Analysis Trends of Ultraviolet B Fluxes in the Continental US with USDA and TOMS data

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Abstract

Many environmental factors, such as stratospheric ozone, aerosols, and clouds, may affect ultraviolet (UV) irradiance. The aim of this study was to investigate the possible association between ultraviolet B (UVB) radiation and total cloud amount, ozone, and aerosols simultaneously, leading to the assessment of possible impacts of climate change on UVB flux variations in the Continental United States (US). Findings indicate that in the past 22 years, while ozone decreased and aerosols increased across the US, the UVB decrease in the northern states was consistent with the increase in aerosols and total cloud amount. Climate change impact resulting in higher total cloud amount in the northern states might result in lower UVB in the future.

Keywords: Aerosols Index, Climate Change, Ozone, TOMS, Total Cloud Amount, UVI.

1 INTRODUCTION

Changes in the Earth's atmosphere caused by anthropogenic and natural pollutants have led to a well-documented decline in the stratospheric ozone layer and a corresponding increase in ultraviolet (UV) irradiance at the Earth's surface at higher latitudes (Kerr and Fioletov, 2008). The amount of ultraviolet radiation penetrating the stratospheric ozone layer to the Earth's surface with wavelengths shorter than 320 nm, ultraviolet B (UVB), can be reduced by ozone absorption, aerosols, clouds, ground albedo, altitude, and Rayleigh scattering in the atmosphere (Herman et al., 1997). However, the amount of solar radiation reaching the Earth's surface or reflecting back to space is primarily governed by the amount of cloud cover and, to a much lesser extent, by Rayleigh scattering, aerosols, and various absorbing gases (e.g., O_3, NO_2, H_2O) (Herman et al., 2009).

Ground truth data collection to support estimates of the daily UV erythemal doses and total column ozone is critical for data verification. Gao et al. (2001) developed a methodology for direct-sun ozone retrieval using the ultraviolet multifilter rotating shadow-bandradiometer (UV-MFRSR). This approach allows the real-time measurement of total vertical column ozone at ground-based stations; three such stations were tracked in this study. This capability fosters advanced intercomparisons between the daily UV erythemal doses and total column ozone calculated with any space-borne data and observations at the USDA ground-based network, as was pursued in the study reported here. In our study, the impacts of time series influential factors such as total ozone, total cloud amount, and aerosols on UVB were investigated and the UVB spatial distribution patterns were analyzed based on TOMS data to explore the causal or differential effect between the changes of total cloud amount and their degree of impact on UVB. Because TOMS data exhibit spatial continuity, whereas the USDA ground-based sensor network can only provide point measurements, we chose TOMS data to carry out this study.

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2 MATERIALS AND METHODS

2.1 TOMS Data and ISCCP data

In contrast to ground observations, satellites provide complete global coverage at a moderate resolution with standardized sensors. UV has been observed from space for more than 30 years. Early satellite UV measurements were made by the Backscatter Ultraviolet (BUV) sensor onboard the Nimbus 4, which was launched in 1970 and continued functioning for several years. Nimbus 7 provided the longest high-quality UV space-borne observation from 1978 to 1993 with TOMS (i.e., version 8.0). This dataset can be used to monitor long-term trends in total column ozone and to investigate seasonal chemical depletions in ozone occurring in both the southern and northern hemisphere polar springs (Herman et al., 1997).

The data of total cloud amount used in this study are derived from ISCCP, established in 1982 as part of the World Climate Research Programme (WCRP) to collect and analyze satellite radiance measurements to infer the global distribution of clouds, their properties, and their diurnal, seasonal, and interannual variations. Data collection began on 1 July 1983 through 30 June 2010. The resulting datasets and analysis products are being used to improve understanding and modeling of the role of clouds in climate, with the primary focus for elucidating the effects of clouds on the radiation balance. These data can also be used to support many other cloud studies for promoting the understanding of the hydrological cycle.

