Cloud and aerosol contributions to variation in shortwave surface irradiance over East Asia in July during 2001 and 2007

Kazuaki Kawamoto¹ and Tadahiro Hayasaka²

1 Faculty of Environmental Studies, Nagasaki University, Nagasaki, Japan

2 Graduate School of Science, Tohoku University, Sendai, Japan

Abstract

It is important to clarify the contributions of clouds and aerosols to the variation of surface shortwave irradiance (S) for climatological studies. This study examined the contributions of clouds and aerosols to the variation in S over East Asia (75°E – 135°E , 20°N – 55°N) in July during 2001 and 2007 using the index of potential radiative forcing (PRF) to characterize the temporal and geographical variation. After confirming the validity of PRF for multiyear analyses, we performed several temporal analyses of clouds and aerosols over the whole research domain. Changes in the geographical distribution, contribution histograms, and averaged values were studied. In agreement with previous studies that treated single-year cases, we confirmed that the magnitudes of the temporal changes in S variations due to clouds and aerosols were highly variable geographically. As for domain-averaged S variations, we did not observe defined trends for the research period. It was also found that the temporal variation between one parameter and its S variation was negatively correlated, from the point analyses at two locations. Based on these results, we concluded that PRF is a promising tool for research into long-term S variations. This kind of information will be quite valuable as basic data for use in climate modeling.

Key words: shortwave irradiance; radiation budget; cloud; aerosol; East Asia

1. Introduction

Shortwave irradiance at the surface (S) represents energy input to the Earth and determines atmospheric and oceanic dynamics and temperature. Moreover, S largely governs surface processes, such as evaporation and associated hydrological components, including snow and glacier melt, and plant photosynthesis [1], and is modulated by various atmospheric and surface parameters. For example, Mallet *et al.* [2] evaluated the impact of dust aerosols on the radiative budget, surface heat flux, and other parameters over West Africa. The solar dimming and brightening phenomenon has also received a great deal of attention [3] and has been investigated actively for various locations worldwide. Riihimaki *et al.* [4] studied the contribution of aerosols to the direct irradiance in Oregon, USA, for almost three decades. Sanchez-Lorenzo *et al.* [5] have tried to relate dimming/brightening to sunshine duration, cloud cover, and atmospheric dynamics over the Iberian Peninsula for more than four decades.

Therefore, it is important to quantify how individual atmospheric parameters such as clouds, aerosols, and water vapor contribute to variation in S . However, few studies have estimated the contributions of each parameter. For this purpose, Kawamoto and Hayasaka [6] (hereafter KH08) defined an index of potential radiative forcing (PRF) as a measure of the sensitivity of S to differential increases from given values of atmospheric parameters, such as the cloud optical depth (τ_c), cloud amount (A_c), aerosol optical depth (τ_a), and precipitable water (w). The expected change in S due to one parameter is obtained as the product of PRF and the change in that parameter.

Subsequently, Kawamoto and Hayasaka [7] (hereafter KH10) described the geographic features of PRF over East Asia.

Time series, especially over long terms, are critical for climatological studies. We calculated the contributions of clouds and aerosols to the variation in surface shortwave irradiance (S) in July during 2001 and 2007 (a 6-year period) using potential radiative forcing (PRF). Hereafter, July during 2001 and 2007 is called the research period. Gridded satellite products of cloud and aerosol properties are available for this research period. Clarifying the mechanisms of changes in atmospheric parameters, which are deeply connected to large-scale dynamics, was beyond the scope of this study. Instead, we focused on the detailed temporal behavior of cloud and aerosol contributions to S variations.

Section 2 briefly describes the derivation and characteristics of PRF, along with the data used in this study. Section 3 presents and discusses the results of the several temporal analyses. The conclusions are summarized in Section 4.

2. Derivation and characteristics of PRF

Surface shortwave irradiance (0.2-5 μm is adopted here) of the target point is determined by various atmospheric and surface parameters such as clouds, aerosols, water vapor and the ground albedo, according to the solar incidence. We consider that S is formulated for a non-reflecting surface as follows:

$$S = S_0 [(1 - A_c)T_a + A_c T_c] , \quad (1)$$

where S_0 is the incident solar irradiance at the top of the atmosphere, which varies with the season and latitude corresponding to the Earth's orbit and solar activity, and T_a and T_c are transmittances under cloud-free- and cloudy-sky conditions, respectively. The

cloud-free-sky is defined as a condition with aerosols, water vapor and no clouds. The total cloud amount A_c is defined as the fraction occupied by cloudiness. The differential of Eq. (1) is obtained in the following equation:

$$\Delta S = S_0 [(1 - A_c) \Delta T_a + A_c \Delta T_c + (T_c - T_a) \Delta A_c] . \quad (2)$$

