies a little in individual summer months. The center of increase moves westward to South China in July with a maximum value of about 1.8 mm d^{-1} per decade. However, the center of increase expands to cover Southwest China and the Yangtze River-Huaihe River valley. In August, the increase occurs mainly in the eastern coastal areas and the decrease dominates central China.

Figure 6 presents the time series of July column total ozone (top), UV irradiance (middle) and precipitation rate (bottom) averaged over central China and the Yangtze River-Huaihe River valley (averaged domain: 30°–35°N and 105°–120°E) with their linear trends. The linear increase of UV irradiance in these regions

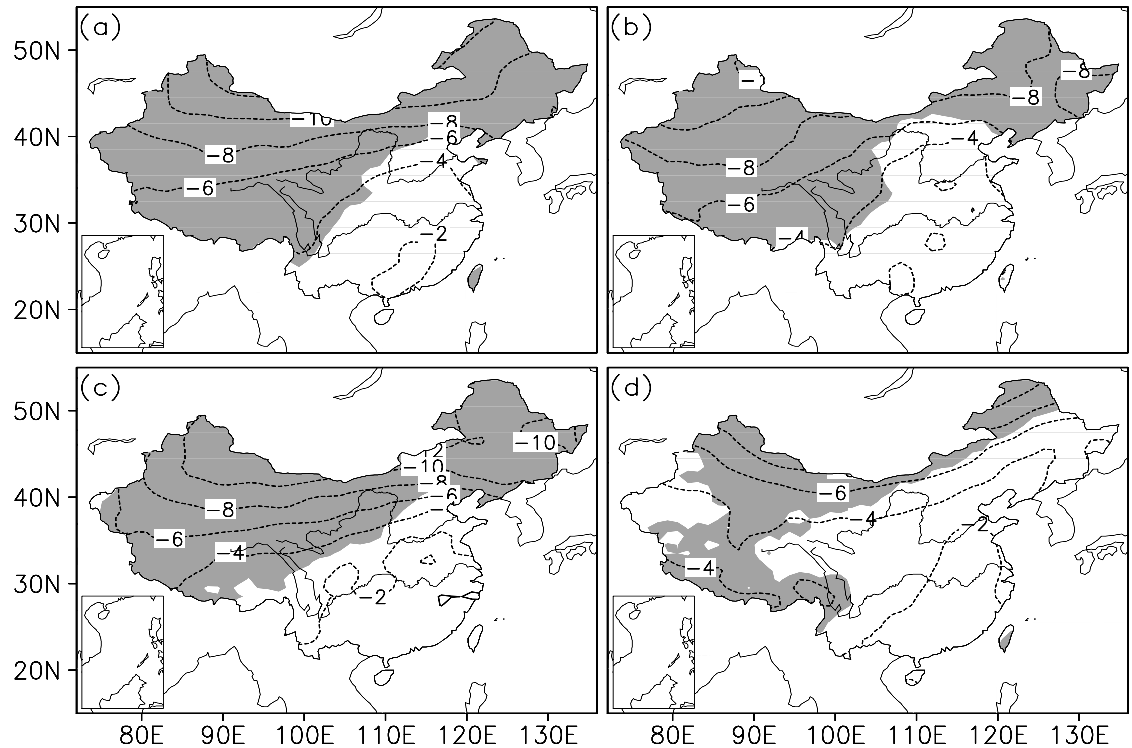

Fig. 4. The same as Fig. 3 but for column total ozone (in Dobson Units). Unit: DU per decade.

