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The Effect of Ozone and Aerosols on the Surface Erythemal UV Radiation estimated from OMI Measurements

Joonsuk Lee[1,2], Won Jun Choi[1], Deok Rae Kim[1], Seung-Yeon Kim[1], Chang-Keun Song[1], Jun Suk Hong[1], Youdeog Hong[1], and Sukjo Lee[1]

[1]*Climate Change Research Division, National Institute of Environmental Research, Incheon, Korea*
[2]*Korea Institute of Atmospheric Prediction Systems, Seoul, Korea*

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Abstract: Surface erythemal UV radiation is mainly affected by total column ozone, aerosols, clouds, and solar zenith angle. The effect of ozone on the surface UV radiation has been explored many times in the previous studies due to the decrease of ozone layer. In this study, we calculated the effect of aerosols on the surface UV radiation as well as that of ozone using data acquired from Ozone Monitoring Instrument (OMI). First, ozone, aerosol optical depth (AOD), and surface erythemal UVB radiation measured from satellite are compared with those from ground measurements. The results showed that the comparison for ozone was good with r^2 of 0.92. For aerosol, there was difference between satellite measurements and surface measurements due to the insufficient information on aerosol in the retrieval algorithm. The r^2 for surface erythemal UV radiation was high (~0.94) but satellite measurements showed about 30% larger values than surface measurements on average by not considering the effect of absorbing aerosols in the retrieval process from satellite measurements. Radiative amplification factor (RAF) is used to access the effect of ozone and aerosol quantitatively. RAF for ozone was 0.97~1.49 with solar zenith angle. To evaluate the effect of aerosol on the surface UV radiation, only clear-sky pixel data were used and solar zenith angle and total column amount of ozone were fixed. Also, RAF for aerosol was assessed according to the single scattering albedo (SSA) of aerosols. The results showed that RAF for aerosol with smaller SSA (< 0.90) was larger than that for with larger SSA (> 0.90). The RAF for aerosol was 0.09~0.22 for the given conditions which was relatively small compared to that for ozone. However, considering the fact that aerosol optical depth can change largely in time and space while the total column amount of ozone does not change very much, it needs to include the effect of aerosol to predict the variations of surface UV radiation more correctly.

Key words: Surface erythemal UV radiation, total column ozone, aerosols, radiative amplification factor

1. Introduction

UV radiation reaching on the Earth's surface causes harmful effect on ecosystem including human, animal, and plants such as skin cancer, cataract, and DNA damage (Bruls *et al*., 1984; Diffey, 1992; Setlow *et al*., 1993; Bothwell, *et al*., 1994; IPCS 1994; WHO, 1994, 1995; Selgrade *et al*., 1997; Neale *et al*., 1998; Hader, 2000; Repacholi, 2000; Vanicek *et al*., 2000). Also, UV is very short wavelength radiation affecting thermal state of atmosphere by involving in various chemical reactions in the atmosphere (UNEP, 2010).

Increase of surface UV radiation due to the destruction of ozone layer has been examined extensively in numerous studies since ozone hole was found in the 1980s and the importance of ozone layer has been emphasized (e.g., McKenzie *et al.*, 1991; Kerr and McElory, 1993; Mims *et al*., 1995; Zerefos *et al*., 1995; McKenzie *et al.*, 1999; Kondratyev and Varotsos, 2000). Using accumulated satellite data from Total Ozone Mapping Spectrometer (TOMS), Solar Backscattered Ultra Violet (SBUV) series, SeaWiFS, and Ozone Monitoring Instrument (OMI), Herman (2010) analyzed that for clear-sky, surface UV radiation increased by 23% at 50°S and 9% at 50°N for 305 nm and 10% at 50°S and 4% at 50°N for 310 nm, respectively during the last three decades from 1979 to 2008.

UV radiation on the surface is also affected by various other factors such as solar zenith angle, clouds, surface albedo, aerosol, and elevation. Solar zenith angle is the main factor determining the amount of UV radiation reaching on the earth's surface. The effect of solar zenith angle can be calculated considering the position and movement of the sun and the earth.

