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Relationship between cloud radiative forcing, cloud fraction and cloud albedo, and new surface-based approach for determining cloud albedo

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This paper focuses on three interconnected topics: (1) quantitative relationship between surface shortwave cloud radiative forcing, cloud fraction, and cloud albedo; (2) surface-based approach for measuring cloud albedo; (3) multiscale (diurnal, annual and inter-annual) variations and covariations of surface shortwave cloud radiative forcing, cloud fraction, and cloud albedo. An analytical expression is first derived to quantify the relationship between cloud radiative forcing, cloud fraction, and cloud albedo. The analytical expression is then used to deduce a new approach for inferring cloud albedo from concurrent surface-based measurements of downwelling surface shortwave radiation and cloud fraction. A decade-long data on cloud albedos are obtained by use of this surface-based approach over the US Department of Energy's Atmospheric Radiation Measurement (ARM) Program at the Great Southern Plains (SGP) site. The surface-based cloud albedo set is further compared against those derived from the coincident GOES satellite measurements. The multiscale (diurnal, annual and inter-annual) variations and covariations of shortwave cloud radiative forcing, cloud fraction and cloud albedo are examined using the three decade-long data sets on collected at SGP site since 1997.

1 Introduction

Quantifying the impact of clouds on the Earth's radiation budget has been the subject of intensive research for several decades (Schneider, 1972; Charlock and Ramanathan, 1985; Ramanathan, 1987; Laszlo and Pinker, 1993; Ramanathan et al., 1989a, b; Harrison et al., 1990; Arking, 1991, 1999; Kiehl, 1994; Wielicki et al., 1995; Rossow and Zhang, 1995; Raschke et al., 2005). One of the quantities that have been increasingly used to gauge the radiative impact of clouds is cloud radiative forcing (CRF, e.g., Ellis, 1978; Coakley and Baldwin, 1984; Charlock and Ramanathan, 1985; Ramanathan, 1987; Cess and Potter, 1987). An advantage of using CRF is that it can be readily

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obtained from satellite radiative measurements or calculated in global climate models (GCMs). Comparison of model-simulated CRF against satellite observations at the top of atmosphere (TOA) have proven to be instrumental in evaluation of climate models and the identification of cloud feedbacks and parameterizations as the key factors contributing to the large uncertainty in GCM climate sensitivity (Cess et al., 1997, 2001; Potter and Cess, 2004; Bony et al., 2006; Stephens, 2005).

Despite its great utility, CRF – and its variation with temperature in studies of cloud feedbacks, alone is not enough for fully understanding cloud-radiation interactions and their effects on climate. Further progress requires relating CRF to other cloud properties such as cloud fraction and cloud albedo. Although it has been long recognized that CRF is related intimately to cloud fraction and cloud albedo and some efforts have been devoted to exploring their relationships (Charlock and Ramanathan, 1985; Harrison et al., 1990), our understanding has been largely qualitative. The quantitative relationship between CRF, cloud fraction and cloud albedo remains elusive.

The roles of cloud fraction and cloud albedo in shaping the Earth's climate had actually been investigated before the introduction of CRF – at least in the 1970s (Arakawa, 1975; Schneider, 1972; Charney, 1979), and continue to defy satisfactory understanding and parameterization (Bony and Dufresne, 2005). For example, Bender et al. (2006) compared the results of global albedo from 22 GCMs and two satellites, and found that GCM-derived values not only exhibit a large spread but also consistently higher values than those observed by the two satellites. These differences between observations and models are likely due to inadequate GCM parameterizations of cloud fraction and/or cloud albedo.

