GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 16, PAGES 2023-2026, AUGUST 15, 1997

Interpreting shortwave albedo-transmittance plots: True or apparent anomalous absorption?

Howard W. Barker

Cloud Physics Research Division, Atmospheric Environment Service, Downsview, Ontario, Canada

Zhanqing Li

Canada Centre for Remote Sensing, Ottawa, Ontario, Canada

Abstract. The coefficients of linear regression lines fit to hourly observations of atmospheric transmittance and TOA albedo have been used previously to address the problem of anomalous cloud absorption (ACA). While these coefficients indicate, reasonably well, the impact of clouds on atmospheric absorptance for 1D model data, this is not necessarily the case for hourly data. This is because for non-uniform clouds, regression coefficients are reduced significantly relative to 1D model results due to the effects of horizontal transport of radiation and poor sampling of transmittance. These reductions are only illusions of ACA because domain-averaged atmospheric absorptances are almost insensitive to cloud geometry. The ramifications of these effects can be seen in hourly data that were used in a previous study which claimed to support ACA. They are also demonstrated with a 3D Monte Carlo, broadband radiative transfer algorithm acting on data generated by a cloud-resolving model.

Introduction

Debate over atmospheric absorption of shortwave radiation [see *Stephens and Tsay,* 1990] has been fuelled by suggestions of ubiquitous, excessive absorption by clouds [*Cess et al., 1995*, 1996; *Ramanathan et al.*, 1995; *Pilewskie and Valero,* 1995]. In turn, these suggestions have been challenged by several studies [*Li et al.*, 1995; *Arking et al.*, 1996; *Stephens*, 1996]. To clarify this issue, methodologies and data employed must be scrutinized.

Crucial pieces of evidence presented in support of anomalous cloud absorption (ACA) involve parameters of the assumed linear relationship between all-sky, broadband top-of-atmosphere (TOA) albedo α and atmospheric transmittance T [*Cess et al., 1995*, 1996]. These studies used hourly-integrated T inferred from a pyranometer(s) and grid-averaged α inferred from collocated satellite imagery. The claim is that because 1D radiation models yield larger regression coefficients than do hourly data, real clouds absorb much more than model clouds. This reasoning is, however, deductively invalid for the premises may be true despite a false conclusion (i.e., coefficients may differ for reasons other than ACA). The purpose of this paper is to discuss mechanisms that create the illusion of ACA on α vs. T plots when hourly observations are assumed to be tantamount to 1D model results.

The second section reviews the α vs. T method, states differences between 1D and hourly data, and shows hourly data that are at odds with 1D theory. The third section shows α vs. T plots which stem from application of a Monte Carlo photon transport algorithm to a 3D atmosphere generated by a cloud-resolving model. Concluding statements are made in the last section.

The α vs. T Method: Applications to 1D and 3D Atmospheres

Let T and α denote surface absorptance and TOA albedo, respectively. The α vs. T method involves creating a scatterplot with pairs of (T,α), from either models or measurements, and fitting

$$\alpha = a - bT, \tag{1}$$

to them via least-squares regression (since T represents surface absorptance, values of b reported here would have been $b\,/\,(1-s)$, were s is surface albedo, had T represented transmittance). If a and b for observational data and 1D model data are to be compared, one must assume that the energy budgets of their respective Earth-atmosphere columns are the same. This means that all measured pairs of T and α must satisfy

$$\mathrm{A} = 1 - a - T, \tag{2}$$

where A is total atmospheric absorptance.

Application of the α vs. T method to hourly data uses instantaneous satellite imagery, measured inside the hour, that contained, statistically, the clouds whose signal determined the pyranometer measurement. Studies that used hourly data and claim to support ACA employed satellite grids of $(\sim 10\text{ km})^2$ to $(\sim 100\text{ km})^2$ [*Cess et al., 1995*, 1996]. These grids form intrinsically ill-defined *columns* that are probably both narrow enough that net horizontal fluxes h through their sides often differ from 0, but wide enough that hourly pyranometer data sample poorly the impact of

