Introducing Potential Radiative Forcing (PRF) for quantifying the Earth radiation budget

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Abstract. In order to investigate the contributions of atmospheric factors to variability in surface shortwave irradiance (S) under both cloud-free and cloudy sky conditions, we defined the sensitivity of S to differential increases from given values of cloud, aerosol, and water vapor as potential radiative forcing (PRF). The expected change in S due to one factor would be the product of the PRF and the change in that factor. We formulated the PRF from a simple equation and described the geographical features of the PRF over China in January and July. We noted some shortcomings, but confirmed the usefulness of the PRF for determining the relative contributions. In particular, we suggested that accurate knowledge of aerosol absorption properties was critical for quantitative radiation budget estimates.

INTRODUCTION

The surface shortwave irradiance (S) drives climate processes through dynamical, thermodynamic, 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 over different timescales. Previous studies have reported that S decreased for several decades before the 1990s and then began to increase (the so-called global dimming and brightening), although the observation points were limited[1]. The reason for this long-term variation is still unclear and is the subject of active discussion. If it is assumed that other atmospheric parameters remained constant, the reports of decreased S between 1960 and 1990 appear contradictory to the decreasing total amount of cloud found in ground measurements over most regions of China[2]. Large quantitative differences still exist between the observed values of S and those produced by simulations of radiative forcing that include anthropogenic aerosols. A new index that represents the sensitivity of S to changes in factors such as clouds, aerosols, and water vapor would be useful because it would allow variability in S to be estimated from observed changes in these factors. Here, we defined an index of potential radiative forcing (PRF) based on the sensitivity of S to differential change in various factors, described the geographical features of PRF over the region including China, and discuss the contributions of the factors to variability in S.

DEFINING POTENTIAL RADIATIVE FORCING (PRF)

Values of S (here, 0.2–5 μm) are influenced by various factors, including clouds, aerosols, water vapor, and surface albedo, depending on the solar incidence at the point of interest. The relationships between S and atmospheric factors can be expressed by simple equations. For a non-reflecting surface, S is formulated as

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

where S_0 is the incident solar irradiance at the top of the atmosphere, which varies with the season, latitude, state of the Earth's orbit, and solar activity; and T_a and T_c are transmittance under cloud-free and cloudy sky conditions, respectively. The cloud-free sky is defined as a condition with aerosols and water vapor, and no clouds. The total amount of cloud A_c is defined as the fraction of sky occupied by cloudiness.

The differential of Eq. (1) is

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

According to Eq. (2), cloud-free and cloudy factors do not alter S independently. If A_c is small, the change in T_a strongly affects S, but the change in T_c does not have a large effect on S. We are interested in the potential radiative forcing (PRF), which we define as the sensitivity of S to the differential change in each factor (cloud optical depth τ_c, aerosol optical depth τ_a, amount of water vapor w, and A_c), according to the following respective expressions:

$$\frac{\partial S}{\partial \tau_c} = S_0 A_c \frac{\partial T_c}{\partial \tau_c} , \tag{3}$$

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

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

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

The expected change in S due to one factor is obtained as the product of PRF and the change in that factor, and the total change in S is estimated by the summation. The PRF is defined for unit optical depth for τ_c and τ_a, 1% for A_c, and 1 mm for w. As is evident from the above equations, the PRF depends on a combination of the values of the factors and S_0 according to A_c. The PRF is always negative, and becomes stronger (more influential on S), when the factor values are small and S_0 is large. Hereafter, 'strong' and 'weak' imply 'large (more negative)' and 'small (less negative)' absolute values for the PRF. Feedback processes among these factors (e.g., indirect aerosol effects) are not explicitly treated in the above equations because of their complexity and the poor understanding of the processes involved. The effects of ozone and other minor constituents on S are not considered because they are negligible. The radiation quantities were computed using a general radiative transfer code RSTAR-5b[3].

GEOGRAPHICAL FEATURES OF PRF

a) Data sets

Because atmospheric factors generally vary greatly with the season, we used monthly instead of annual mean data for the analyses. The monthly averaged PRF in January and July over the region containing China and neighboring countries (75°–135° E, 20°–55° N) was calculated using the RSTAR-5b radiation code. The inputs were τ_c at visible wavelength, A_c from the International Satellite Cloud Climatology Project (ISCCP) data sets[4], τ_a at 0.55 μm from the Moderate Resolution Imaging Spectroradiometer (MODIS) products[5], 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 based on the availability of the advanced MODIS instrument. We used the ISCCP-derived ground albedo in our calculations, although Eqs. (1) to (6) assumed a non-reflecting surface for simplicity.

b) Clouds

Figure 1 shows the PRF due to τ_c. Hereafter, the upper and lower panels are for January and July, respectively, in all figures. In the upper panel, the PRF was weak over the north (> 45° N) and the south (< 30° N). We attributed the former effect to the moderately thick clouds and small S there, and the latter to the large τ_c in the east and small A_c in the west, respectively. There was a stronger PRF in the central area, caused by optically thin clouds. In the lower panel, these clouds were generally weak over the south and the Korean Peninsula, where moderately optically thick clouds were present. The inland desert and mountainous regions had a particularly strong PRF because of the optically thin clouds there. This was also the case over the East China Sea.