Also, there have been many studies regarding not only the instant effect of cloud but also how the long-term variability of clouds can affect surface UV radiation (Frederick and Lubin, 1988; Bais *et al*., 1993; Madronich, 1993; McKenzie, R. L., 1998; Josefsson and Landelius, 2000; Lindfors and Arola, 2008). Generally, clouds reduce incident UV radiation by 20-30% through absorption and scattering processes in the clouds (McKenzie *et al*., 1991; Lubin *et al*., 1998; McKenzie *et al*., 1998). However, some studies showed that cloud can increase surface UV radiation when sky is partly covered by cumulus type clouds without obstruction of direct beam (Schafer *et al*., 1996; Sabburg *et al*., 2003). Nevertheless, exact quantification of cloud effects is still challenging due to high variability of clouds.

Aerosol which also varies irregularly in time and space also affect significantly on the surface UV radiation, possibly offsetting the increase of UV radiation due to the depletion of

Corresponding Author: Chang-Keun Song, Climate Change Research Division, National Institute of Environmental Research, Environmental Research Complex, Incheon 404-708, Korea.
E-mail: cksong@korea.kr

stratospheric ozone layer (Erlick and Frederick, 1998; Krotkov *et al*., 1998; Krzyscin and Puchalski, 1998; Seckmeyer, 2000). Acosta and Evans (2000) have shown that air pollution in Mexico City caused the decrease of surface UV radiation by 20%. Ilyas *et al*. (2001) also showed that noontime UV-B irradiance was reduced 23% during haze event due to forest fires in Indonesia compared to UV-B irradiance during non-haze period. Therefore, it is essential to correctly assess the effect of ozone or aerosol on the surface UV radiation to understand and predict the change of UV radiation at the surface.

The effect of ozone and aerosol on the surface UV radiation has been studied mainly using data obtained from surface measurements which have temporal and spatial limitations (Bais *et al*., 1993; Fioletov *et al*., 1997; Dubrovsky, 2000; Kim *et al*., 2008). With the development of satellite technologies, it is possible to cover whole global region without interruption in measurement time. In this study, total column ozone, aerosol optical depth, and surface erythemal UV radiation data obtained from Ozone Monitoring Instrument (OMI) are used to investigate the effect of ozone and aerosol on the surface UV radiation.

2. Data and methodology

a. Satellite data

OMI is a spectrometer on board National Aeronautics and Space Administration (NASA)'s Aura satellite measuring reflected and backscattered spectral radiance from 270 nm to 500 nm with a spectral resolution of about 0.5 nm to produce information on ozone, NO_2, SO_2, aerosol, HCHO, and surface UV radiation. Aura's equator crossing time is 1345 LST local time and OMI's cross track scanning width is 2600 km with spatial resolution of 13×24 km at nadir (Levelt *et al*., 2006). We used total column ozone, aerosol optical depth, and surface erythemal UV radiation from OMI for this study.

OMI provides total column ozone data processed by OMI-Total Ozone Mapping Spectrometer (TOMS) method (Bhartia *et al*., 2004; Bhartia, 2007) and OMI-Differential Optical Absorption Spectroscopy (DOAS) method (Veefkind *et al.*, 2006). OMI-TOMS algorithm produces TOMS-like ozone data for the continuation of long term ozone observation since 1978. OMI-DOAS method is developed by Koninklijk Nederlands Meteorologisch Instituut (KNMI) utilizing the advantage of hyperspectral radiance measurement of OMI. OMI-TOMS uses radiance at two wavelength to retrieve total column ozone, while OMI-DOAS uses absorption characteristics of narrow band in the UV and visible (Rosanov and Rosanov, 2010 and references therein). Total column ozone retrieved by both methods showed good agreement within 2% compared to ground measurements or airborne measurements (Balis *et al*., 2006; Kroon *et al*., 2008).