Paper number 97GL02019.
0094-8534/97/97GL-02019$05.00

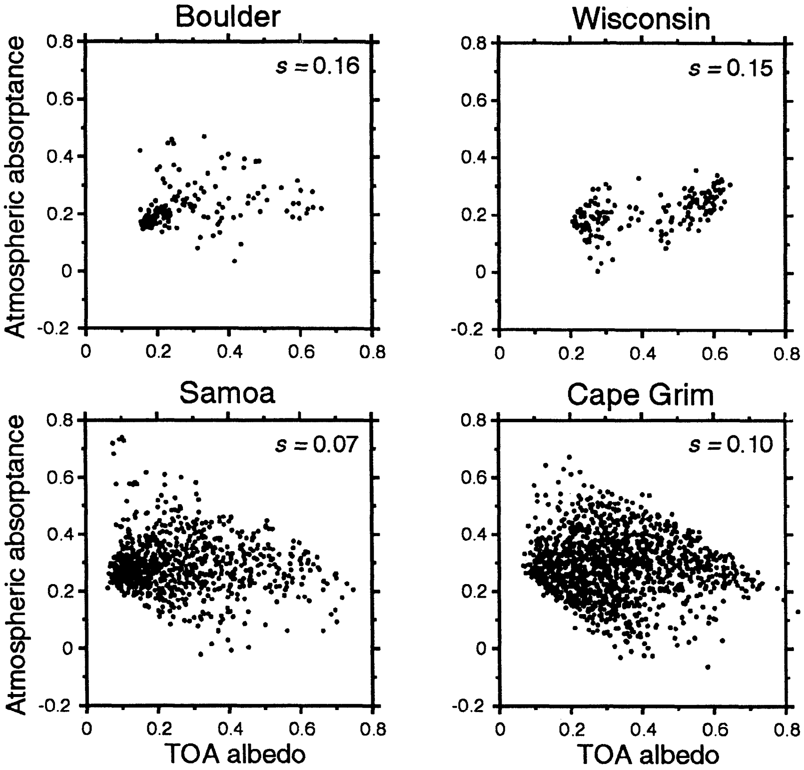

Figure 1. Implied values of atmospheric absorptance as a function of TOA albedo obtained by applying (2) to four datasets used by *Cess et al.* [1995; 1996]. Assumed values of surface albedos are listed on the plots: Boulder's value was measured.

cloud variability over their bases. These conditions invalidate (2) and raise the questions: for hourly data, what are the impacts on an α vs. *T* plot of: (i) *h* different from 0; and (ii) poor sampling of mean surface absorptance ‹*T*›? While the latter was addressed using a simple conceptual model [*Arking et al.,* 1996], both questions are investigated in the next section using a more rigorous model simulation.

But first, consider some hourly data that display definite signs of incongruity with 1D model data. Figure 1 shows values of A obtained by assuming (2) for hourly data used by [*Cess et al., 1995*, 1996]. The enormous ranges of A (from < 0 to > 0.7) are sure signs of large |*h*| and poor sampling of ‹*T*› and cast doubt on any attempt to use them to assess 1D models and ACA. Note also the peculiar patterns of conditional variance for A: small when α is very small (clear); huge for intermediate α (partly cloudy); and tapering to small again for large α (cloudy). The extreme variance of A for intermediate α is an expected by-product of both large |*h*| and poor sampling of ‹*T*›. On the other hand, both these effects are minimized for extremely small and large α which correspond to clear-sky and extensive overcast. Thus, it is significant that for three of the plots in Fig. 1, A is ~0.2 for both clear-skies and heavy overcasts.

Apparent Anomalous Cloud Absorption: An Example

The purpose of this section is to demonstrate, by example, how large |*h*| and poor sampling of ‹*T*› manifest themselves in hourly data and create the illusion of ACA on α vs. *T* plots. This was achieved for a single cloud field used as input for a 3D Monte Carlo (MC), broadband radiative transfer algorithm [*Barker et al.,* 1997] that accounts for: scattering by cloud droplets and air molecules; absorption by droplets; and absorption by water vapour, ozone, and six uniformly mixed gases. Cloud optical properties follow *Slingo's* [1989] 24-band parameterizations and gaseous transmittance functions for 375 bands are based on HITRAN92 data. Each simulation used $5x10^6$ photons, a Lambertian surface with albedo 0.06, and cyclic horizontal boundary conditions.

The 3D cloud field was generated by the Regional Atmospheric Modeling System's [*Pielke et al.,* 1992] simulation of the mesoscale convective system EMEX9 [*Alexander,* 1995]. Horizontal grid-spacing was 1.5 km and domain size was 120 x 144 km. Only cloud liquid water and water vapour were used. Inclusion of ice, which blanketed the domain, reduced the clarity of this example but did not alter the main conclusions. Clouds were advecting at ~40 km hr^{-1} and most were at altitudes between 3 km and 7 km (though a few towers reached 13 km). Vertically-projected cloud fraction was ~0.45, and mean cloud optical depth (at 0.5 μm) was ~120 but several towers had optical depths in excess of 1000.