To fill this gap, here we first derive an analytical formulation of the relationship between the surface shortwave CRF, cloud fraction, and cloud albedo, and then use this relationship to derive cloud albedo from surface-based measurements of cloud fraction and shortwave radiation. This expression is then applied to obtain time series for cloud albedo from the decade-long surface-based measurements of downwelling shortwave (SW) radiation flux collected by the US Department of Energy's Atmospheric

Radiation Measurement (ARM) program at the Southern Great Plain (SGP) site since 1997 (Stokes and Schwartz, 1994; Ackerman and Stokes, 2003), and compared to the satellite measurements. The decade-long triple datasets are examined to determine their multiscale variations and co-variations.

2 Analytical relationship between surface cloud radiative forcing, cloud fraction and cloud albedo

2.1 Concept of relative cloud radiative forcing

Cloud radiative forcing (CRF) was originally defined as the difference between clear-sky and all-sky net radiation fluxes, and was first applied to study radiation budgets measured with satellites at the top of atmosphere (TOA) (Ellis, 1978; Coakley and Baldwin, 1984; Charlock and Ramanathan, 1985; Ramanathan, 1987; Cess and Potter, 1987). The concept of surface CRF has been later applied to surface-based radiation measurements (Dong et al., 2002; Mace et al., 2006; Mace and Benson, 2008). Despite its usefulness and popularity, the CRF thus defined suffers from the drawback of being affected by factors other than clouds (e.g., solar zenith angle, definition of what constitutes a clear-sky reference, and specification of the surface albedo), and much effort has been devoted to minimizing the effects of these non-cloud factors on computation of the CRF (Li et al., 1995; Imre et al., 1996; Li and Trishchenko, 2001; Vavrus, 2006; Betts and Viterbo, 2005; Betts, 2007; Betts et al., 2009). Among existing attempts, the non-dimensional metric proposed by Betts and his co-workers is probably the best, and is detailed below for the surface shortwave CRF.

The surface shortwave CRF (F_{cld}) is defined in terms of downwelling flux such that,

$$F_{\text{cld}} = F_{\text{all}}^{\text{dn}} - F_{\text{clr}}^{\text{dn}} \quad (1)$$

where $F_{\text{all}}^{\text{dn}}$ and $F_{\text{clr}}^{\text{dn}}$ denote the all-sky and clear-sky surface downwelling SW radiation fluxes, respectively, with positive values being indicative of downward fluxes. Replacing

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net flux with downwelling flux reduces the effect of surface albedo (see Vavrus, 2006 for more discussion). To further minimize the effects from other non-cloud factors, Betts and Viterbo (2005) proposed a non-dimensional measure for the surface CRF defined as (see also Betts, 2007 and Betts et al., 2009),

$$\alpha_{\text{cld}}^{\text{SRF}} = -\frac{F_{\text{cld}}}{F_{\text{clr}}^{\text{dn}}} = 1 - \frac{F_{\text{all}}^{\text{dn}}}{F_{\text{clr}}^{\text{dn}}} \quad (2)$$

The minus sign is introduced to reflect that the effect of shortwave CRF on climate is cooling ($F_{\text{cld}} < 0$) and a positive $\alpha_{\text{cld}}^{\text{SRF}}$ is more convenient. They named $\alpha_{\text{cld}}^{\text{SRF}}$ as the effective cloud albedo, as the net shortwave radiative flux can be described in a symmetric form of surface albedo and $\alpha_{\text{cld}}^{\text{SRF}}$

$$F_{\text{all}}^{\text{net}} = F_{\text{all}}^{\text{dn}} - F_{\text{all}}^{\text{up}} = (1 - \alpha_{\text{srf}}) \left(1 - \alpha_{\text{cld}}^{\text{SRF}} \right) F_{\text{clr}}^{\text{dn}}, \quad (3)$$

It is noteworthy that as will become evident later, $\alpha_{\text{cld}}^{\text{SRF}}$ is actually a product of cloud fraction and cloud albedo, and that the variation of $\alpha_{\text{cld}}^{\text{SRF}}$ conforms more closely to that of cloud fraction than cloud albedo. To avoid the potential misunderstanding that $\alpha_{\text{cld}}^{\text{SRF}}$ is more related to cloud albedo compared to cloud fraction, $\alpha_{\text{cld}}^{\text{SRF}}$ will be referred to as the relative cloud radiative forcing in this paper.