OMI also provides two types of aerosol information. One is OMI near-UV (OMAERUV) method which uses radiance at 354 and 388 nm to produce UV aerosol index (UVAI), aerosol extinction optical depth (AOD), single scattering albedo (SSA) and aerosol absorption optical depth (AAOD) at 354, 388, and 500 nm. The other is OMI multiwavelength algorithm (OMAERO) which uses 19 spectral radiances between 330 nm to 500 nm to retrieve aerosol optical depth, aerosol type, and aerosol absorption indices. The OMAERUV method is useful in retrieving aerosol properties due to the fact that the surface reflectance at near-UV is small compared to reflectance at visible or near-IR spectral region so that the effect from the surface is minimized. Aerosol properties from OMAERUV method are calculated by a standard inversion technique utilizing pre-calculated look-up table of reflectance. Three major aerosol types originated from desert dust, biomass burning, and industrial and seven models for each aerosol type with different optical and physical properties including single scattering albedo, particle size distribution, and aerosol layer height are considered in the calculation of reflectance. Aerosol optical depth and single scattering albedo are retrieved from the pre-calculated look-up table considering the ratio of reflectance between 354 and 388 nm and reflectance at 388 nm. The OMAERO method retrieves aerosol information by minimizing the difference between the measured spectral reflectance and pre-calculated spectral reflectance. Spectral reflectance is pre-calculated considering possible combinations of aerosol optical depth, aerosol type, size distribution, single scattering albedo, height of aerosol layer, and surface reflectance. Those aerosol properties used in the modeling simulation which best fit the measured spectral reflectance are provided as the OMAERO products. Due to the uncertainties of aerosol optical and physical properties used in the calculation of reflectance, the accuracy of OMI SSA is about 0.1 (Torres *et al*., 2002). Liu and Hong (2012) compared the SSA from OMI with that from AERONET and found that OMI SSA is 3.5% higher than AERONET SSA globally with good relationship in seasonal variation between them despite the daily discrepancy due to the uncertainties. The detail description of each retrieval algorithm can be found in Torres *et al*. (2007), Ahn *et al*. (2008), and references therein. We used AOD at 388 nm from OMI OMAERUV method to compare with surface measurements and AOD at 354 nm to estimate the effect of aerosol on the surface UV radiation.

Surface UV products from OMI (OMUVB) includes spectral UV irradiances at 305, 310, 324, and 380 nm, erythemal UV rate at local solar noontime, and daily erythemal UV dose. First, clear sky surface spectral UV irradiance is calculated by radiative transfer model using total column ozone and other parameters measured from OMI and climatological surface albedo information (Tanskanen, 2004). Then, clear sky irradiance is corrected for the effect of clouds and non-absorbing aerosols by multiplying cloud modification factor which can be estimated by comparing measured OMI spectral radiance with precalculated lookup tables. However, it should be noted that OMI provides UV products for local solar noontime value while actual OMI measurement time is around 1:45 pm. The

variation of total column ozone and cloud with time is not considered for the conversion between those two time steps (Tanskanen *et al*., 2007; Torres *et al*., 2007 and references therein), which can introduce an additional error source.

b. Surface measurement data

Surface ozone and erythemal UV radiation data measured at Yonsei University, Seoul, Korea (37.57°N, 126.98°E) and aerosol optical depth data from Aerosol Robotic Network (AERONET) site at Anmyoundo (36.53°N, 126.32°E), Korea were used for the comparison with satellite observations. Yonsei University has been monitoring total column ozone over Seoul, Korea from 1984 using Dobson spectrophotometer (#124) and is registered as a World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) Global Ozone Observing System (GO3OS) station (#252). Dobson spectrophotometer is a standard instrument for measuring total column ozone at the surface and about 100 instruments are deployed worldwide. Dobson measures ozone using two pairs of wavelengths to remove the effect of aerosol on the retrieval of total column ozone (Basher, 1982). One wavelength in each pair is strongly absorbed by ozone and the other weakly affected by ozone. Total column ozone is estimated from the difference of intensity at those two wavelengths.

Surface UV radiation is measured by UV-B Biometer (Solar Light Model 501) which has a spectral response very similar to erythema action spectrum. Photobiological effect of UV radiation varies with spectrum so that spectral UV radiation reaching at the surface are multiplied by action spectrum to assess each different biological effect of UV radiation. There are several action spectra such as erythema action spectrum (McKinlay and Diffey, 1987), DNA to protein cross links (Peak and Peak, 1986), DNA breaks (Peak *et al*., 1987), polychromatic action spectrum (Caldwell *et al*., 1986), phytoplankton photoinhibition (Mitchell, 1990), and typhimurium killing (MacKay *et al*., 1976) depending on each different biological effect of UV radiation.

Erythema action spectrum weighting is applied to the UV spectral radiation to assess the effect of UV induced erythema on human skin. Erythemal UV radiation (EUV) is calculated by integrating spectral UV irradiance multiplied by erythema action spectrum from 280 to 320 nm as follows (McKinlay and Diffey, 1987)

$$EUV = \int_{280nm}^{320nm} I(\lambda)W(\lambda)d\lambda \quad (1)$$

Where $I(\lambda)$ is spectral UV radiation in $mWm^{-2}nm^{-1}$ and $W(\lambda)$ is erythema action spectrum. Erythemally weighted UV radiation can be converted to UV index if EUV at noontime is divided by 25 mWm^{-2}, which was originally proposed by Canadian Atmopheric Environment Service (AES) and became international standard by World Meteorological Organization (WMO) in scaling the intensity of UV radiation.

