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<tr>
<td>Citation</td>
<td>Geophysical Research Letters, 35(17), L17809; 2008</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2008-09-16</td>
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<td>URL</td>
<td><a href="http://hdl.handle.net/10069/22497">http://hdl.handle.net/10069/22497</a></td>
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Relative contributions to surface shortwave irradiance over China:

A new index of potential radiative forcing

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The contributions of atmospheric factors to surface shortwave irradiance ($S$) variability was investigated, using radiative transfer calculations to examine all sky (both cloud-free and cloudy) conditions. We defined the sensitivities of $S$ to differential increases from given values of cloud, aerosol, and water vapor as potential radiative forcing (PRF). Thus, the expected change in $S$ due to one factor would be the product of the PRF and the change in that factor. Geographical features of the PRF were described over China in January and July, and then the PRF was applied to evaluate the relative contributions of related factors to $S$ variability over Jinan (the central-eastern China) during 1984 and 1990. Although some shortcomings were pointed out, the usefulness of the PRF was confirmed for determining the relative contributions. In particular, to use accurate aerosol absorption properties was suggested to be crucial for quantitative radiation budget estimates.
1. Introduction

The surface shortwave irradiance ($S$) received by the Earth’s surface drives climate-system changes through dynamical, thermodynamical, and radiative processes. Scattering and absorption by air molecules, aerosols, and cloud particles influence $S$ before it reaches the surface. Because the effects of these factors vary temporally and spatially, $S$ shows large variability at different time scales.

Previous studies have reported that $S$ decreased for several decades before around 1990 but then began to increase (so-called the solar dimming and brightening), although observation points were limited [e.g., Gilgen et al., 1998; Stanhill and Cohen, 2001, Wild et al., 2005]. The reason for this long-term variation is still unclear and is the subject of active discussion. For example, reports of decreased $S$ between 1960 and 1990 appear contradictory to decreasing trends in cloud amount found by ground measurements over most parts of China [Qian et al., 2006], assuming that other atmospheric parameters remained the same. Meanwhile, large quantitative differences still exist in $S$ produced by simulations of radiative forcing including anthropogenic aerosols and observed $S$ [Takemura et al., 2005]. Given this background, a new index that represents the sensitivities of $S$ to changes in related factors such as clouds, aerosols, and water vapor should be useful, since $S$ variability can then be estimated from observed changes in related factors.

Here we 1) define an index of potential radiative forcing (PRF) based on the sensitivity of $S$ to differential change in individual factors, 2) describe the geographical features of PRF over China, and 3) discuss the contributions of the factors to $S$ variability.
2. Definition of potential radiative forcing (PRF)

Shortwave irradiance (0.2-5 μm considered in this study) is influenced by various factors, including clouds, aerosols, water vapor, and surface albedo, according to the solar incidence of the considered point. The relationships between $S$ and atmospheric factors can be expressed by simple equations. For a non-reflecting surface, $S$ is formulated as follows:

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

where $S_0$ is the incident solar irradiance at the top of the atmosphere, which varies with the season and latitude and in accordance with 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 as follows:

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

According to Eq. (2), cloud-free and cloudy factors would not independently affect the change in $S$. If $A_c$ is small, the change in $T_a$ largely affects $S$, but the change in $T_c$ does not have a large effect on $S$. Here, we want to know the sensitivity of $S$ to differential change of each factor (cloud optical depth $\tau_c$, aerosol optical depth $\tau_a$, water vapor amount $w$ and $A_c$) which we define as the potential radiative forcing (PRF), according to the following expressions:
\[ \frac{\partial S}{\partial \tau_c} = S_0 A_c \frac{\partial T_c}{\partial \tau_c}, \quad (3) \]

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

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

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

The expected change in \( S \) due to one factor is obtained as the product of PRF and the change in that factor. The PRFs are defined by the unit optical depth for \( \tau_c \) and \( \tau_a \), 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 factors and \( S_0 \) according to \( A_c \). PRFs are always negative, and become stronger (more influential on \( S \)), when the factor values are small and \( S_0 \) is large. Hereafter, ‘strong’ and ‘weak’ denote ‘large (more negative)’ and ‘small (less negative)’ of absolute values for PRFs. Feedback processes among these factors (e.g., indirect aerosol effects) are not explicitly treated in the above equations due to the complexity and our poor understanding of these processes. The effects of ozone and other minor constituents on \( S \) are also not considered, since they are negligible.

The radiation quantities were computed using a general radiative transfer code RSTAR-5b [Nakajima and Tanaka, 1988]. In the code, cloud top and bottom heights were set to 2 km and 1 km, respectively, and the aerosol layer intervened from the ground to 2 km. A vertical profile of water vapor amount was assumed in reference to standard model atmospheres. Surface shortwave irradiances would generally receive small perturbations from different cloud heights and geometrical thicknesses. PRFs are, however, obtained
via differentiation or subtraction from radiation quantities themselves. Consequently, numerical simulations revealed at most 8% errors to resultant PRF values with various sets of cloud layering.