The Equation (2) means cloud-free and cloudy factors do not independently affect the change in S . The sensitivities of S to differential change of each parameter which were defined as the potential radiative forcing (PRF), and are expressed as below:

$$\frac{\partial S}{\partial \tau_c} = S_0 A_c \frac{\partial T_c}{\partial \tau_c} , \quad (3)$$

$$\frac{\partial S}{\partial \tau_a} = S_0 \left[(1 - A_c) \frac{\partial T_a}{\partial \tau_a} + A_c \frac{\partial T_c}{\partial \tau_a} \right] , \quad (4)$$

$$\frac{\partial S}{\partial w} = S_0 \left[(1 - A_c) \frac{\partial T_a}{\partial w} + A_c \frac{\partial T_c}{\partial w} \right] , \quad (5)$$

$$\frac{\partial S}{\partial A_c} = S_0 (T_c - T_a) . \quad (6)$$

From the terms of these equations, we understand that PRFs due to aerosols and water vapor have influence both clear and cloudy conditions, and PRF due to cloud amount is expressed by the difference between cloudy and clear transmittance. Then the expected change in S due to one parameter is obtained as the product of PRF and the change in that parameter. PRFs are calculated by the unit optical depth for τ_c and τ_a , 1% for A_c , and 1 mm for w . As evident from the above equations, the PRFs depend on a combination of the values of the parameters and S_0 according to A_c . The value of PRF is always negative and becomes stronger (i.e., has a stronger influence on S) when the values of the atmospheric parameters are small and S_0 is large. Here, ‘strong’ and ‘weak’ denote ‘large (more negative)’ and ‘small (less negative)’ of absolute values of PRFs.

For all the calculations in this study, we used a general radiative transfer package, *RSTAR-5b*, which solves the detailed radiative transfer with a combined discrete-ordinate/matrix-operator method [8] [9] with Lowtran-7 gas absorption model [10].

To calculate PRFs, following datasets were used as input for τ_c at visible wavelength, A_c and w from International Satellite Cloud Climatology Project (ISCCP) datasets [11], τ_a at 0.55 μm from Moderate Resolution Imaging Spectroradiometer (MODIS) products [12]. Values of T_a and T_c were calculated with changing τ_c , τ_a and w using this radiation package, and then PRFs were obtained together with A_c as formulated in eqs. (3)-(6). As for other minor constituents such as ozone, carbon dioxide and methane, we used their climatology in radiative transfer calculations, but did not investigate the effects of their changes on S in this study. The ISCCP-derived ground albedo datasets [11] were utilized in our actual PRF calculations, although equations (1) to (6) assumed a non-reflecting surface for simplicity. Other detailed description on PRF was given in KH08. The research domain was some parts (75°E–135°E, 20°N–55°N) over East Asia with 2.5° spatial resolution, following KH08 and KH10. Data sources of clouds and aerosols were the same as ones we used in calculating PRFs.

3. Results and Discussion

In this section we discuss the temporal behavior of variation in S (hereafter dS) obtained by multiplying the difference in the parameter by PRF. First, the summation of dS due to τ_c , A_c , τ_a , and w with PRF is compared with the value of dS obtained from ISCCP products over 3 years to examine the validity of PRF for multiyear use. Then, several temporal analyses of dS due to τ_c , A_c , and τ_a are performed over the whole

research domain using geographical distributions, histograms, and averaged values. Finally, the values of dS due to τ_c , A_c , and τ_a are contrasted temporally using τ_c , A_c , and τ_a at two points in central and southeastern China.

3.1 Validation of multiyear analyses using PRF

To examine the validity of multiyear analyses obtained using PRF, the summation of dS due to τ_c , A_c , τ_a , and w with PRF and corresponding values from the ISCCP S products were compared. Because the ISCCP S and w products were available only until December 2004, Figure 1 shows a scatter plot of the dS values between the PRF-derived and ISCCP products in July during 2001 and 2004. A fitted equation (dotted line) is also shown. A total of 1008 samples were analyzed (24 points in the longitudinal direction, 14 points in the latitudinal direction, measured over 3 years). The slope and intercept of the equation were 0.85 and 1.89, respectively. The dS values obtained using the PRF showed reasonable agreement with the ISCCP-derived values, with a correlation coefficient (r) of 0.81. This means that the PRF method can be used for multiyear analysis.