Surface aerosol optical depth (AOD) data are obtained from Anmyoundo which is one of Aerosol Robotic Network (AERONET) organized by NASA Goddard Space Flight Center to examine global characteristics of aerosols. AODs at AERONET are measured at 340, 380, 440, 500, 670, 870, 940, 1040 nm using Cimel sunphotometer (Holben *et al*., 1998). We used AOD at 380 nm from AERONET at Anmyoundo for this study.

c. Radiation amplification factor

The effect of ozone and aerosol on the surface UV erythemal radiation is commonly estimated by Radiation Amplification Factor (RAF) proposed by *Madronich* (1993). RAF is defined as

$$RAF = -\frac{\frac{\Delta F}{F}}{\frac{\Delta X}{X}} \quad (2)$$

where, F is surface UV radiation and X is a variable which affects the surface UV radiation such as ozone or aerosol. RAF represents the percentage change of UV radiation caused by 1% change of ozone or aerosol when other factors which affect UV are assumed to be same. Eq. (2) an be rearranged as

$$F = aX^{-RAF} \quad (3)$$

RAF is a useful variable to estimate the effect of ozone or aerosol on the surface UV radiation but it should be noted that RAF can be useful only for the small amount of change around the mean value of ozone or aerosol because surface UV radiation varies nonlinearly or exponentially with the change of ozone or aerosol.

The assessment of ozone effect on surface UV in terms of RAF has been done in many previous studies using surface measurement or model simulation. Madronich *et al*. (1998) have provided RAF values for various action spectra obtained from model simulation and Micheletti *et al*. (2003) have simulated sensitivity of biologically active UV radiation to stratospheric ozone change and calculated RAF values for various ozone amounts and solar zenith angle. Also, they emphasized that the use of action spectrum and corresponding RAF is a very useful method to estimate the biological effect of increased surface UV radiation due to the decrease of total column ozone. In this study, RAF on the surface UV radiation by ozone and aerosol was calculated using Eq. (3).

3. Results

Figure 1a shows the comparison between satellite measurements and surface measurements for ozone for the measurement period from 2005 to 2006 for clear-sky conditions (OMI cloud fraction < 0.2). Total column ozone data from OMI within ± 0.5° of ground site (Yonsei University) were averaged for the comparison. Satellite measurement and surface measurement showed relatively good relationship with r^2 of 0.92. However, it should be noted that surface measurement for