3. Geographical features of PRF over China

a) Datasets used

Because atmospheric factors generally exhibit large seasonality, we used monthly data instead of annual mean values for the analyses. Monthly averaged PRF in January and July over the region including China (75°E–135°E, 20°N–55°N) were calculated using the RSTAR-5b radiation code; inputs were $\tau_c$ at visible wavelength and $A_c$ from International Satellite Cloud Climatology Project (ISCCP) datasets [Rossow and Duenas, 2004], $\tau_\alpha$ at 0.55 μm from Moderate Resolution Imaging Spectroradiometer (MODIS) products [Kaufman et al., 2002], and $w$ archived by the European Center for Medium-range Weather Forecasts (ECMWF). Four-year (2002–2005) climatologies were constructed with 2.5° resolution. This period was selected because of the availability of the advanced MODIS instrument. The above factors showed the following features. For $\tau_c$, large values (~15) were observed in January over southeastern China and extending to the East China Sea. Moderate $\tau_c$ (~10) occurred over two areas (around 80°E and 115°E) along the belt of 42.5°N–52.5°N. Otherwise, $\tau_c$ was small (<4). In July, moderate $\tau_c$ (~10) was found over southwestern China and the Korean Peninsula. Over the central arid region, $\tau_c$ was particularly low (<3) compared to surrounding areas. For $A_c$,
values in January were small (<20%) in the southwest and central arid areas (~30%) but larger (~80%) over the East China Sea. Otherwise, \( A_c \) was moderate (~50%). In contrast, large \( A_c \) (~80%) was found over the southwest in July. In other areas, \( A_c \) was about 60%, with the exception of the north where \( A_c \) was ~70%. For \( \tau_a \), large values (0.4~0.6) were observed over the eastern half of China and neighboring coastal areas. Moderate \( \tau_a \) (~0.4) was found over the west, with the exception of the Tibetan Plateau (77°E–103°E, 28°N–35°N) \((\tau_a<0.1)\). In July, \( \tau_a \) was larger than in January as a whole, particularly over highly populated coastal areas (>1). For \( w \), the spatial distributions for both months were quite similar (small in the north, high in the south, and very small over the Tibetan Plateau), but amounts were several times larger in July than in January. Additionally, we used the ISCCP-derived ground albedo [Rossow and Duenas, 2004] in our calculations, although Eqs. (1) to (6) assume a non-reflecting surface for simplicity,

b) Clouds

Figure 1 shows the PRF due to \( \tau_c \). Hereafter, the upper and lower panels present January and July, respectively in all figures. In the upper panel, PRFs were weak over the north (>45°N) and the south (<30°N). The former is attributed not only to moderately thick clouds but to small \( S_0 \), while the latter is attributed to large \( \tau_c \) in the east and small \( A_c \) in the west, respectively. Stronger PRFs were found in the central area, caused by optically thin clouds. In the lower panel, there were generally weak over the south and the Korean Peninsula, where moderately optically thick clouds occurred. Inland desert and
mountainous areas had especially strong PRFs due to optically thin clouds. The same features applied over the East China Sea.

Figure 2 illustrates the PRF due to $A_c$. As shown in the upper panel, PRFs were relatively weak over the north and strong over the southeast and the East China Sea. The lower panel shows strong PRFs over the Tibetan Plateau caused by moderately large $\tau_c$ and small $\tau_a$. The central arid area was weak as a result of small $\tau_c$ and moderate $\tau_a$. These effects are associated with the contrast of $T_c$ and $T_a$ as expressed in Eq. (6).

c) Aerosols

Figure 3 indicates PRF due to $\tau_a$. In the upper panel, weaker PRFs occurred over a narrow belt in the north. The western part of the southern region had stronger PRFs, while other areas appeared intermediate. In contrast to the January case, PRFs were stronger over the north and the East China Sea and weaker over the south in the lower panel. Particularly strong PRFs were found around the middle of the northern area reflecting the thin clouds there.

Hayasaka et al. (2006) numerically showed the importance of aerosol absorption even in a cloudy-sky condition. The aerosol absorption property is largely decided by the imaginary part ($k_i$) of the refractive index. In this study, $k_i$ was given as 0.02, which corresponds to a moderately absorptive property, such as that of dust and carbonaceous aerosols. When necessary, PRFs calculated assuming a less absorptive property of 0.005, like that of sulfate, were used for comparison purposes. The single-scattering albedos
were 0.882 and 0.968 when \( k_i \) equaled 0.02 and 0.005, respectively.

d) Water vapor

Figure 4 presents PRFs due to \( w \). In January, PRFs over Tibet were strong, reflecting dry conditions; on the other hand, over most other areas, PRFs were rather weak. In July, relatively strong PRFs were found from the north to the west, where \( w \) was small. Other areas generally appeared only weak effects. As described in subsection 3a, \( w \) showed similar geographical distributions but different total amounts for the two months. Owing to those features of \( w \) and the seasonal change of \( S_o \), the seasonal difference of PRF due to \( w \) was much smaller than those of PRF due to other factors.

