Two Methods for Removing the Effect of Horizontal Fluxes from Stacked Aircraft Measurements of Shortwave Absorption by Clouds

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Introduction

Cloud absorption, as inferred from the difference between net fluxes measured with stacked aircraft, is strongly affected by horizontal inhomogeneity. The simplest way to compensate for variability effects is to perform grand averages over flight legs (Valero et al. 1997). If the flight legs are long enough (several hundred km), averaging leads to a reliable estimate of column absorption (Ramanathan and Vogelmann 1997). The only problem here is that the amount of information on "true" absorption (the data harvest) returned from an expensive measurement program is very limited.

In this paper, we discuss how to enhance the harvest of true absorption data using two related methods, which we call a) subtraction method and b) conditional sampling. Both methods use additional spectral information assuming that, simultaneously with broadband measurements (or absorbing narrowband measurements), nonabsorbing narrowband fluxes are also available. Both methods are related to Ackerman and Cox's (1981) correction and offer an alternative to spatial averaging; namely, differencing fluxes in transparent and absorbing bands will supposedly remove three-dimensional (3-D) effects and produce, thus, an estimate of true absorption (Hayasaka et al. 1995):

$$A(x) = \left[R_{no\_abs}(x) - R_{abs}(x)\right] + \left[T_{no\_abs}(x) - T_{abs}(x)\right], \quad 0 \le x \le L. \tag{1}$$

For simplicity, we assumed no upward fluxes below clouds. A(x), R(x), T(x) are respectively estimates of absorption and measurements of albedo and transmittance, all at point x; L denotes the outer scale (for models) or a flight leg (for measurements).

Cloud Model

A bounded cascade model (Cahalan 1994) is used to simulate horizontal variability of cloud optical depth. In addition to internal cloud structure, gaps are added in an ad hoc manner (Marshak et al. 1998a). Cloud top variability is "H = 1/3" fractional Brownian motion, uncorrelated with the bounded cascade, and standard deviation matching nine marine stratocumulus observed by cloud radar during the Atlantic Stratocumulus Transition Experiment (ASTEX) (Zuidema and Evans 1998).

Marshak et al. (1997) used a narrowband around 0.94 mm, with strong but horizontally homogeneous (water vapor) absorption and inhomogeneous (liquid water) scattering. Here we do not specify a spectral band; rather we study the effect of different degrees of absorption and scattering (by the inhomogeneous liquid water) with no water vapor absorption.

Absorption and Horizontal Fluxes

We need to distinguish between "apparent" and "true" column absorption. True absorption is

$$A_{true}(x) = \int_{z_b}^{z_t} \sigma_{abs}(\varpi_0, x, z) \int_{4\pi} I(\Omega; x, z)\, d\Omega\, dz, \quad 0 \le x \le L \tag{2}$$

where z_b and z_t are (constant) cloud bottom and (maximal) top altitudes, respectively; $\alpha_{abs}(\varpi_0,x,z)$ is the absorption coefficient, and I(Ω;x,z) is radiance. Apparent absorption is defined as the difference between two net fluxes at z_b and z_t,

$$A_{app}(x) = [1 - R(x)] - [T(x) - 0]$$
$$= 1 - \int_{2\pi+} \Omega / I(\Omega; x, z_t)\, d\Omega - \int_{2\pi-} \Omega / I(\Omega; x, z_b)\, d\Omega \quad (3)$$

Differencing absorptions (2–3) yield horizontal fluxes at each x (Ackerman and Cox 1981, Davis et al. 1997, Marshak et al. 1998a, Titov 1998),

$$H(x) = A_{app}(x) - A_{true}(x) \quad (4)$$

Horizontal flux averaged over scale L (denoted by $\langle\cdot\rangle$) vanishes if L is large enough; we can express this as

$$\langle A_{app} \rangle \to \langle A_{true} \rangle, \; L \to \infty \quad (5)$$