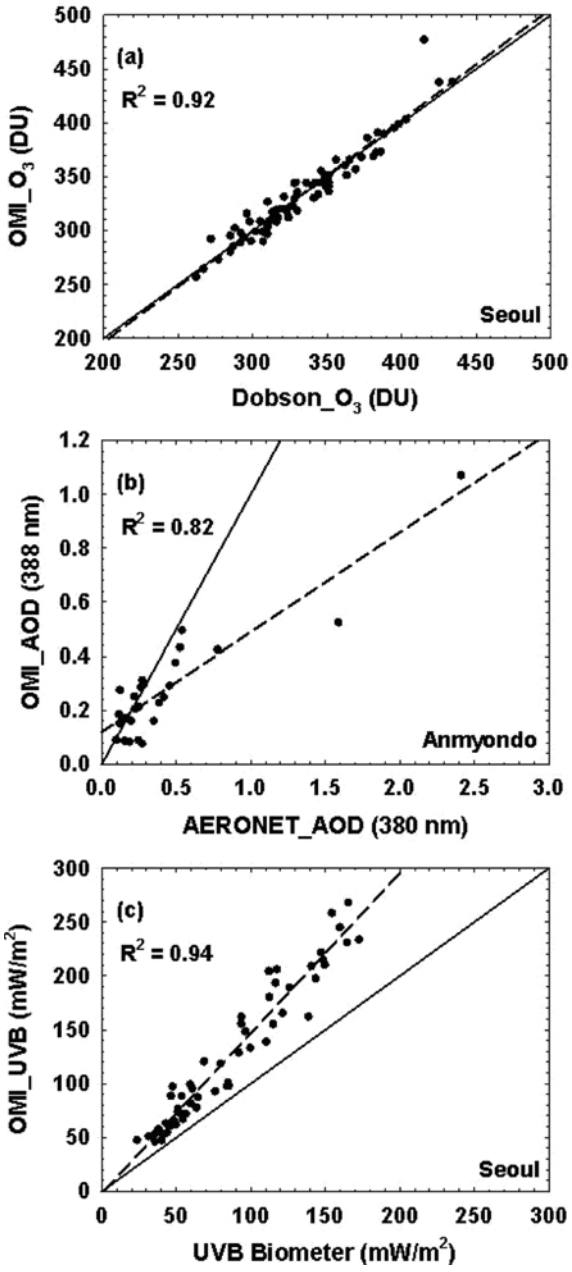

Fig. 1. The comparison between OMI measurements and surface measurements for (a) total column ozone, (b) aerosol optical depth, (c) surface erythemal UVB radiation. Dashed line represents linear regression line and solid line is one-to-one line.

ozone is done at solar zenith angle of 60° and OMI measures ozone 1345 LST. There is difference in measurement time between surface and satellite measurement because the time of SZA 60° changes every day. However, those two measurements showed similar results because daily total column amount of ozone does not vary much in such short period time unless there is sudden chemical reactions or transport.

The relationship between surface and satellite measurements for AOD is not as good as ozone as seen in Fig. 1b. Here, AOD at 380 nm from Anmyondo and AOD at 388 nm from OMI were compared for the measurement period from January 2006 to May 2007. Available AERONET AOD data within ± 30 minute of 1345 LST were averaged, whereas OMI AOD data within ± 0.5° of Anmyond were averaged for the collocation between two data sets. Many previous studies pointed out that OMI aerosol optical depth retrieval algorithm has some limitations because AOD is not directly retrieved from the measurements but it is retrieved indirectly from the simulation using aerosol properties as input data such as aerosol type, shape, and size distribution and those information cannot be obtained independently (Torres *et al*., 2007; Livingston *et al*., 2009). AOD from satellite measurements underestimated that from surface. However, if three largest AOD from surface measurements are excluded, the r^2 decreases ($r^2 = 0.53$) but the regression line becomes closer to one-to-one line (not shown here). Christopher *et al*. (2011) pointed out that AOD from satellite measurements showed good relationship with AERONET surface measurements. However, satellite AOD underestimates airborne measurement for high AOD (AOD > 1), while matches well with for low AOD case. Further analysis is needed to assess and verify these differences. In this study, we could not verify it clearly due to the lack of data.

Figure 1c shows the comparison for surface erythemal UVB radiation for clear-sky. For the collocation of data, UV data from UV-Biometer within ± 10 minute of local solar noontime were averaged and OMI UV data within ± 0.5° of Yonsei University were averaged for the comparison for the measurement period from September 2006 to May 2007. To assure data quality, we used UV-Biometer data from September 2006 after the calibration was done in August 2006. The surface data were recalculated as the value at the mean Sun-Earth distance to consider the seasonal variation of Sun-Earth distance. The result shows that the relationship is very high ($r^2 = 0.94$) between two types of measurements but OMI overestimates surface measurement about 30% on average. Other comparison studies also showed this tendency and pointed out that the disparity came from the lack of absorbing aerosol effect in retrieving surface UV radiation from OMI (Tanskanen *et al*., 2007; Ialongo *et al*., 2008; Kazadzis *et al*., 2009; Buntoung and Webb, 2010). Also, OMI UV radiation is a noon value converted from overpass measurement around 1345 LST. When OMI UV is converted to noon value, additional error can arise by using the same cloud conditions between measurement time and noontime in the numerical model simulation. However, the correction of OMI erythemal UV radiation is beyond the scope of this study.

Figure 2 shows the effect of ozone on the surface erythemal UVB radiation by RAF from Eq. (3). Clear-sky data from June 2005 to May 2007 over the whole global region are used for the analysis. To remove solar zenith angle effect, those data with solar zenith angle within ± 0.25° are chosen at 20°, 30°, 40°, and 50° of SZA. RAF for ozone varies from 0.97 to 1.49 with SZA, showing RAF decreases with increasing SZA. The result is comparable with other studies which estimated ozone RAF as 1.0~1.7 (Madronich *et al*., 1998; Micheletti *et al*.,