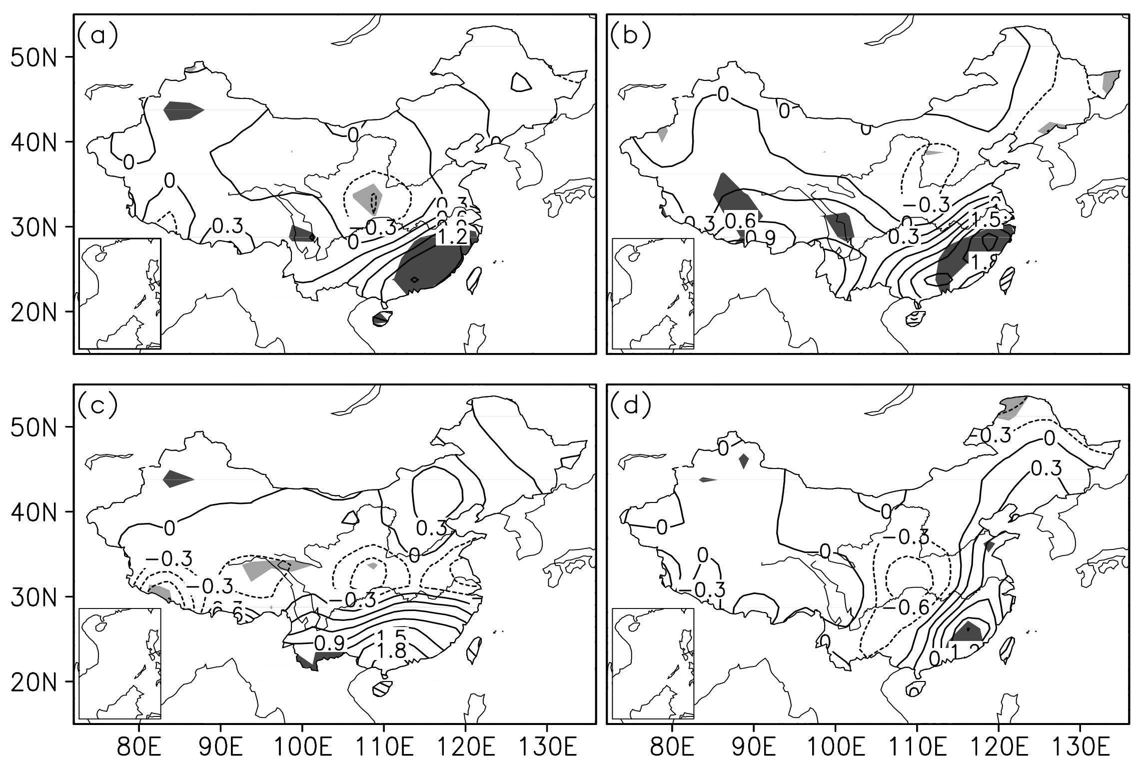

Fig. 5. The same as Fig. 3, but for rate of precipitation from CMAP in 1979–2001. Unit: mm d^{-1} per decade.

