On the Interpretation of Shortwave Albedo-Transmittance Plots

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Abstract

The coefficients of linear regression lines fit to 1D model values of broadband surface absorptance *T* and top-of-atmosphere albedo α indicate the impact of clouds on atmospheric absorptance *a*. It is argued here that these coefficients cannot be compared directly to corresponding values for hourly observed data. This is because 1 - α - *T* = *a* for 1D models, but not for hourly observations. A 3D Monte Carlo radiative transfer algorithm and a realistic atmosphere are used to demonstrate that hourly data create an *illusion* of anomalous absorption by clouds on α vs. *T* plots. This is because of horizontal transport of radiation and inherently poor sampling of *T*. It would, however, be safer to compare 1D model regression coefficients to those for at least diurnal mean observations averaged over large grids containing several surface pyranometers.

Introduction

Recent debate over anomalous absorption (AA) of shortwave radiation by clouds has hinged largely on the fact that when hourly observational broadband TOA albedo α and surface absorptance (or transmittance) *T* are fitted with

$$\alpha = \alpha_0 - \beta T \qquad (1)$$

via least-squares regression, α_0 and β are smaller than corresponding values for 1D radiative transfer models. It has been assumed that this implies that real clouds must absorb much more than model clouds (Cess et al. 1995; 1996). This reasoning is, however, deductively invalid, for the premises may be true, but the conclusion may be false (i.e., differences in α_0 and β need not be due to AA). Arguments are presented indicating that for hourly data, conditions leading to this logical error can be expected. These conditions are demonstrated using a 3D, broadband Monte Carlo photon transport algorithm and an atmosphere generated by a cloud-resolving model. Results presented here are elaborated on by Barker and Li (1997).

α vs. *T*: 1D vs. 3D Atmospheres

If one wishes to compare α vs. *T* results for observational data and 1D model data, one must assume that the energy budgets of the earth-atmosphere columns are the same. This means that for all measured *T* and α,

$$a = 1 - \alpha - T \qquad (2)$$

where *a* is total atmospheric absorptance. Studies that used hourly data and claim to support AA employed satellite grids measuring $(\sim 10\,\text{km})^2$ to $(\sim 100\,\text{km})^2$ (Cess et al. 1995; 1996). These grids are probably narrow enough that in many cases, net horizontal fluxes *h* differ from 0, but large enough that hourly pyranometer data samples of the impact of cloud variability over a grid are poor. These are not issues for 1D models. Hence, for hourly data, what are the impacts of $h \neq 0$ and poor sampling of *T*?

In the real 3D atmosphere, radiation is channelled horizontally from locally thick columns to locally thin columns (Davis 1992). Thus, on an α vs. *T* plot, in which *T* are averaged over the bases of columns, points for optically thick 3D columns will tend to be below and left of their 1D counterparts. Likewise, points associated with 3D columns receiving horizontally transported photons will tend to be above and right of their 1D counterparts. Given the fractal scaling nature of clouds (Cahalan and Snider 1989), this 1D-to-3D see-saw effect set up by $h \neq 0$ will occur over a range of magnitudes and scales across α vs. *T*-space with general differences being the following: on the left → 3D points are below and left of 1D points; mid-range → a scattering of 3D points surrounding 1D points; on the right → 3D points are above and right of 1D points. Therefore, relative to 1D model results, $h \neq 0$ will lever regression lines towards smaller α_0 and β. Satellite grid size can be increased in an attempt to make $h \rightarrow 0$, but a balance must be struck, for if grid size gets too big, poor sampling of T becomes a problem. If a satellite grid is large [e.g., $\gtrsim$ (50 km)^2], an hourly measurement of T represents a random sample drawn from a population characterized by a probability density function $p(T)$ whose mean is $\langle T \rangle$. Having error in T violates the common regression model (Arking et al. 1996) and can be shown to reduce both α_0 and β. If, however, several pyranometers are employed and $\langle T \rangle$ is known well, one runs the risk of having too many pyranometers near the perimeter of the grid and contaminated by $h \neq 0$.

Figure 1 shows values of a obtained by assuming (2) for data used by Cess et al. (1995; 1996). The unbelievably large ranges of a indicate that these data are afflicted by $h \neq 0$ and poor sampling of T. These cast doubt on any attempt to use them to assess 1D models. Note also the peculiar pattern of conditional variances for a: small for low α; huge for intermediate α; and tapering to small again for large α. This illustrates the inherent difficulty of dealing with partially cloudy cases. On the other hand, cases with largest α correspond to extensive, dense cloud conditions in which sampling errors for T were probably of little importance, and three of the four plots in Figure 1 indicate that as $\alpha \rightarrow 0.8$, $a \rightarrow$ ~0.2 (which may yet be overestimates given a likely