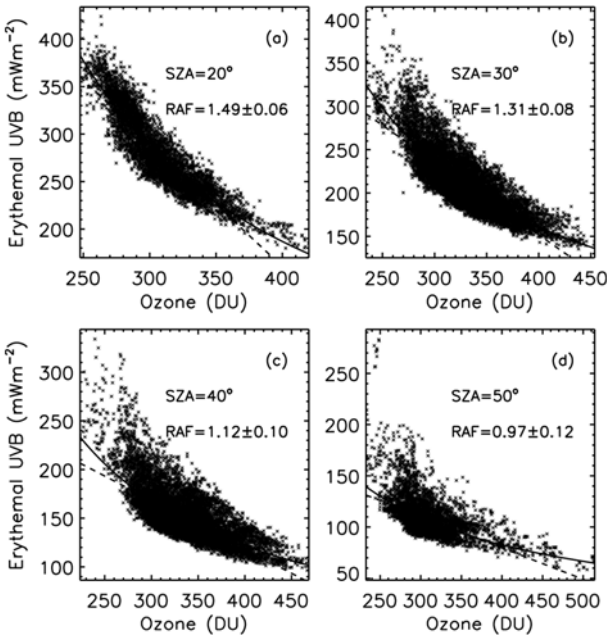

Fig. 2. The relationship between total column ozone and surface erythemal UVB radiation for solar zenith angle at (a) 20°, (b) 30°, (c) 40°, and (d) 50°, respectively. Solid line represents power fit for RAF and dashed line is a linear regression line. Note that the scales of x and y axis are different for each figure.

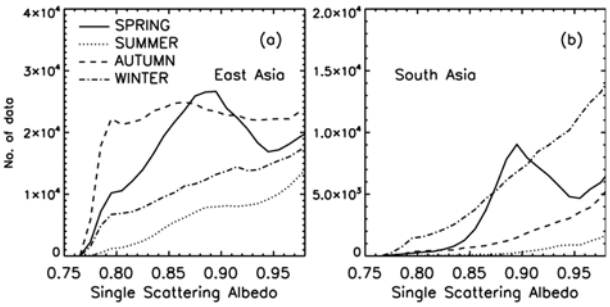

Fig. 3. Histogram of single scattering albedo at (a) East Asia and (b) South Asia. Note that the scales of y axis are different for each figure.

2003; Herman, 2010). Micheletti *et al*. (2003) explained that RAF for erythema action spectrum decreases with increasing SZA because the absorption at shorter wavelength ($\lambda < 320$ nm) increases as the photon path length increases so that the importance of irradiance at longer wavelength becomes larger. However, erythemal UV radiation at longer wavelength is less affected by total column ozone change by the characteristics of erythema action spectrum which decreases sharply after 310 nm.

Figure 3 shows the histogram of single scattering albedo (SSA) over Asia region. We used OMI aerosol data of which "Algorithm flag" in OMAERUV is 0 to minimize cloud contamination in the retrieval process. SSA is a very important factor which determines optical properties of particles. Absorbing aerosols such as desert dust or carbonaceous aerosols have small SSA, while non-absorbing aerosols such as sulfates, nitrates, and sea-salt have large SSA. Largely, Asia is mainly

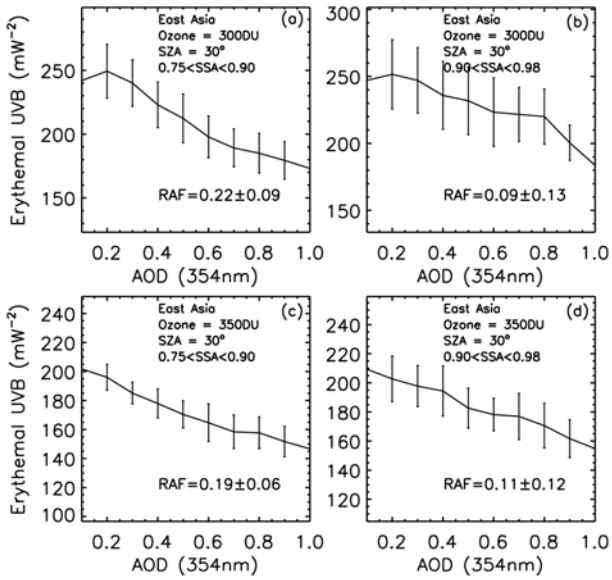

Fig. 4. Relationship of aerosol optical depth and surface erythemal UVB radiation under each different condition. Error bar represents one standard deviation on either side of mean value. Note that the scales of y axis are different for each figure.

influenced by non-absorbing aerosols. In East Asia (100-140°E, 30-50°N), nob-absorbing aerosols are dominant in summer and winter and absorbing aerosols in spring due to desert dust and pollution (Fig. 3a). Distribution in South Asia (90-125°E, 10°S-25°N) shows similar pattern with that in East Asia but the increased number of absorbing aerosols in spring season mainly comes from the effect of biomass burning (Fig. 3b).