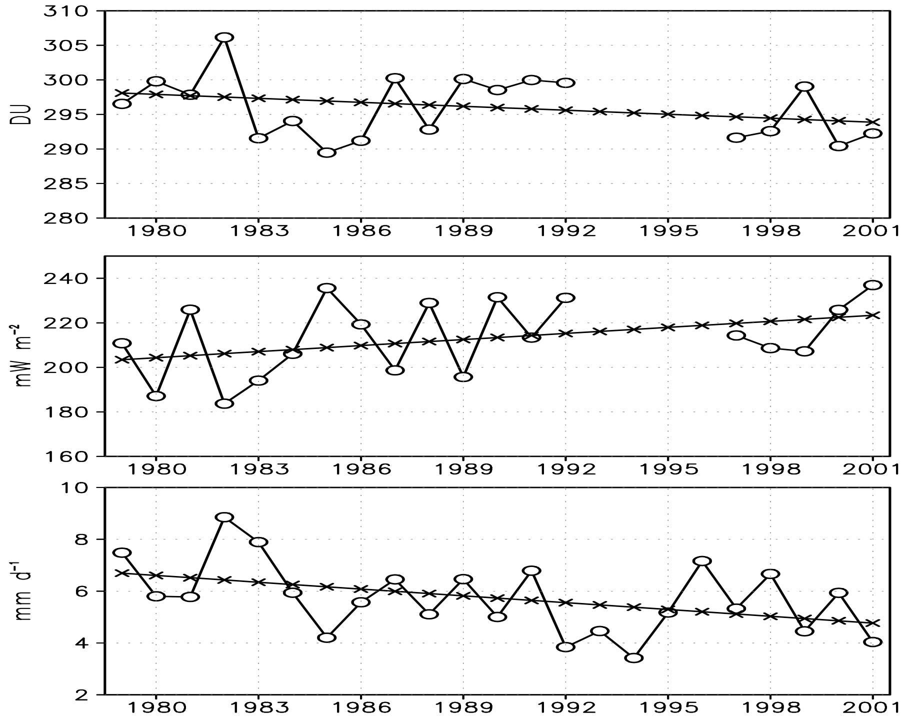

Fig. 6. The interannual variation of July column total ozone (top), erythemal UV exposure (middle) and rate of precipitation (bottom) in central China and the Yangtze River-Huaihe valley (averaged domain: 30°–35°N, 105°–120°E, open circles) with its linear trend.

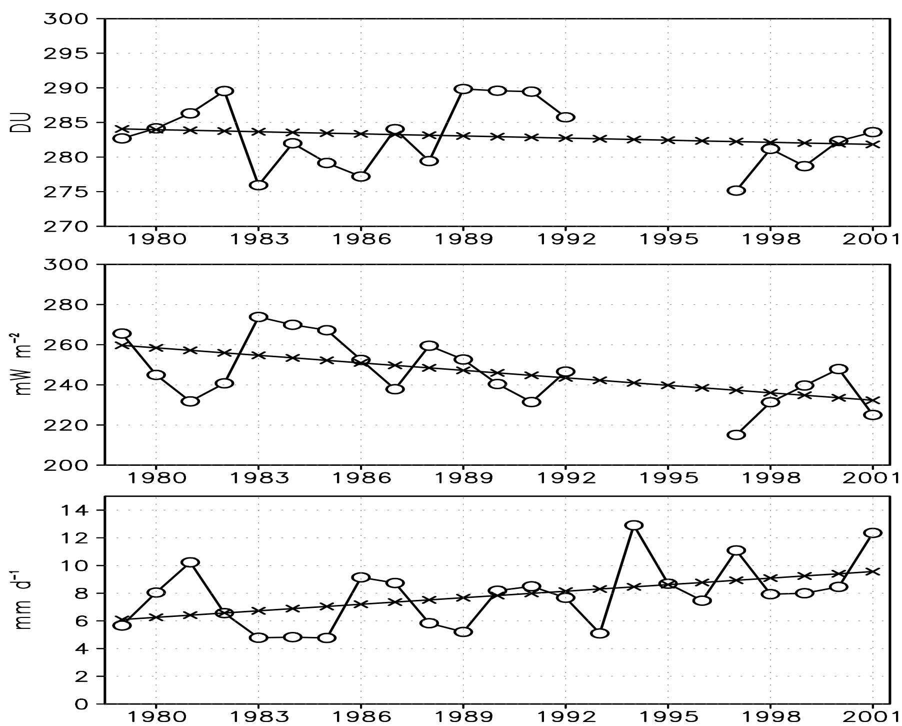

Fig. 7. The same as in Fig. 6, but for South China (averaged domain: 20°–25°N and 100°–120°E).