Figure 2 illustrates the PRF due to A_c. As shown in the upper panel, the PRF over the north was relatively weak in comparison with that over the southeast and the East China Sea. The lower panel shows a strong PRF over the Tibetan Plateau, which was caused by moderately large τ_c and small τ_a. The PRF in the central arid region was weak because of the small τ_c and moderate τ_a there. These effects were associated with the contrast between T_c and T_a, as expressed in Eq. (6).
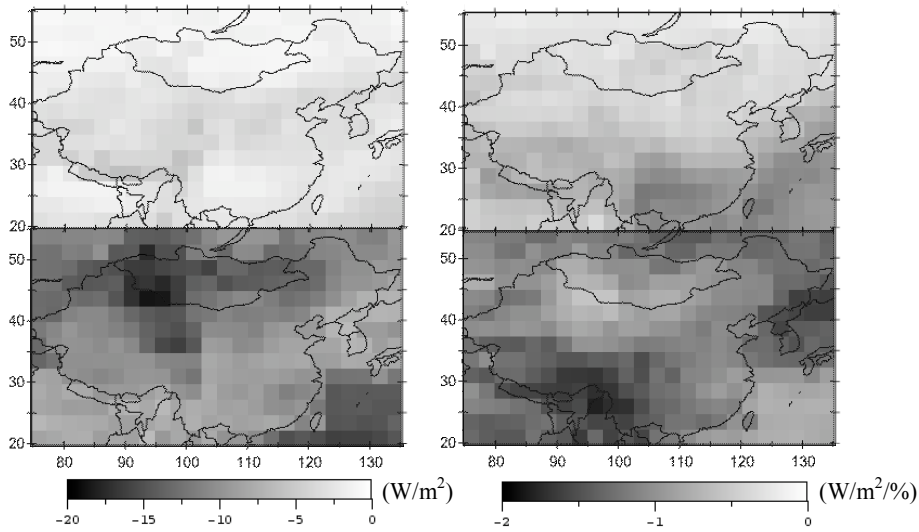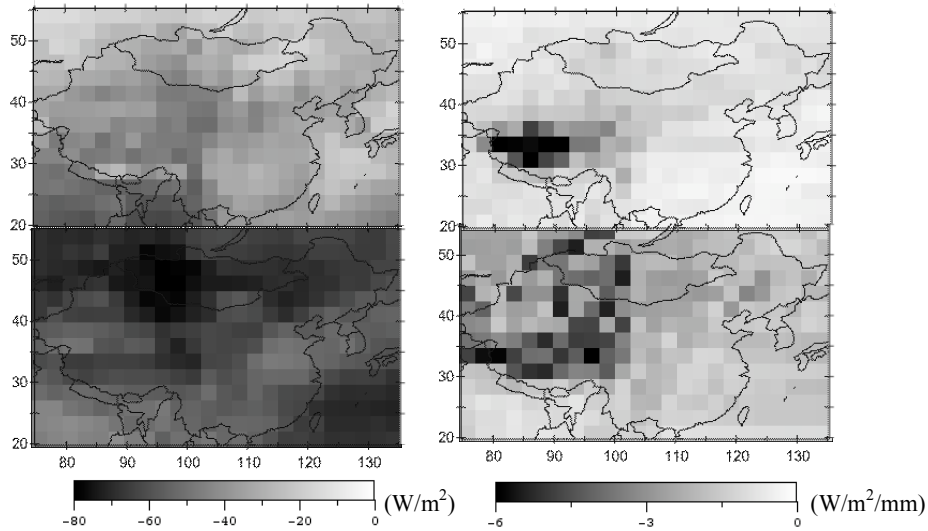
Figure 1

Figure 2

Figure 3

Figure 4

c) Aerosols

Figure 3 shows the PRF due to τ_a. In the upper panel, the PRF was weaker over a narrow latitude band in the north; the PRF in the western part of the southern region was stronger, whereas that in the other regions appeared moderate. In contrast to that in the January case, the PRF over the north and the East China Sea was stronger, and that over the south was weaker in the lower panel. The PRF over the middle of the northern area was particularly strong because of the thin clouds there. The aerosol absorption property is largely decided by the imaginary part (k_i) of the refractive index. We set k_i to 0.02, corresponding to moderately absorptive substances such as dust or carbonaceous aerosols.

d) Water vapor

Figure 4 shows the PRF due to w. In January, the PRF over Tibet was strong, reflecting dry conditions. Over most other regions, however, the PRF was rather weak. In July, the PRF from the north to the west, where w was small, was relatively strong. The effects in other regions were generally weak. Although values of w had similar

geographical distributions, different total amounts for the two months. Because of these results and the seasonal change in S_o, the seasonal difference in PRF due to w was much smaller than that due to other factors.

CONCLUDING REMAKS

We defined a PRF index based on the sensitivity of S to differential increases in affecting factors (clouds, aerosols, and water vapor). We then described the geographical distributions of the factors and PRF in January and July. Our results demonstrate the usefulness of the PRF index in all sky conditions (including cloudy sky) as well as cloud-free-sky cases addressed by some field campaigns[6]. Additionally, Our method has potential for use in modeling studies, although further refinement is needed for comprehensive elucidation of the variability in S.

There are several shortcomings to our method. First, a fixed value for k_i was assumed over the entire region, even though k_i can vary widely, especially over China, depending on the aerosol composition[7]. The parameters related to aerosol absorptivity, including size distributions, need to be properly determined. Second, 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[8]. It is likely that other unidentified feedbacks also exist. Improving the knowledge of these feedbacks is critical.

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