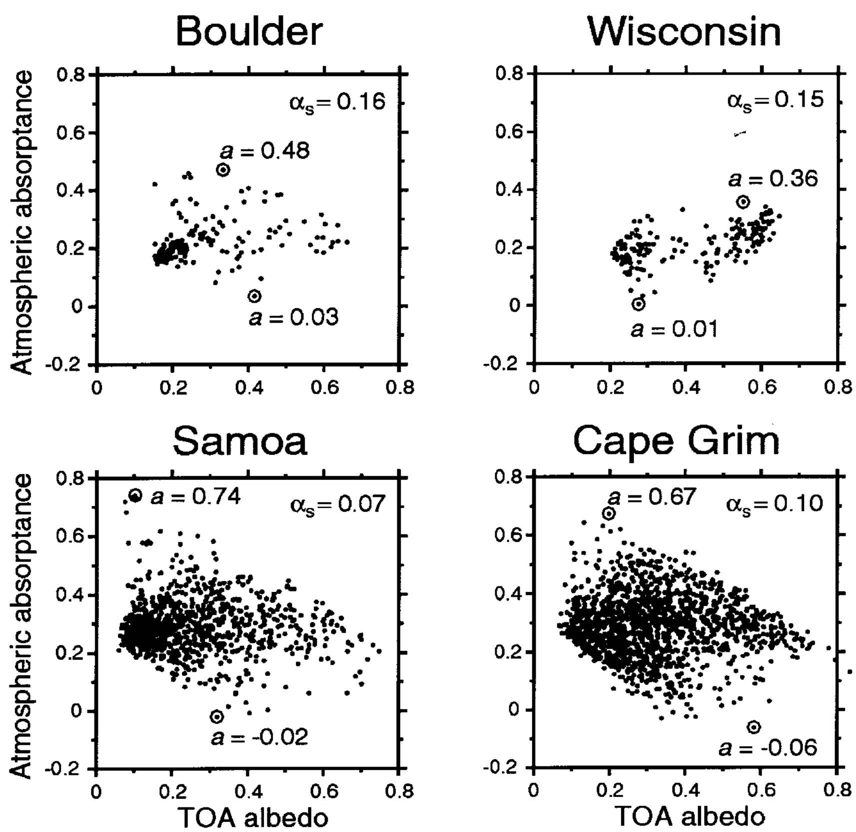

Figure 1. Implied values of a [obtained by applying (2)] as a function of TOA albedo for four datasets used by Cess et al. (1995; 1996). Assumed surface albedos are listed on the plots. Prevalence of anomalously small and large a for intermediate to small α are consistent with our arguments regarding non-vanishing h and poor sampling of T. Note the tendencies for a to be between 0.2 and 0.3 for large α and little trend in a as α increases; these do not support anomalous cloud absorption.

tendency for radiation to flow horizontally out of these columns). Certainly, values of *a* near 0.2 for heavily overcast conditions do not suggest extremely large cloud absorptances.

An Example of Illusory AA

This section demonstrates that hourly observational data cannot be treated as though it were 1D model data. This was achieved by initializing a 3D, broadband Monte Carlo (MC) radiative transfer algorithm with data from a cloud-resolving model. The MC algorithm is described by Barker et al. (1997). Each simulation used 5×10^6 photons, cyclic horizontal boundary conditions, and a Lambertian surface with albedo 0.06. The 3D cloud field was generated by a numerical simulation of the mesoscale convective system EMEX9 (Alexander 1995). Horizontal grid-spacing was 1.5 km and domain size was 120x144 km. Most clouds were at altitudes between 3 km and 7 km, though some reached 13 km.

MC estimates of α were generated by concatenating and averaging 1.5-km grid values into rectangular arrays (satellite grids) measuring 36x60 km (longest side almost parallel with advection). *T* were obtained either by averaging over satellite grids (i.e., $\langle T \rangle$), or by averaging two adjacent 1.5-km wide swaths (two swaths to improve MC statistics) running the length (60 km) of each grid. The latter method is more realistic as it approximates samples drawn from $p(T)$. Corresponding 1D results were obtained by simply setting the horizontal size of each column to 10^6 km and averaging as in the full 3D cases. Thus, they are actually grid-averaged results for independent 1D columns. Data were generated for four solar zenith angles (0°, 30°, 60°, and 75°) each using a fixed, but randomly selected, solar azimuth angle.

Figure 2a shows that for 36x60 km grids, the slope associated with 1D results β_{1D} [see (1)] using $\langle T \rangle$ is 0.85, which is consistent with other studies (e.g., Li et al. 1995). The corresponding 3D slope β_{3D} is just 0.54. This difference is *not* due to differences in domain-averaged (energy-weighted) *a*, for they are almost equal (see Figure 2a; cf., Barker et al. 1997; Marshak et al. 1997). Rather, it is due to the effects of $h \neq 0$. To solidify this point, the MC experiments were repeated with all atmospheric absorption eliminated. This produced $\beta_{1D} = 1$ (as expected) and $\beta_{3D} \approx 0.67$. Figure 2b shows that when twelve 3x60-km swaths of *T* are sampled from each grid, β_{3D} decreases from 0.54 to 0.38. This demonstrates the impact of effectively reducing pyranometer sampling time or number of pyranometers in a grid (i.e., poor representation of $\langle T \rangle$). A similar experiment, using scattered