The aerosol absorption property is represented by the imaginary part (k_i) of the refractive index. For simplicity, KH08 and KH10 fixed k_i at a single value (*e.g.*, 0.05 and 0.002) in their analyses. However, KH08 noted that the determination of k_i was crucial for the quantitative evaluation of S and that incorporating the more realistic aerosol absorptivity in creating PRF was an emergent task. Numerical model simulations calculated that the aerosol single-scattering albedo ranges from 0.92 to 0.97 (*ca.* 0.014 to 0.005, respectively, for k_i) over East Asia [13]. Therefore, the PRF was calculated using more realistic values from the above model instead of fixing an

assumed value in this study. Applying three types of aerosol absorptivity ($k_i = 0.02$, 0.005 , and model outputs) to the dS calculations, we confirmed that using PRF from the model outputs would not always bring results closer to dS values from ISCCP products than using PRF of fixed k_i values. Several reasons help to explain for this discrepancy: the model-computed aerosol absorptivity may have some bias; no climatic feedback mechanisms, such as aerosol indirect effects, were considered in formulating PRF; and other unidentified phenomena likely exist.

3.2 Temporal and spatial behavior of dS due to clouds and aerosols

Cloud products from the ISCCP are available from July 1983 to December 2007, and MODIS aerosol products, such as the optical depth and particle size index, are available from February 2000 onward. To examine the roles of both clouds and aerosols, we adopted a research period of July during 2001 and 2007, when gridded satellite products were available. As we noted earlier, in the present study, we did not attempt to investigate the mechanisms behind the variations in aerosol and cloud distributions.

Figures 2, 3, and 4 show the geographical distributions of dS due to τ_c , A_c , and τ_a in the research period, respectively. We divided the entire research period into 1-year periods, such as 2001 to 2002 as period 1, 2002 to 2003 as period 2, and 2006 to 2007 as period 6. Consequently, (a), (b), (c), (d), (e), and (f) in the figures correspond to periods 1, 2, 3, 4, 5, and 6, respectively. Positive changes in dS due to one parameter were basically caused by negative changes of that parameter, as KH08 noted.

Below, we briefly summarize the temporal characteristics of geographical distributions for dS by giving examples of remarkably variable areas. Note that the scales differ for the variables. For dS due to τ_c (Fig. 2), the examples given are

northeastern India, southern China, Tibet, the East China Sea including the Korean Peninsula, and Japan. During period 4, dS was generally small compared to other periods, except for a single remarkable decrease (about -10 W m^{-2}) over northeastern India. For the dS due to A_c (Fig. 3), middle China, the area from southern China to Taiwan, the East China Sea, and Mongolia are given as examples. Compared to other parameters, the A_c case had the most variation in both absolute and geographic terms. Judging from the geographical features, there was some linkage between dS due to τ_c and A_c . For the dS due to τ_a (Fig. 4), the examples are middle China, northeastern India, Lake Baikal to eastern Mongol, northeastern China, and some parts of northwestern China. Weakly variable regions can be seen over the East China Sea. Although the direct effect of anthropogenic aerosols would influence dS [4], natural aerosols such as yellow dust particles would not significantly contribute to dS in July. Yellow dust particles are dominant mostly in springtime [2].

3.3 Differences in histograms of dS due to clouds and aerosols in the research domain

To show annual differences in the dS distributions more clearly, we produced histograms of dS due to τ_c , A_c , and τ_a during the research period (Fig. 5(i), (ii), and (iii), respectively). From Fig. 5(i), the width of dS was approximately in the range of $\pm 20 \text{ (W m}^{-2}\text{)}$. Relatively large positive values were found in the first three periods, particularly the second period. Among the three factors, the A_c case was the least sharp near the 0 point. This meant that dS values due to A_c were more variable compared to those in the other cases. Although the dS values were within $\pm 40 \text{ W m}^{-2}$ in most cases, some reached as strong as $\pm 60 \text{ W m}^{-2}$. From Fig. 5(i–iii), it was found that the dS due to A_c was the

largest, while that due to τ_c was the smallest over this research domain. This was generally caused by larger variations of A_c during the research period.

3.4 Temporal changes of averaged dS over the domain and of dS and parameters at two points

To illustrate the overall situation, temporal changes of domain-averaged dS due to τ_c , A_c , and τ_a are shown in Fig. 6 alongside the standard deviations. As can be seen, defined trends in dS due to any parameters were not observed for this period and domain. The amplitudes of dS were -1.5 to 2.5 , -5.5 to 2.7 , and -3.6 to 4.0 for τ_c , A_c , and τ_a , respectively, and standard deviations were approximately five times larger than the averaged values in most cases.