2.2 The statistical methods

To analyze the global trends and spatiotemporal patterns of UVB in relation to total cloud amount and aerosols, some spatial statistics methods such as coefficient of variation (CoV), correlation coefficient, and the slope of a linear regression equation were employed in this analysis. In statistics, CoV is computed as the standard deviation (σ) divided by the mean (μ) of the time series data (Sun et al., 2010; Milich and Weiss, 2000; Vicente-Serrano et al., 2006) as follows:

$$CoV = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})}}{\frac{1}{n}\sum_{i=1}^{n}X_i} \quad , \tag{1}$$

in which n is the total number of the pixels in remote sensing images in our study. For pattern analysis, group heterogeneity of pixels increases turnover rates. The formulas of correlation coefficient or Pearson product-moment correlation coefficient represents a measure of the strength of the linear relationship between two variables (X and Y), which is defined in terms of the (sample) covariance of the variables divided by their (sample) standard deviations. It describes a broad class of statistical dependence relationships between two or more random variables or observed data values (equation 2):

$$r = \frac{\sum(X - \overline{X})(Y - \overline{Y})}{\sqrt{\sum(X - \overline{X})^2 \sum(Y - \overline{Y})^2}} \quad , \tag{2}$$

where, in the above equations (1) and (2), X_i is the i_{th} sample (value) of a variable (pixel); n is the number of samples; $\overline{X}$ is average value of this sample; Y_i is the i_{th} sample (value) of a variable (pixel); and $\overline{Y}$ is average value of this sample.

However, regardless of the true pattern of association between two random variables, a linear regression model between CoV and time may provide further insight into spatiotemporal patterns based on the slope of the equation (equation 3):

$$z = \alpha + \beta t \tag{3}$$

where β is the slope; α is a constant in the prescribed linear regression equation; t_i is the i_{th} year; m is the number of years; $\overline{t}$ is average value of years; z_i is the i_{th} sample (value) of a variable (pixel); $\overline{z}$ is average value of this sample; β is slope; and α is constant in the linear regression equation. If the slope (β) of this

regression exhibits a negative sign showing a statistically decreasing trend over time, we can conclude that the temporal variability of parameter (UVI or total cloud amount) was declining; conversely, if the slope (β) of this regression line shows a positive sign indicating a statistically increasing trend, we can conclude that the temporal variability of parameter (UVI or total cloud amount) was increasing. With these equations, we analyzed the changes or trend of UVB, total ozone, AI, and total cloud amount with time series data using the GIS spatial analysis method (i.e., ARC/INFO software) and the spatial statistical analysis with the aid of SPSS software.

3 RESULTS

Seasonal UVB changes over different locations are caused by a series of complex factors. These factors include solar activity, solar zenith angle, altitude and latitude, atmospheric absorption (the absorption of O_3, SO_2, and NO_2), scattering (the Rayleigh scattering of air molecules and the Mie scattering of clouds and aerosol particles), and surface reflection. All of the atmospheric molecules, clouds, and aerosol particles have an additive effect on UVB of absorption and scattering; however, each plays a dominant role at a certain time. Such a combination resulted in the decadal changes of UVB across the US.

The factors affecting on UVI variations are complex, and their spatial and temporal changes are diverse at the decadal scale; therefore, there is a certain degree of difficulty in fully describing the characteristics and causes of UV variations when using both methods of field measurements and model simulation (Ilyas, 1987; Bais et al., 1993). The long-term changes of UVI were not driven entirely by a single factor, such as total ozone, however. In fact, UVI changes were also driven by total cloud amount, aerosols, albedo, and other factors, as well as geographical location and elevation. The relative importance of these factors to UVI depends on the varying situations that compound the investigation (Gao et al.,2010a,2010b).
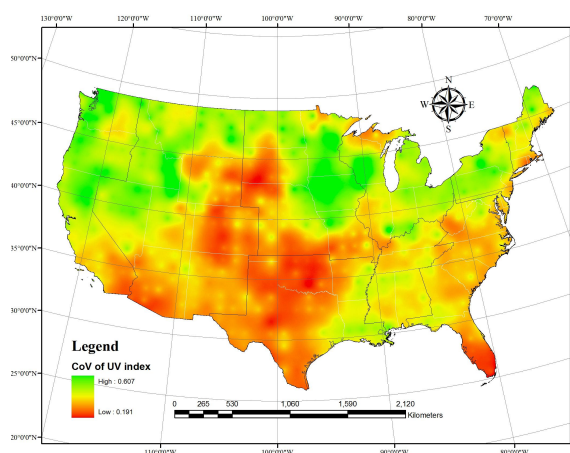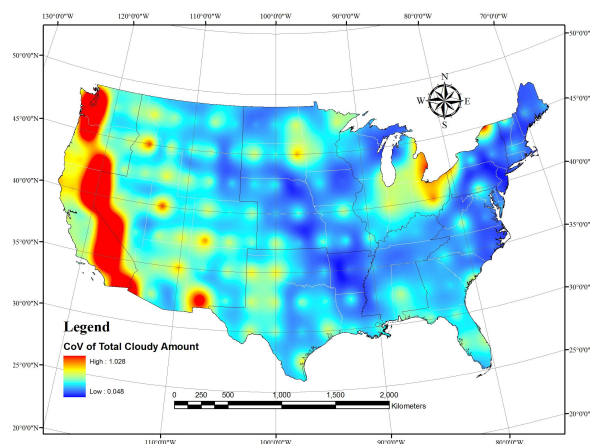