MC estimates of α were generated by grouping 1.5 km values into rectangular (satellite) grids. Results are presented only for grids of 36 x 60 km which are probably ideal for hourly data. *T* were obtained two ways: (i) by averaging over satellite grids (i.e., ‹*T*›); and (ii) by averaging two adjacent 1.5 km swaths running the 60 km length of grids almost parallel with advection. The latter method approximates a pyranometer which actually corresponds to swaths about 5 cm across (two swaths were used simply to improve MC statistics). To get corresponding 1D results, MC simulations were performed using horizontal grid-spacings of 10^6 km. Thus, 1D values of ‹*T*› and α are actually grid-

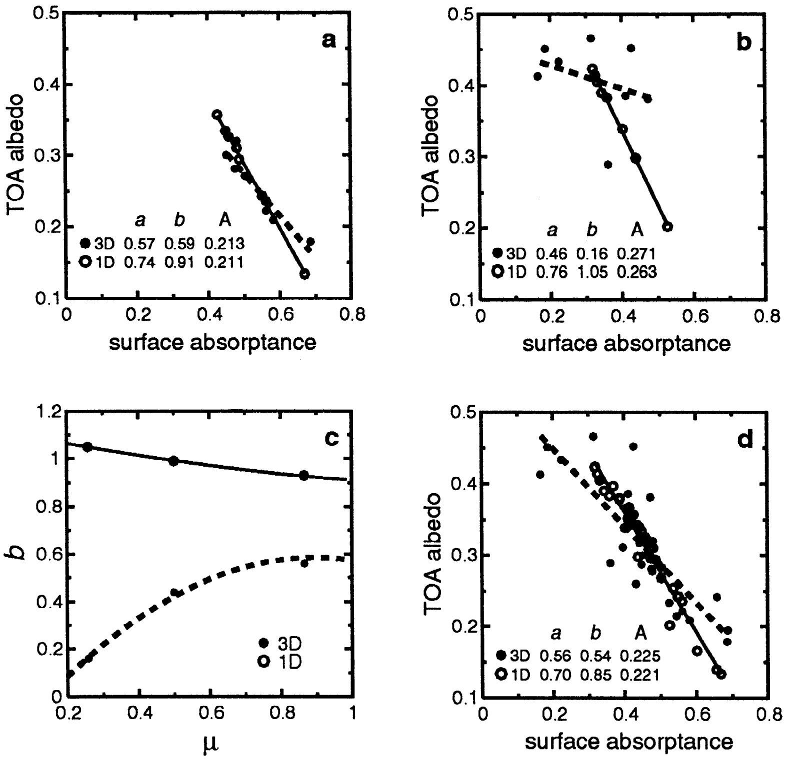

Figure 2. (a) α vs. T plot for Monte Carlo (MC) simulations using cloud resolving model data for θ = 0°. Points labelled as 1D and 3D refer to radiative transfer simulations done using horizontal grid-spacings of 10^6 km (i.e., independent columns) and 1.5 km, respectively. Each point represents mean α and T (i.e., $\langle T \rangle$) for grids measuring 36 x 60 km. As such, MC errors are < 0.0006. Solid and broken lines are least-square linear regression fits to 1D and 3D data. Regression intercepts and slopes, and domain-averaged absorptances are listed on the plots. (b) Same as (a) except for θ = 75°. (c) Slopes of regression lines as functions of cosine of the solar zenith angle μ. (d) As in (a) and (b) but points for all θ (0°, 30°, 60°, and 75°) are included and fit with regression lines whose parameters are listed on the plot. Domain-averaged atmospheric absorptances were weighted by μ and averaged.

averaged independent column approximations which have (a,b) that are very similar to those for homogeneous 1D models. Four solar zenith angles θ were used: 0°, 30°, 60°, and 75°. For each θ, solar azimuth angle ϕ was fixed but selected at random (1D results are independent of ϕ and almost independent of grid size).

Figure 2 shows α vs. T plots in which $\langle T \rangle$ were used. Figure 2a shows that for high Sun (θ = 0°), a(3D) – a(1D) = –0.17 and b(3D) – b(1D) = –0.32 are strikingly large yet have nothing to do with cloud absorption or the impact of clouds on A, for as listed on the plots, domain-averaged A differ by less than 1% (the insignificant edge going to 3D). For this case, all clouds cast shadows into their own grid. Therefore, differences between 1D and 3D coefficients are due to scattered radiation giving rise to non-zero h.