Finally, two cases of the point analysis are given at central (105°E , 35°N) and southeastern (118°E , 28°N) China in Figs 7 and 8. Figure 7(a) presents time series of dS due to τ_c , A_c , and τ_a at central China during the research period. Note that the scales differ for the variables. As shown in the figure, the amplitudes of dS due to τ_c and τ_a (-4 to 4 W m^{-2}) were smaller than those due to A_c (-20 to 20 W m^{-2}). Figure 7(b) shows time series of τ_c , A_c , and τ_a at the same point and period; again, the scales differ in each case. On the other hand, Figures 8(a) and (b) are the same as Figs 7(a) and (b), respectively, except southeastern China. Maximum values of dS due to τ_c and τ_a in Fig. 8(a) were much greater than those in Fig. 7(a). In particular, variation of τ_a in Fig. 8(b) was greater by several times than that in Fig. 7(b). From these two cases, we observe that, for instance, the variation between τ_c and dS due to τ_c was temporally coincident and opposite, as noted earlier. Nevertheless, the contribution was determined by a

combination of other relevant parameters and behaved nonlinearly. As dS shows fairly diverse temporal and geographic variations, it is meaningful to calculate the contribution of each atmospheric parameter to dS using PRF.

4. Conclusions and Overview

To characterize the temporal and geographical features of dS over East Asia in July during 2001 and 2007, several time-series analyses were conducted using PRF. First, the validity of PRF for multiyear analyses was confirmed by comparing the PRF method and ISCCP S products. Realistic aerosol absorptivity values from the numerical model were used to calculate PRF instead of an assumed fixed value (k_i). However, compared to the PRF using fixed k_i values, the PRF using model-output values did not always give results closer to the dS values from the ISCCP products. Despite the reasons given for these differences, more work is needed to reconcile these estimates.

Several temporal methods were applied over the whole research domain, including use of the geographical distribution, contribution histograms and averaged values. The geographical distributions of dS due to each parameter were illustrated for the research period, and remarkably variable areas were noted. The dS relationship between τ_c and A_c was implicated geographically. Together with the indirect effects of aerosols, it is important to connect these three parameters. Domain-averaged values, defined trends in dS due to any parameters were not observed for the research period.

Variation in the cloud and aerosol parameters was contrasted with dS from the point analysis in central and southeastern China. The analysis confirmed that the variation between a single parameter and dS due to that parameter was coincident and basically opposite, as pointed out by KH08. The contribution behaved nonlinearly and was

determined by a combination of other relevant parameters. These findings demonstrate that PRF is a promising tool for long-term analyses of dS and can provide valuable basic data for use in climate modeling studies.

Satellite remote sensing of aerosols over land requires several specific channels, from ultraviolet to infrared wavelengths. Due to satellite sensor capabilities, little long-term grid data for aerosol properties over land are available before 2000. In place of satellite data, the aerosol optical depth compiled from ground-based solar measurements [14] can be used. Alternatively, visibility is another possible indicator of atmospheric turbidity. Although it is a subjective parameter, long-term archives are available for more than five decades at various locations around the world. For example, Wang *et al.* [15] estimated the aerosol optical depth globally from visibility. These datasets may be able to help the PRF method to perform global-scale and long-term analyses as the next research steps.

Acknowledgements

One of the authors (K. K.) was supported by a Japan Society for the Promotion of Science (JSPS) grant for scientific research (C) and by the President's Discretionary Funds of Nagasaki University. Aerosol single scattering albedo data were computed by Dr. T. Takemura of Kyushu University. Cloud and aerosol products were provided by the ISCCP and MODIS science teams.

References

- [1] Wild, M.. Global dimming and brightening: A review. *J Geophys Res* 2001; 114, D00D16, doi:10.1029/2008JD011470.
- [2] Mallet, M., Tulet, P., Serca, D., Solmon, F., Dubovik, O., Pelon, J., Pont, V., Thouaron, O.. Impact of dust aerosols on the radiative budget, surface heat fluxes, heating rate profiles and convective activity over West Africa during March 2006. *Atmos Chem Phys* 2009;(18):7143-7160.
- [3] Wild, M., et al.. From dimming to Brightening: Decadal changes in solar radiation at Earth's surface, *Science*, 2005; 308: 847-850.
- [4] Riihimäki, L. D., Vignola, F. E., Long, C. N.. Analyzing the contribution of aerosols to an observed increase in direct normal irradiance in Oregon. *J Geophys Res* 2009; 114, D00D02, doi:10.1029/2008JD010970.
- [5] Sanchez-Lorenzo, A., Calbo', J., Brunetti, M., Deser, C.. Dimming/brightening over the Iberian Peninsula: Trends in sunshine duration and cloud cover and their relations with atmospheric circulation. *J Geophys Res* 2009; 114, D00D09, doi:10.1029/2008JD011394.
- [6] Kawamoto, K., Hayasaka, T.. Relative contributions to surface shortwave irradiance over China: A new index of potential radiative forcing. *Geophys Res Lett* 2008; 35, L17809, doi:10.1029/2008GL035083.
- [7] Kawamoto, K., Hayasaka, T.. Geographical features of changes in surface shortwave irradiance in East Asia estimated using the potential radiative forcing index. *Atmos Res* 2009;doi:10.1016/j.atmosres.2009.09.016.
- [8] Nakajima, T., Tanaka, M.. Matrix formulations for the transfer of solar radiation in a