Fig. 1. Spatial CoV of UVI.

Fig. 2. Spatial CoV of total cloud amount.

Although the UVB and total cloud amount were decreasing at some local areas, the increasing trend of aerosol was offset by the decreasing trend of total ozone over the US within the same time frame. However, the spatial variations and trends of UVB and total cloud amount may be correlated with each other such that the impact of total cloud amount on UVB may be quantified with the aid of spatial statistics including CoV, correlation coefficient, and the slope of a linear regression equation. The CoVs of UVB and total cloudy amount of each pixel were calculated over the US (Fig. 1 and 2). In each period, the areas with larger value of CoV show that the interannual variations of UVB and total cloud amount were significant in these areas. Conversely, the areas with smaller value of CoV show that the interannual variations of UVB and total cloud amount were not phenomenal in these areas.

The interannual variations of UVB in central and southern of Mountain region, West South Central region, and East Coast South Atlantic region with greater CoVs were significant (Fig. 3 and 4), yet, the interannual variations of UVB were weak in the Mountain region, Pacific-West region, West North Central region, and East North Central Northern region with smaller CoVs. Further, the interannual variations of total cloud amount were greater in Pacific-West region and Mountain region with larger CoV. The interannual variations of total cloud amount were not phenomenal in other regions with smaller CoV.
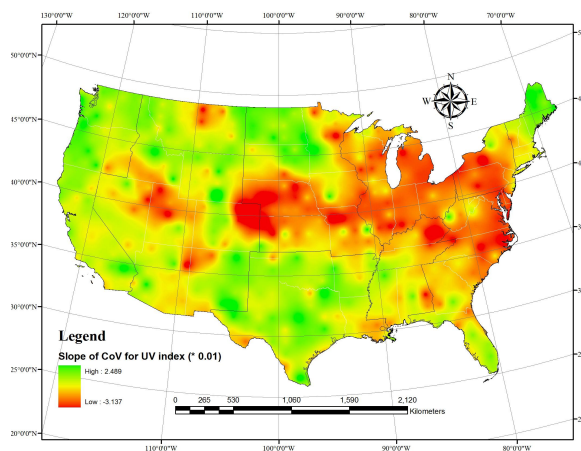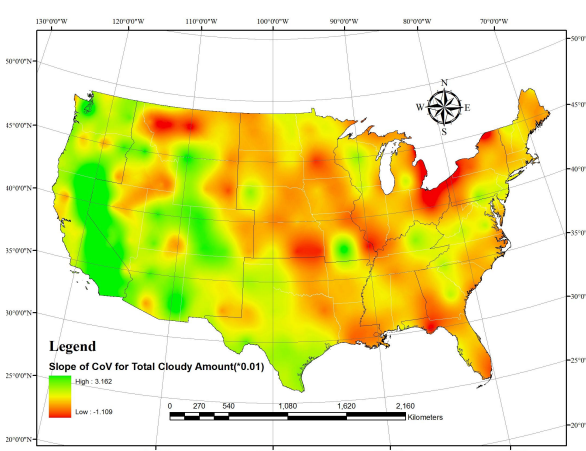
Fig. 3. Spatial slope of UVI.