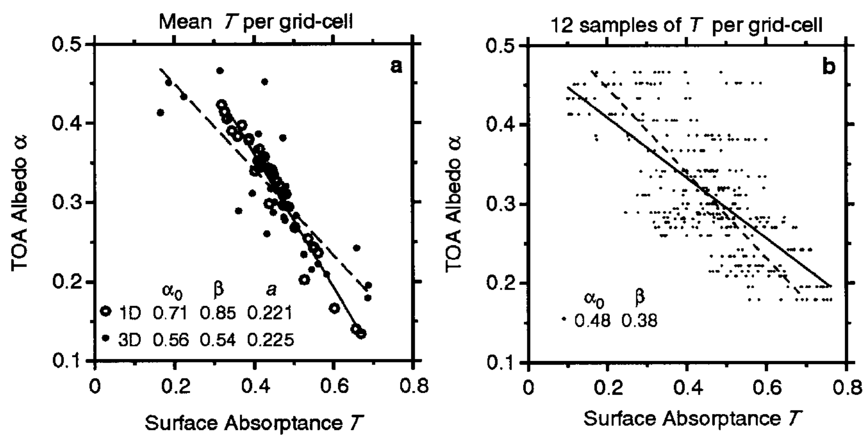

Figure 2. (a) Points formed using mean values of TOA albedo and surface absorptance averaged over the base of the satellite grids which measured 36x60 km. 1D values are for the Monte Carlo run in independent column mode, while 3D values are the full 1.5 km horizontal resolution. Regression line parameters are listed on the plot in addition to grid-averaged atmospheric absorptances *a*. (b) Rather than using mean *T* over the grids, surface absorptances were estimated for 12 swaths in each grid. Each swath measured 3x60 km and approximated what pyranometers would have measured. Solid regression line is for this case (parameters listed) and dashed line is the 3D line in (a).

very shallow cumulus (satellite grids measured ~8x30 km) showed horizontal transport to be unimportant (i.e., $h \approx 0$ almost everywhere) but poor sampling of T reduced α_0 and β by about 0.07 relative to use of $\langle T \rangle$.

For 1D models, it can be shown that the ratio R between domain-averaged, energy-weighted accumulations of surface cloud radiative forcing (CRF) and TOA CRF is *approximately* equal to $1/\beta_{1D}$ (provided the α vs. T analysis avoids very low sun conditions). For the 1D experiment, $R = 1.06$ which is fairly close to $1/\beta_{1D} \approx 1.18$. On the other hand, for the 3D case, $R = 1.09$ but, depending on the method used to get T, $1/\beta_{3D}$ ranges from 1.85 to 2.63. This illustrates that $h \neq 0$ and uncertain T destroy the simple 1D relation between R and $1/\beta$.
α_{1D}
As for the α-intercept, $\alpha^{1D}{}_0$ is 0.71, while the values of α^{1D}_0 are 0.56 when $\langle T \rangle$ are used and 0.48 when twelve 3-km wide swaths of T for each grid are used. Again, these differences have nothing to do with cloud absorption, just apparent absorption (Zuev and Titov 1995). Moreover, note that α_0 is a rather extreme quantity when viewed as the extrapolation of the phase portrait of the radiative transfer process back to infinite optical depth for overcast cloud.

Conclusion

The horizontal dimensions of ill-defined atmospheric columns associated with hourly measurements of α and T are: small enough that h through their sides are non-negligible, yet large enough to admit substantial sampling errors in T. Thus, unlike 1D models, for any pair of measured (T, α), one cannot be sure that $1 - \alpha - T = a$ is true, where a is actual column absorptance. In the real atmosphere, radiation tends to flow horizontally from regions of relatively high to relatively low optical density. Hence, α and T for hourly data will tend to be less than corresponding 1D values for relatively dense regions and greater than 1D values for regions of relatively low density. Moreover, since a pyranometer only samples T over the base of a column, uncertainties in T stemming from cloud variability enhance the range of T, while leaving α untouched. Thus, regardless of grid-averaged a, regression lines for hourly data will be more horizontal and have smaller α-intercepts than their 1D counterparts.

These effects cannot be averaged out of hourly data and can conspire to create the *illusion* of anomalous cloud absorption (as long as hourly radiometric observations are assumed to be tantamount to 1D model data). This was demonstrated using a 3D Monte Carlo algorithm and a model-generated cloud field. In short, results obtained from α vs. T analyses of hourly observational data and 1D radiative transfer models are not comparable: differences presented in previous studies (Cess et al. 1995; 1996) cannot be attributed solely to anomalous absorption. Based on the arguments and results presented here, suitable conditions needed to intercompare observational and 1D model α vs. T analyses are: several pyranometers in a large satellite grid with long averaging periods (see Figure 1; cf., Li et al. 1995).

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