plane-parallel scattering atmosphere. *J. Quant. Spectrosc. Radiant. Transfer*, 1986; 35, 13-21.

[9] Nakajima, T., Tanaka, M.. Algorithms for radiative intensities calculations in moderately thick atmospheres using a truncation approximation. *J Quant Spectrosc Radiat Transfer*, 1988; 40, 51– 69.

[10] Kneizys, F. X., Shettle, E. P., Arbeau, L. W., Chetwynd, J. H., Anderson, G. P., Gallery, W. O., Selby, J. E. A., Clough, S. A.. Users guide to LOWTRAN-7. Air Force Geophysics Laboratory Tech. Rep. 1988; AFGL-TR-88-0177, 137pp.

[11] Rossow, W. B., Duenas, E. N.. The International Satellite Cloud Climatology Project (ISCCP) Web site - An online resource for research. *Bull Am Meteorol Soc* 2004; 85, 167-172.

[12] Kaufman, Y. J., Tanré, D., Boucher O.. A satellite view of aerosols in the climate system. *Nature*, 2002; 419, 215-223.

[13] Takemura, T., Nozawa, T., Emori, S., Nakajima, T. Y., Nakajima, T.. Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. *J Geophys Res* 2005; 110, D02202, doi:10.1029/2004JD005029.

[14] Luo, Y., Lu, D., Zhou, X., Li, W., He, Q.. Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years. *J Geophys Res*, 2001; 106, 14,501– 14,513.

[15] Wang, K., Dickinson, R. E., Liang, S.. Clear sky visibility has decreased over land globally from 1973 to 2007. *Science* 2009; 323, 1468 ;doi: 10.1126/science.1167549.

Figure captions

Figure 1 Comparison of the S variations between the PRF-derived and ISCCP products in July during 2001 and 2004 together with a regression line.

Figure 2 (a) Geographical distribution of the S variations due to τ_c during the period 1.

Figure 2 (b) Geographical distribution of the S variations due to τ_c during the period 2.

Figure 2 (c) Geographical distribution of the S variations due to τ_c during the period 3.

Figure 2 (d) Geographical distribution of the S variations due to τ_c during the period 4.

Figure 2 (e) Geographical distribution of the S variations due to τ_c during the period 5.

Figure 2 (f) Geographical distribution of the S variations due to τ_c during the period 6.

Figure 3 (a) The same as Figure 2 (a) except due to A_c .

Figure 3 (b) The same as Figure 2 (b) except due to A_c .

Figure 3 (c) The same as Figure 2 (c) except due to A_c .

Figure 3 (d) The same as Figure 2 (d) except due to A_c .

Figure 3 (e) The same as Figure 2 (e) except due to A_c .

Figure 3 (f) The same as Figure 2 (f) except due to A_c .

Figure 4 (a) The same as Figure 2 (a) except due to τ_a .

Figure 4 (b) The same as Figure 2 (b) except due to τ_a .

Figure 4 (c) The same as Figure 2 (c) except due to τ_a .

Figure 4 (d) The same as Figure 2 (d) except due to τ_a .

Figure 4 (e) The same as Figure 2 (e) except due to τ_a .

Figure 4 (f) The same as Figure 2 (f) except due to τ_a .

Figure 5 (i) Contribution histograms of the S variations due to τ_c during the research period.

Figure 5 (ii) The same as Figure 5 (i) except due to A_c .

Figure 5 (iii) The same as Figure 5 (i) except due to τ_a .

Figure 6 Time series of domain-averaged S variations due to τ_c , A_c , and τ_a with the standard deviations.

Figure 7(a) Time series of dS due to τ_c , A_c , and τ_a at one point in central China ($105^\circ E$, $35^\circ N$) during the research period.

Figure 7(b) Time series of τ_c , A_c , and τ_a at the same point and period as Figure 7(a).

Figure 8(a) The same as Figure 7(a) except in southeastern China (118°E, 28°N)

Figure 8(b) The same as Figure 7(b) except in southeastern China (118°E, 28°N)