2.2 Analytical formulation

Betts and his coworkers (Betts and Viterbo, 2005; Betts, 2007; Betts et al., 2009) examined $\alpha_{\text{cld}}^{\text{SRF}}$ derived from the International Satellite Cloud Climatology Project (ISCCP) data over several river basins in comparison with those from different reanalysis datasets (ERA-40 and ERA-Interim). Although attempts have been made to connect $\alpha_{\text{cld}}^{\text{SRF}}$ to cloud fraction and cloud albedo empirically, the quantitative relationship between the three quantities still remains elusive theoretically, and is a focus of this section.

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3 Cloud albedo from surface-based observations

3.1 Approach

Relative to cloud fraction and CRF, cloud albedo is much less measured and known, hindering investigation of cloud-climate interactions and aerosol indirect effects. Probably the most direct way to measure cloud albedo is using instrumented aircrafts (Griggs, 1968; Salomonson and Marlatt, 1968; Hayasaka et al., 1994); but, such aircraft-based in situ measurements are limited in both time and space. Long-term global records of albedo have primarily relied on satellite (Wielicki et al., 2005).and earthshine measurements (Palle et al., 2003, 2009); however, both actually measure global albedo that depends not just on cloud albedo, but on cloud fraction and surface reflective properties as well. Seeking an adequate satellite-based approach to estimating cloud albedo is still an area of active research (Bender et al., 2011).

An alternative surface-based approach that permits long-term measurements of cloud albedo cannot be overemphasized. An approach that capitalizes on surface-based remote sensing techniques as used at the ARM SGP site is even more desirable in view of the widely demonstrated fidelity of these remote sensors (Stokes and Schwartz, 1993; Ackerman and Stokes, 2003). Equation (5c) suggests just such a technique if $\alpha_{\text{cld}}^{\text{SRF}}$ and f can be measured simultaneously, i.e.,

$$\alpha_r = \frac{\alpha_{\text{cld}}^{\text{SRF}}}{f}. \quad (6)$$

ARM has provided high-quality continuous measurements of multiple quantities essential to cloud-radiation interactions by integrating multiple surface-based remote sensors at the SGP site. Especially useful to this study is the shortwave flux analysis value-added product (VAP) (Long and Ackerman, 2000). This VAP dataset includes quality controlled measurements of the surface downwelling SW radiation fluxes, estimates of the surface downwelling SW radiation fluxes, and average fractional sky cover over the hemispheric dome with 15-min resolution, and covers the period of 25 March 1997 to

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present. Therefore, we can first obtain the series of $\alpha_{\text{cld}}^{\text{SRF}}$ from the surface radiation measurements using Eq. (2), and then substitute data on $\alpha_{\text{cld}}^{\text{SRF}}$ and f into Eq. (5) to obtain the data on cloud albedo.

3.2 Comparison with satellite-derived cloud albedo

Broadband shortwave albedo and cloud fraction are derived from GOES-8/11 narrowband observations by the NASA Langley cloud and radiation group (Minnis et al., 2008a) using narrowband-to-broadband conversion functions (Minnis and Smith, 1998) and a clear vs. cloudy pixel classification based upon variations from an observed background state including the surface albedo characteristics (Minnis et al., 2008b) on a $0.5^\circ \times 0.5^\circ$ grid over the SGP region. For the purposes of comparing to surface observations at the ARM SGP central facility, we choose the single nearest satellite gridpoint. For the single layer cloud model with cloud fraction f as described by Eq. (4a), it can be shown that the total scene albedo is given by

$$\alpha = f\alpha_{\text{cld}} + (1 - f)\alpha_{\text{crl}}, \quad (7a)$$

This equation was used and verified by Cess (1976) in investigation of the meridional distributions of zonally averaged values of total albedo, cloud fraction and cloud albedo. Rearranging Eq. (7a) leads to the expression for deriving cloud albedo:

$$\alpha_{\text{cld}} = \alpha - \frac{1 - f}{f}\alpha_{\text{s}}, \quad (7b)$$

To validate the new surface-based approach, Fig. 1 compares the hourly cloud albedos derived from the surface-based approach with those from the satellite measurement over the SGP site. The two sets of cloud albedo data are correlated to each other reasonably well with a correlation coefficient of 0.69, which is encouraging in view of the uncertainties in both satellite-and surface-based retrievals. The surface-based cloud albedo is relatively higher than the satellite one when the cloud albedo is larger than

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~0.3, which may arise from several factors, e.g., cloud absorption, multiple reflections, cloud thickness, and cloud inhomogeneity.

4 Multiscale variations

Equation (5c) clearly reveals that the uncertainty in reported values of CRF simulated by different GCMs may arise from inadequate treatments of both cloud albedo and cloud fraction. Systematic examination of $\alpha_{\text{cld}}^{\text{SRF}}$ only started very recently by Betts and his coworkers by using indirect satellite surface radiation measurements. No similar study has been reported using the direct surface-based, high-resolution ARM measurements at the SGP site. The 15-min data are further aggregated to examine the diurnal (Fig. 2a), annual (Fig. 2b) and interannual variations (Fig. 2c) of $\alpha_{\text{cld}}^{\text{SRF}}$, f , and α_r . A few points can be drawn from these figures. First, the three quantities all exhibit strong diurnal and annual variations. Although the diurnal cycle is not complete due to missing nighttime downwelling shortwave radiation flux measurements, the minima around local noon (GMT noon minus 6 h) are remarkably obvious, with 0.26, 0.48 and 0.52 for $\alpha_{\text{cld}}^{\text{SRF}}$, f and α_r , respectively. Two maxima appear for $\alpha_{\text{cld}}^{\text{SRF}}$ and f . The first occurs in local morning (0.41, 0.71 and 0.59 for $\alpha_{\text{cld}}^{\text{SRF}}$, f and α_r) and the second in local afternoon (0.32, 0.59 and 0.60 for $\alpha_{\text{cld}}^{\text{SRF}}$, f and α_r). On monthly scales, the summertime minima are evident, with $\alpha_{\text{cld}}^{\text{SRF}} = 0.19$ and $f = 0.41$ in July and $\alpha_r = 0.45$ in August. The maxima for $\alpha_{\text{cld}}^{\text{SRF}}$ (0.30) and f (0.56) occur in March while for α_r (0.57) in October. The basic characteristics of the diurnal (morning maximum and noon minimum during daytime) and annual (wintertime maximum and summertime minimum) variations of cloud fraction are consistent with previous analyses (e.g., Lazarus et al., 2000; Dong et al., 2006; Kollias et al., 2007). The annual variation of $\alpha_{\text{cld}}^{\text{SRF}}$ is similar to that observed in other continental areas such as Amazon and Missouri (Betts, 2007, 2009; Betts et al., 2009). Second, the three quantities exhibit relatively less interannual variation; with the 13 yr averages of $\alpha_{\text{cld}}^{\text{SRF}}$, f and α_r are 0.26, 0.50 and 0.52, respectively. Finally, although

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the three quantities tend to vary largely in phase, the variation of $\alpha_{\text{cld}}^{\text{SRF}}$ is correlated more with f than with α_r . This can be seen more clearly in Fig. 3a, b. Together with Eq. (4), the higher correlation with f suggests that f varies slightly more than α_r . The in-phase relationship between $\alpha_{\text{cld}}^{\text{SRF}}$ and f was also found in Betts et al. (2009).