4. Application of PRF to the relative contributions of factors

A period from 1984 to 1990 was taken for examining the applicability of PRF by comparing with pyranometer measurements of \( S \), in terms of availability of ISCCP grid cloud datasets and past reports on continuous decreasing trends of \( S \) until around 1990. Linear regression statistics were used to estimate variations of \( \tau_c \) and \( A_c \) from ISCCP datasets, \( \tau_a \) from ground-based solar and meteorological observations [Luo et al. 2001] and \( w \) from sonde measurements [Zhai and Eskridge, 1997] together with \( S \) from pyranometers [Shi et al. 2008]. For example, a decrease in \( S \) by -15.7 W/m\(^2\) (0.65 for the correlation coefficient \((r)\) and 20.7 W/m\(^2\) for the standard deviation \((\sigma)\)) was estimated at
Jinan (117.0°E 36.7°N) in January from 1984 to 1990. Both $\tau_c$ and $A_c$ increased by 2.1 (0.69 for $r$ and 1.00 for $\sigma$) and 14.21% (0.83 for $r$ and 5.57% for $\sigma$). Increases in $\tau_a$ and $w$ were approximately 0.03 and 0.1 mm, respectively. Datasets of $\tau_a$ and $w$ were less detailed and non-grid information, thus their dispersions were difficult to be quantified.

Combining PRFs with variations of each factor, contributions of -5.61 W/m$^2$, -4.82 W/m$^2$, -0.018 W/m$^2$ and -0.044 W/m$^2$ were obtained for $\tau_c$, $A_c$, $\tau_a$ and $w$, respectively. The Jinan case for this period suggested dominant effects of clouds (larger effect of $\tau_c$) and small effects of $\tau_a$ and $w$ using PRFs to the observed variation of $S$. A value of 0.02 for $k_i$ was used for aerosol absorption in this example, but an assumption of 0.005 instead produces -5.97 W/m$^2$, -3.42 W/m$^2$, -0.019 W/m$^2$ and -0.047 W/m$^2$. Note that using different $k_i$ would influence all the factors’ contributions. Accordingly, accurate determination of the aerosol absorptivity is crucial to quantitative radiation budget estimates. The summation of all the factors’ contributions did not completely match the pyranometer result. As possible reasons, 1) The PRF values should be calculated using factors’ values when the considered period began. 2) An assumed $k_i$ was uncertain. 3) we did not consider feedback processes among related factors. 4) The comparison was made among datasets having different spatial scales (such as a point monitoring, sonde measurements and satellite observations). 5) Errors of used observations and uncertainties associated with the linear regression were introduced. 6) The wavelength at which Luo et al. [2001] scaled $\tau_a$ was 0.75 $\mu$m. 7) There would still exist unidentified phenomena we do not even expect in the climate system. Our primary purpose in this study is, however, to evaluate relative contributions of the clouds, aerosols and water vapor to $S$ variabilities using a
new index of PRF. The above discussion achieves this purpose, regardless of shortcomings raised.

5. Concluding remarks

In this study, we defined a PRF index based on the sensitivities of $S$ to differential increases in affecting factors (clouds, aerosols and water vapor). We then described the geographical distributions of the factors and PRFs in January and July. The PRFs were applied over Jinan in January during 1984 and 1990 to examine the impacts of individual factors on $S$ variability. Consequently, relative contributions of each factor were evaluated for a limited period. This result demonstrates the usefulness of the PRF index for all sky conditions (including cloudy sky) as well as cloud-free-sky addressed by some field campaigns [e.g., Nakajima et al., 2003] and implies collaborative potential with modeling studies, although further refinement is needed for more comprehensive elucidation of $S$ variabilities.

There are several shortcomings in the current methodology. Particularly, 1) to obtain the PRF value, factor values must be available from the beginning of the period considered. We used PRF calculated with averaged data for 2002–2005 to examine past events. 2) An assumed value for $k_i$ was fixed over the entire region, although $k_i$ can vary widely, especially over China, depending on the aerosol composition [Yu et al., 2006]. Parameters related to aerosol absorptivity (including size distributions, commonly assumed bimodal shapes) need to be properly determined. 3) Feedback processes among
clouds, aerosols, and water vapor were not considered. For example, the indirect aerosol
effect is one of the most uncertain phenomena in climate problems [e.g., Kawamoto et al.,
2006]. Other unidentified feedbacks also likely exist. Improving knowledge of the
feedbacks involved is critical.

Acknowledgments

The authors were supported by research project 2-1 of the Research Institute for
Humanity and Nature (RIHN). One of the authors (K. K.) was also supported by a Japan
Society for the Promotion of Science (JSPS) grant-in-aid for young scientists (B) and
scientific research (C) and the President’s discretionary funds of Nagasaki University. We
used atmospheric and surface products provided by the ISCCP and MODIS science
teams.

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Figure captions

Fig.1 PRF due to $\tau_c$. Upper and lower panels show January and July, respectively.

Fig.2 PRF due to $A_c$. Upper and lower panels show January and July, respectively.

Fig.3 PRF due to $\tau_a$. Upper and lower panels show January and July, respectively.

Fig.4 PRF due to $w$. Upper and lower panels show January and July, respectively.
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