In a 3D atmosphere, scattered radiation is channelled horizontally from relatively thick columns to relatively thin columns [*Davis,* 1992]. Thus, relative to 1D points on an α vs. T plot, this translates into a tendency for points on the left (relatively thick columns) to leak radiation horizontally to points further right (relatively thin columns). As is evident from Fig. 2a, 3D points on the left tend to be below their 1D counterparts while, points further right tend to be above and right of their 1D counterparts [cf., *Welch and Wielicki,* 1984; *Barker et al.,* 1997]. Given the fractal scaling nature of clouds [*Cahalan and Snider,* 1989], this effect will occur for a range of magnitudes and scales across α vs. T-space with general differences being: on the left, 3D points below 1D points; in the mid-range, a scattering of 3D points sur- rounding 1D points; on the right, 3D points above and right of 1D points.

Figure 2b is for much lower Sun (θ = 75°). For the 3D case, unlike its 1D counterpart, the relationship between α and $\langle T \rangle$ has almost vanished. This stems from clouds casting shadows into neighbouring grids which increasingly impact $\langle T \rangle$ strongly but have little effect on α [cf., *Arking et al.,* 1996]. As a result, a(3D) and b(3D) decline substantially with increasing θ, but note again that domain-averaged A for 1D and 3D are almost identical.

Figure 2c shows b(1D) and b(3D) as functions of μ (= cosθ). Despite the decline of b(3D) with decreasing μ, *Barker et al.* [1997] show that this 3D cloud field reduces A relative to clear-sky absorptance for μ < 0.3. This demonstrates the potential deceptiveness of the α vs. T method: b can be << 1 yet all-sky A can be *less than* clear-sky A.

Figure 2d is the usual α vs. T plot in which all points are fit with a single regression line. Since a(1D) and b(1D) are less than their μ-specific counterparts, this indicates that even for 1D models α vs. T can be ambiguous. This then highlights yet another contribution to the illusion of ACA, and shows that care must be taken when comparing coefficients for instantaneous and time-averaged 1D model data. Despite these slight anomalous reductions, overall values of a(3D) and b(3D) are still 0.15 and 0.31 less than their

1D companions. Hence, if 3D and 1D datasets were assumed to be tantamount, one would conclude from Fig. 2d that 3D clouds are far more absorptive than 1D clouds which is not true [*Barker et al.,* 1997; *Marshak et al.,* 1997]. To solidify the main point, the MC experiments were repeated with all atmospheric absorption eliminated. This yielded $b(1D) = 1$ (as expected) and $b(3D) = 0.73 << 1$.

In an attempt to minimize h, satellite grids could be expanded but a balance must be struck for if grids become too large, poor sampling of $\langle T \rangle$ becomes a problem. This is because hourly measurements of T represent random samples drawn from a population characterized by a probability density function whose mean over the base of the satellite grid is $\langle T \rangle$. Having error in T, which increases with gridsize, invalidates the regression model advocated by [*Cess et al., 1995*, 1996] and can be easily shown [*Arking et al.,* 1996] to reduce both a and b relative to use of $\langle T \rangle$. If several pyranometers are employed and $\langle T \rangle$ is known well, one returns to the original problem and risks having too many pyranometers near the perimeter of the grid and contaminated by non-zero h.

To illustrate this sampling issue, when T for each 36 x 60 km grid was represented by a single 3 x 60 km swath selected at random, the mean and standard deviation of $b(3D)$ for 15 realizations was 0.40+/−0.04. A similar experiment using sampled T for a field of scattered, very shallow cumulus (satellite grids of ~8 x 30 km) showed $h \cong 0$ almost everywhere but poor sampling of $\langle T \rangle$ reduced a and b by about 0.07 relative to use of $\langle T \rangle$.

Finally, 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 $1 / b(1D)$ (avoiding sampling over very wide ranges of θ). For the 1D experiment, $R = 1.06$ which is very close to $1 / b(1D)$ evaluated for high Sun (see Figs. 2a and 2c). For the 3D case, however, $R = 1.09$ which is far less than $1 / b(1D)$ regardless of how T is obtained. This illustrates that non-zero h and uncertain T destroy the simple 1D relation between R and $1 / b$.