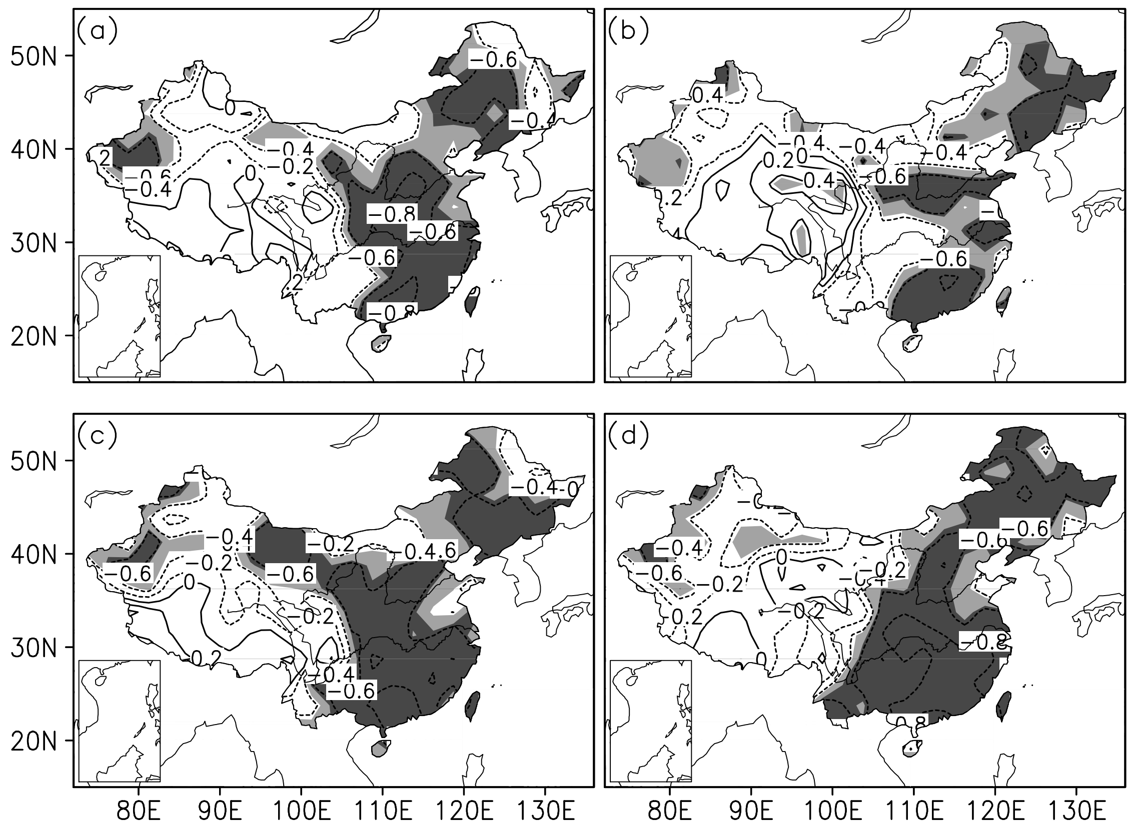

Fig. 8. Correlation patterns between UV irradiance and precipitation rate for (a) summer (JJA), (b) June, (c) July, and (d) August. Correlation coefficient is calculated between UV irradiance and precipitation rate at each grid point. Heavy and light shadings indicate significant values at the 99% and 95% confidence levels, respectively.

is remarkable, which has increased from about 205 mW m^{-2} to about 222 mW m^{-2}. The total increased dose amounts to about 8% of the climatic value in these areas. Both the column total ozone and the precipitation rate have decreased over the past 23 years. The precipitation rate has decreased from about 6.7 mm d^{-1} to about 4.8 mm d^{-1}. The rate of decrease reaches about 0.83 mm d^{-1} per decade. The total amount of decrease accounts for about 1/3 of the climatic value. The correlation coefficient is −0.51 between UV and ozone and −0.74 between UV and precipitation rate. A substantially larger fraction (∼50%) of variance of the UV irradiance can be explained by the variation in precipitation rate, while the ozone variation accounts for about 25% of the total variance of UV irradiance. After the linear trends of these three time series are removed, the variation of precipitation rate can explain about 47% of the total variance, while the ozone explains about 20% of the total variance in these regions.

Figure 7 shows the July column total ozone (top), UV irradiance (middle) and precipitation rate (bottom) and their linear trends over South China (averaged domain: 20°–25°N and 100°–120°E). The UV irradiance over these regions has decreased significantly from about 259 mW m^{-2} to about 233 mW m^{-2}, which accounts for about 10% of the irradiance amount in these regions. The column total ozone has decreased while the precipitation rate has increased over the past 23 years. The precipitation rate in South China has increased from about 6.0 mm d^{-1} to about 9.7 mm d^{-1}. The rate of increase reaches 1.6 mm d^{-1} per decade, which results in an increase of about 47% of the climate amount. The correlation coefficient between UV and ozone is −0.21, and that between UV and precipitation rate is −0.87. About 75% of the variance of the UV irradiance can be explained by the precipitation rate variation, while the ozone accounts for only about 4.5% of the total variance of UV irradiance. After the linear trends of these three time series are removed, the precipitation rate variation can explain about 66% of the total variance, while the ozone explains about 13% of the total variance.