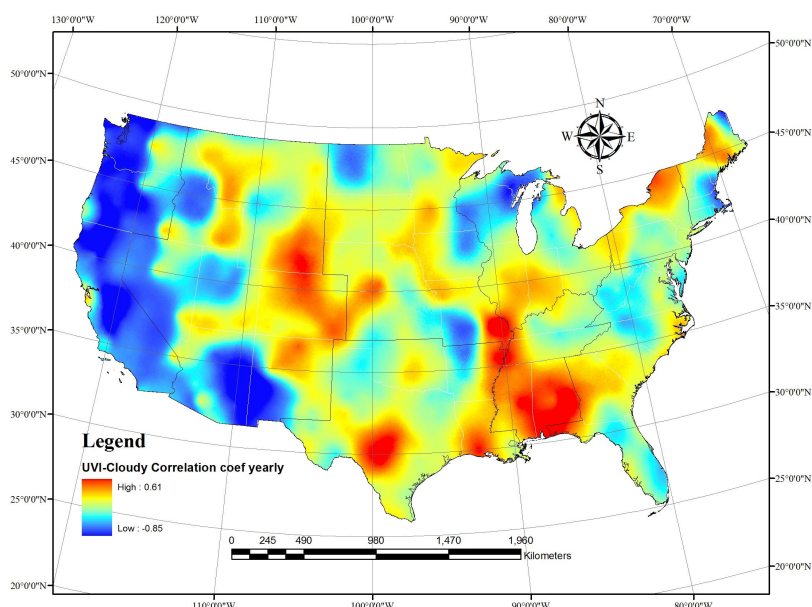Fig. 4. Spatial slope of
total cloud amount.

Fig. 5. The map of spatial correlation coefficients between UVI and total cloud amount.

The slope of a regression model between CoVs of each pixel associated with UVI or total cloud amount and time were calculated the US for further evaluation (Fig. 3 and Fig. 4). The areas with negative slope values show that the UVB or total cloud amount was simultaneously decreasing over time, whereas the areas with positive slope values show that the UVB or total cloud amount was simultaneously increasing over time. The negative slope of UVI CoV is located at the Mountain region, Pacific-West region, and West North Central region (Fig. 3 and 4), indicating that the UVB was decreasing over time in these regions, and the positive slope of total cloud amount CoV associated with some of the areas confirms that the total cloud amount was increasing over time. To further isolate these regions with such a high relevancy, the correlation coefficients between UVB and total cloud amount can be calculated (Fig. 5). The area with a correlation coefficient <0 is a negatively correlated area where the UVB decreases when the total cloud amount increases in this area. Thus, the impact of total cloud amount on UVB is significant in areas with greater negative correlation coefficients. The UVB was affected significantly by the total cloud amount in these regions of Pacific-West, Mountain, East North Central, and the north of East Coast (Fig. 5).

Based on the map of spatial correlation coefficients between UVI and total cloud amount (Fig. 5), these regions, such as Pacific-West region and Mountain region, were closely related with each other when both

aerosols and total cloud amount increased along with decreasing UVB. We can infer that although the reduction of total ozone led to the increase of UVB in most areas of the US, the increase of aerosols and total cloud amount also caused the reduction of UVB, especially in the Pacific-West Coast and Mountain regions.

4. CONCLUSIONS

Based on TOMS data and ISCCP long-term observations, this study carried out spatiotemporal analysis of UVI in relation to total ozone, total cloud amount, and AI via a GIS platform. Long-term analysis based on remote sensing shows that the culminating effect among three influential factors, namely total ozone, cloud amount, and aerosols, is salient. Although the UVB and total cloud amount were decreasing at the some local areas, the increasing trend of aerosols was offset by the decreasing trend of total ozone over the US within the same time frame. The northern areas with decreased UVB (the north of Pacific-West, the northern Mountain region, the north of West North Central, East North Central) were highly associated with areas of increased total cloud amount and AI. Overall, the trend characteristics of UVB over the US between 1980 and 2002 were mainly driven by the effects of total ozone variations combined with some auxiliary factors, such as aerosols and total cloud amount. The total ozone reduction led to the increasing tendency of UVB, as the increasing aerosols and the changes of total cloud amount resulted in the concurrent, collective fluctuations at the peak of the total ozone reduction. The ultimate offset determined the final value of UVB over space and time.

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