Conclusion

The main point of this paper is that linear regression parameters obtained by fitting hourly measurements of α and T cannot be compared with corresponding parameters for 1D models in order to assess whether anomalous cloud absorption (ACA) exists. This is because the horizontal dimensions of ill-defined atmospheric columns associated with hourly measurements are both small enough that fluxes through their sides are non-negligible, yet large enough to admit substantial sampling errors in T. By applying a 3D Monte Carlo algorithm to a cloud field generated by a cloud-resolving model, it was demonstrated that these effects create the illusion of ACA as long as hourly radiometric observations are assumed to be tantamount to 1D model data. The illusion stems from the fact that both effects act to reduce the coefficients of linear regression lines associated with hourly data relative to their 1D counterparts. The ramifications of these effects are clearly visible in hourly data used by [*Cess et al., 1995*, 1996]. At the very least, our analysis demonstrates that differences between hourly and 1D model α vs. T coefficients cannot be ascribed solely to ACA.

Acknowledgements. We are grateful to G. D. Alexander for providing EMEX9 data, J.-J. Morcrette for creating gaseous transmittance functions for the MC algorithm, and B. Wielicki for computer time. Discussions with A. Arking, A. Davis, A. Marshak, L. Oreopoulos, and G. Stephens were very helpful.

References

Alexander, G.D., The use of simulations of mesoscale convective systems to build a convective parameterization scheme, Ph.D. dissertation; atmospheric science paper No. 592, Colorado State University, 232pp., 1995.

Arking, A., M.-D. Chou, and W.L. Ridgway, On estimating the effect of clouds on atmospheric absorption based on flux observations above and below cloud level, *Geophys. Res. Let., 23*, 829-832, 1996.

Barker, H.W., J.-J. Morcrette, and G.D. Alexander, Broadband solar fluxes and heating rates for atmospheres with 3D broken clouds, *Q. J. R. Meteorol. Soc.* in press, 1997

Cahalan, R.F. and J.B. Snider, Marine stratocumulus structure, *Remote Sens. Environ., 28*, 95-107, 1989.

Cess, R.D., et al., Absorption of solar radiation by clouds: Observations versus models, *Science, 267*, 496-499, 1995.

Cess, R.D., M.H. Zhang, Y. Zhou, X. Jing, and V. Dvortsov, Absorption of solar radiation by clouds: Interpretations of satellite, surface, and aircraft measurements, *J. Geophys. Res., 101*, 23299-23309, 1996.

Davis, A.B., Radiative transport in scale invariant optical media. Ph.D. thesis, McGill University, 332pp., 1992.

Li. Z., H.W. Barker, and L. Moreau, The variable effect of clouds on atmospheric absorption of solar radiation, *Nature, 376*, 486-490, 1995.

Marshak, A., A. Davis, W. Wiscombe, W. Ridgway, and R. Cahalan, Biases in shortwave column absorption in the presence of fractal clouds, *J. Climate*, in press 1997.

Pielke, R.A., et al., A comprehensive meteorological modeling system - RAMS, *Meteorol. Atmos. Phys., 49*, 69-91, 1992.

Pilewskie, P. and F.P.J. Valero, Direct observations of excess solar absorption by clouds, *Science, 267*, 1626-1629, 1995.

Ramanathan, V., et al., Warm pool heat budget and shortwave cloud forcing: A missing physics?, *Science, 267*, 499-503, 1995.

Slingo, A., A GCM parameterization for the shortwave radiative properties of water clouds, *J. Atmos. Sci., 46*, 1419-1427, 1989.

Stephens, G.L. and S.-C. Tsay, On the cloud absorption anomaly, *Q. J. R. Meteorol. Soc., 116*, 671-704, 1990.

Stephens, G.L., How much solar radiation do clouds absorb?, *Science, 271*, 1131-1133, 1996.

Welch, R.M and B.A. Wielicki, Stratocumulus cloud field reflected fluxes: The effect of cloud shape, *J. Atmos. Sci., 41*, 3085-3103, 1984.

H.W. Barker, Cloud Physics Research Division (ARMP), Atmospheric Environment Service, 4905 Dufferin St., Downsview, ON, Canada, M3H 5T4. (e-mail: howard.barker@ec.gc.ca)

Z. Li. Canada Centre for Remote Sensing, 588 Booth St., Ottawa, ON, Canada, K1A 0Y7. (e-mail: li@ccrs.emr.ca)

(Received February 28, 1997; revised: June 19, 1997;
accepted: July 8, 1997.)