Figure 8 shows the correlation patterns between UV irradiance and precipitation rate for summer (JJA) and each summer month. The correlation coeffi-

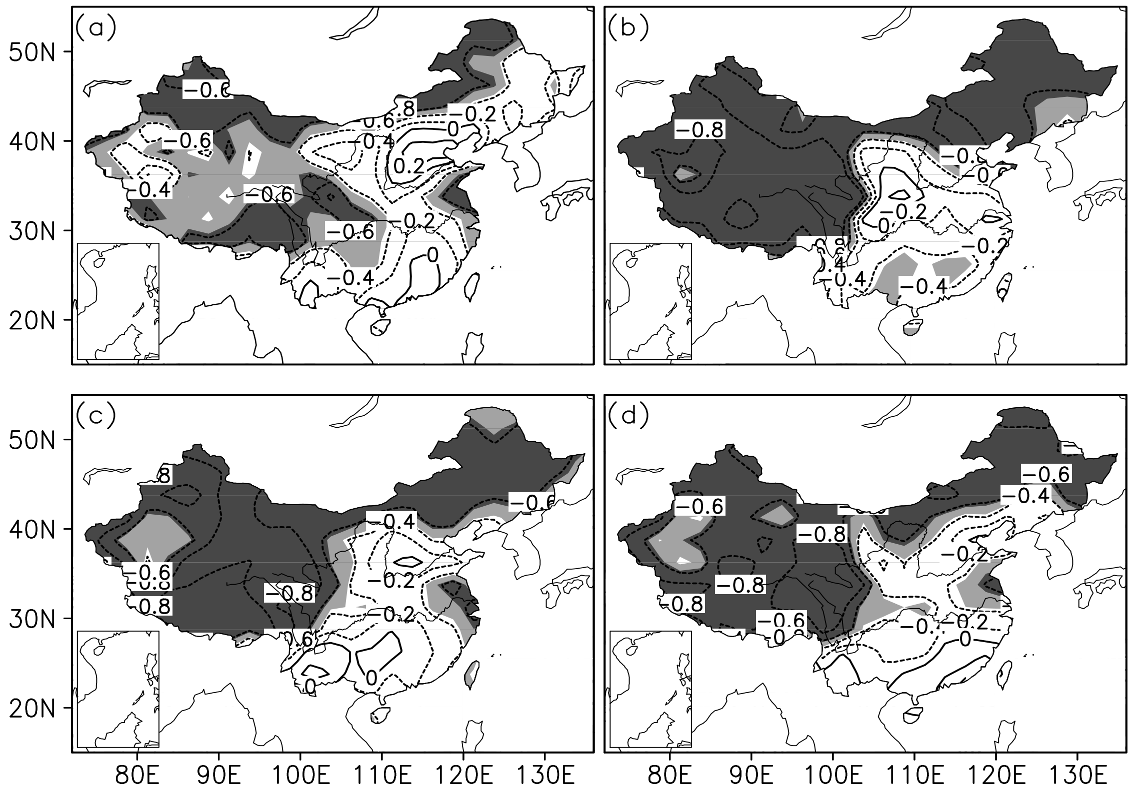

Fig. 9. The same as in Fig. 8, but for the correlation pattern between UV irradiance and column total ozone.

cients are calculated between UV irradiance and precipitation rate at each grid point. Heavy and light shadings in the figure indicate significant values at the 99% and 95% confidence levels, respectively. The correlation between UV irradiance and precipitation rate is significant at the 99% confidence level in most parts of eastern China in summer and also in each month. The correlation patterns between UV irradiance and total ozone column are presented in Fig. 9. The significant correlations appear mainly in West China and Northeast China, indicating that the UV increase caused by the ozone depletion is not evident except in the west of China where rainfall is scarce. Therefore, we can claim that the UV variations in the east of China are mainly related to the precipitation variation.