Figure 4 shows the effect of aerosol on the surface UVB radiation. In this case, SZA is fixed at $30° \pm 0.25°$ and total column ozone is fixed at 300 ± 2.5 DU and 350 ± 2.5 DU to remove the effect of SZA and ozone on the surface UV radiation. Effect of cloud is also removed by using only clear-sky data (OMI cloud fraction < 0.2). To account for the effect of absorbing aerosol, surface erythermal UV radiation was adjusted following the method suggested by Krotkov *et al.* (2005). OMI UV product was corrected by multiplying a correction factor f defined as

$$\tau_{abs} = \tau_{aer}(1-\omega) \tag{4}$$

$$f = \frac{1}{1+a\,\tau_{abs}} \tag{5}$$

where ω is the aerosol single scattering albedo, τ_{aer} is the aerosol optical depth, τ_{abs} is the aerosol absorption optical depth, and $a = 3$.

The RAF for aerosol is calculated according to SSA to assess the effect of aerosol depending on the optical properties of aerosols. The RAF for aerosol varies between 0.09~0.22 under given conditions. Kim *et al*. (2008) showed that RAF for aerosol is about 0.20 and Krzyscin (2004) estimated that aerosol RAF is about 0.10. The result shows that RAF for aerosol is larger when SSA is small, that is absorbing aerosol has larger

effect on the reduction of surface erythemal UV radiation than non-absorbing aerosol does. For non-absorbing aerosols, more radiation can reach at the surface by forward scattering and multiple scattering processes, while radiation is reduced as much as absorbed if absorbing aerosols dominate. It should be noted that RAF for aerosol from this study is better to understand as qualitatively rather than quantitatively due to the uncertainties and limitations in aerosol and surface erythemal UV radiation retrieved from OMI. Although RAF for aerosol is small compared to that for ozone, the effect of aerosol properties including AOD and SSA on the surface UV radiation should be considered for the better understanding and prediction of surface UV changes especially in those regions where pollution is high or aerosol properties can change suddenly due to dust storm, biomass burning, wildfire, or volcanoes.

4. Conclusions

The concern for increasing surface UV radiation due to destruction of ozone layer has been increased since ozone hole was found in 1980's because UV radiation is known to affect earth's system in various ways such as involving in chemical reactions, changing biological processes, and affecting biogeochemical cycles. Surface UV radiation can be affected by many factors such as solar zenith angle, clouds, total column ozone, aerosols, and surface reflectivity, etc. In this study, we compared satellite measurements with surface measurements for total column ozone, AOD, and surface erythemal UV radiation and evaluated the effect of ozone and aerosol on the surface erythemal UV radiation. The comparison showed relatively good relationship between them for total column ozone despite the difference in measurement time. There is difference in AOD due to the insufficient information for aerosol characteristics in the retrieval algorithm of AOD. Two measurements showed relatively good relationship for low AOD, whereas OMI underestimated surface measurement for high AOD values. Surface erythemal UV radiation measured by OMI was larger than surface measurement by 30% on average for clear-sky conditions in mega-city, Seoul because the effect of excessive absorbing aerosol in the lower atmosphere is not included in the surface UV retrieval algorithm.

The effect of ozone and AOD on surface UV is assessed based on RAF calculation. RAF for ozone is 0.97~1.49 depending on SZA and that for aerosol is 0.09~0.22 at SZA of 30^{o} and total column of ozone of 300 DU and 350 DU. Also, it was found that absorbing aerosols have larger effect on the surface UV radiation than non-absorbing aerosols. RAF for aerosol is small compared to that for ozone but AOD can vary very large in short period time. Also, aerosol can affect surface UV radiation in heavily loaded region by pollution, biomass burning, desert dust storm, and volcanic activities, etc. Thus, it is essential to consider the effect of aerosol as well as ozone on the surface UV radiation to correctly estimate or predict surface erythemal UV radiation.

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