5 Concluding remarks

An analytical relationship between the relative surface shortwave cloud radiative forcing, cloud fraction and cloud albedo is derived theoretically. The analytical relationship not only reveals that the relative surface shortwave CRF is approximately a product of cloud fraction and cloud albedo, it also suggests a new approach to inferring cloud albedo from surface-based concurrent measurements of surface downwelling shortwave radiative fluxes and cloud fraction. This new surface-based approach is applied to the long-term measurements collected at the ARM SGP site, and the surface-based estimates of cloud albedo compare favorably with those obtained from the concurrent GOES satellite data.

The decade-long high resolution data are examined to discern their multiscale (diurnal, annual and interannual) variations and covariations of the relative surface shortwave cloud radiative forcing, cloud fraction and cloud albedo. The diurnal variations of all the three quantities exhibit a strong minimum around local noon. The annual variations exhibit a minimum in summertime and a maximum in wintertime. No discernable year-to-year trends exist in the interannual variations of all the three quantities. The variation of relative surface shortwave cloud radiative forcing is more in phase with that variation of cloud fraction than cloud albedo.

This study clearly demonstrates and reinforces the usefulness of the relative cloud radiative forcing in isolating the cloud radiative effect from non-cloud factors, and further relating it to cloud fraction and cloud albedo. Nevertheless, the study is just a beginning, and much remains to be done. First, ARM has supported other SGP-like sites in different climatic regimes. Application of the approaches presented here to

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these sites will test the applicability of the presented approaches in different climatic regimes. Furthermore, increasing number of surface sites like the ARM SGP site has been established to measure surface radiation around the world such as the Baseline Surface Radiation Network (BSRN, Ohmura et al., 1998). Further application of the new approaches to these measurements will provide a much needed global data set for cloud albedo based on radiation measurements at surface. Second, model evaluation against observations is essential to identifying model deficiencies, and this important endeavor demands long-term data of high quality and resolution. The surface-based data thus obtained will be valuable and complementary to the widely used satellite measurements. Third, the focus of this paper is on solar radiation at surface, similar ideas are expected applicable to solar radiation at TOA and terrestrial infrared radiation measurements. Finally, to capture the physical essence with simple analytical expressions, the theoretical framework is formulated to represent the first order effect under a few simplifying assumptions, including neglect of cloud absorption, multiple reflections, and multiple vertical layering. Examining the effects of relaxing these assumptions on the resultant relationships is underway. .

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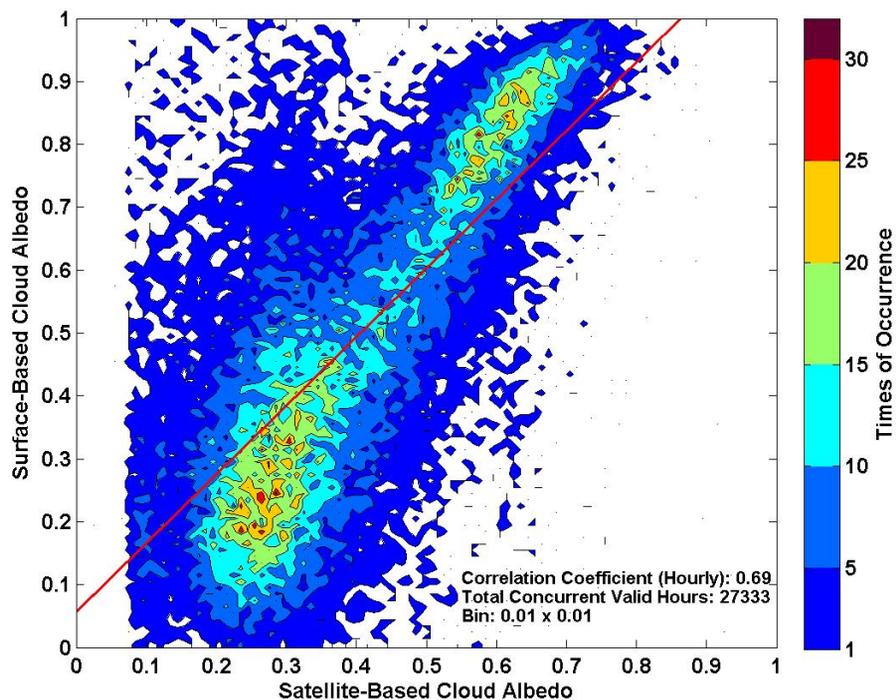


Fig. 1. Comparison of the surface-based cloud albedo with those derived from the GOES satellite.