The consistency between the precipitation rate and the UV irradiance changes in the past two decades reveals that the factors related to rainfall may be the major ones influencing UV irradiance in the eastern part of China. Hence, the trend of precipitation can be used as a hint of the trend of UV exposure in these regions.

6. Conclusions and discussions

As a result of the Montreal Protocol and its Amendments and Adjustments to reduce substances that deplete the ozone layer, it can be inferred that the ozone depletion will finally be lessened in the future. Scientific assessment of ozone depletion (WMO, 2003) reported that the total chlorine abundance in the stratosphere is at or near a peak, while the bromine abundance is probably still increasing. Meanwhile, the CFCs that deplete the ozone layer are all long-lived substances. The suggested earliest recovery of the ozone layer will be after the 2050s. The ozone depletion and related environmental problems will still remain in the near future. Thus, the UV radiation will still be strong in the coming decades related to the changes of ozone.

In the paper, the climatology and long-term trend of the erythemal UV irradiance in China are studied by analyzing the TOMS UV data. It is found that the UV irradiance increases from north to south and from east to west with the largest UV irradiance appearing over Tibet (the largest value exceeds 420 mW m^{-2} in June and July). However, the largest standard deviation of UV irradiance occurs in the Yangtze River valley, indicating the most obvious interannual variations there. The summer UV irradiance has increased significantly from central China to the northern and western parts of China, especially in central China near Chongqing, Shaanxi, and Hubei provinces (about 6% of its climatic dose over the whole 23-year period); however, the UV irradiance has decreased significantly in the southern part of China, especially in South China (11%–13% of its climatic dose). In July, the month when the UV irradiance reaches its summit and causes the most serious damage, the UV irradiance has increased by about 13% over central China and about 11% over the lower reaches of the Yangtze River, while it has decreased by about 10% over South China.

At the same time, the total ozone amount has fallen over China in summer with the most serious depletion in Northeast China and Northwest China (~7% of the climatic value). It is found that the thinning of the ozone layer is not the main reason for the UV irradiance trend in the eastern and southern parts of China, while the rainfall and the related cloud variations may dominate the long-term changes of the UV irradiance there. In the eastern and southern parts of China, about 40%–70% of the variance of the UV irradiance can be explained by precipitation change; in the western and northern parts of China, however, the total ozone variation explains a large fraction (about 30%–70%) of the variance of the UV irradiance.

Xu et al. (2003, 2004) used simulation results of seven GCM models from IPCC III to study the future climate in China. Her results showed that the precipitation would increase in the south of the Yangtze River and decrease in the north of the Yangtze River when the effects of both greenhouse gases increase and sulfate aerosols are considered. Bueh (2003) and Bueh and Lin (2003) analyzed the future change of the East Asian monsoon via a simulation using the ECHAM4/OPYC3 CGCM model. The A2 and B2 scenarios from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) were used in the simulation. Wei (2005) used the same model and scenarios considering both the direct and indirect effects of aerosol to document the future changes of the East Asian Monsoon. All of the results predicted that rainfall would increase in North China and decrease in Southeast China. The increasing rainfall in North China means more cloud attenuating the UV radiation. Yet the rainfall decrease in Southeast China will be companied by a UV hazard to the people living there. However, the projected precipitation change in the Yangtze River valley is complicated, which shows no systematic changes in the first half of the 21st century and an increase in the second half. This suggests that UV radiation would possibly increase in the second half of the 21st century in the Yangtze River valley. As the IPCC (2001) pointed out, there are still uncertainties in the simulations of climate models, especially in the regional climate models. The simulated duration and strength of the East Asian monsoon are largely determined by the model's ability to reproduce the monsoon variability. Therefore, it is important to improve the ability of climate model simulations to understand the climate change in China and to evaluate and respond to the climatic hazards in the future, such as those caused by variation of UV radiation.

Acknowledgments. The authors would like to thank the two anonymous reviewers for their comments. This work was supported by the Chinese Key Developing Program for Basic Sciences (Grant No. 2004CB418303) and the National Natural Science Foundation of China (Grant Nos. 40375021 and 40575026).

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