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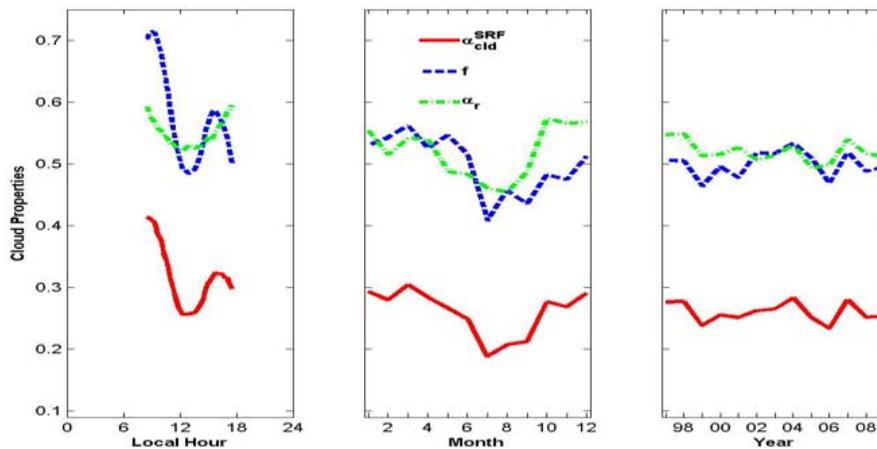


Fig. 2. Diurnal (left), annual (middle) and interannual (right) variations of the relative surface shortwave cloud radiative forcing (red solid), cloud fraction (green dashed) and cloud albedo (blue dotted).

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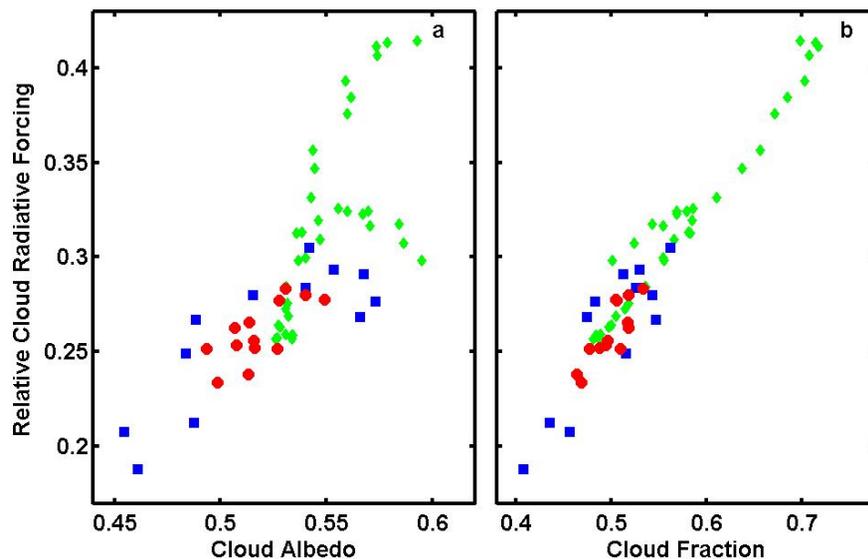


Fig. 3. Scatter plots showing correlation between the relative surface shortwave cloud radiative forcing and cloud fraction **(a)**, and cloud albedo **(b)**. The colors of red, green and blue denote hourly, monthly, and annual averages, respectively.

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