For all scales r < L, we have, at best,

$$A_{app}(r; x) = \frac{1}{r} \int_x^{x+r} A_{app}(x')\, dx'$$
$$\approx \frac{1}{r} \int_x^{x+r} A_{true}(x')\, dx' = A_{true}(r; x) \quad (6)$$

To measure how well A_{app} approximates A_{true} at scale r, we introduce the relative discrepancy,

$$E(r) = \frac{\langle | A_{app}(\cdot, r) - A_{true}(\cdot, r) | \rangle}{\langle A_{true} \rangle} = \frac{\langle | H(\cdot, r) | \rangle}{\langle A_{true} \rangle} \quad (7)$$

Let E* > 0 be an accuracy threshold; solution of

$$E(r) = E^* \quad (8)$$

gives us a corresponding averaging scale r*. The integer part of ratio L/r* is an estimate of the number of non-overlapping spatially averaged data where the accuracy of measurements of column absorption is better than E*. For oblique illumination and complex cloud structure/geometry, the ratio L/r* can become sufficiently small (even less than 1); hence, little (if any) information on column absorption is returned after the flight leg of length L. Below we describe a procedure that modifies A_{app} by using spectral information (Ackerman and Cox 1981) and radiative smoothing theory (Marshak et al. 1995, Davis et al. 1997); this reduces r*.

Subtraction Method

Fluctuations of the apparent absorption (3) do not follow those of the true absorption (2). Figure 1 shows wavenumber spectra S(k) of a scale-invariant model of cloud optical depth along with those of true and apparent absorptions. First, we see that true absorption fields $A_{true}(x)$ are also scale-invariant, with a similar spectral exponent to the optical depth field. This is true for all solar angles. In contrast, the apparent absorption $A_{app}(x)$ has three distinct regimes: small scales where $A_{app}(x)$ is smoother than $A_{true}(x)$; intermediate scales where $A_{app}(x)$ is the more variable; and large scales where the two fields have similar fluctuations.

It follows from here that, to improve the performance of a true absorption estimate based on its apparent counterpart, we need to adjust the behavior of A_{app} for both small and intermediate scales. In this section, we focus on the intermediate scales using net flux measurements in a conservative spectral band.

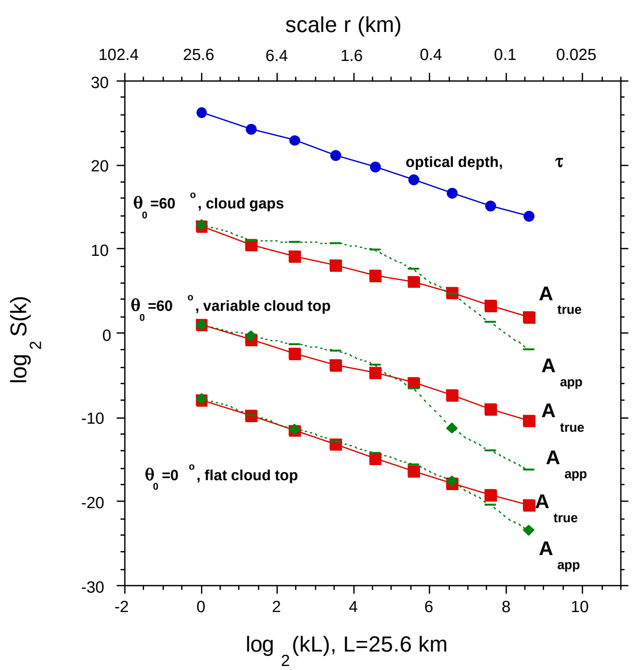

Figure 1. Wavenumber spectra of optical depth and true and apparent absorption fields for ϖ_0 = 0.99. All statistics are averaged over 10 realizations of the cloud model. For clarity, the two lower pairs curves are shifted by 15 and 20, respectively. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/wiscombe-98.pdf*.)

Following Ackerman and Cox (1981), we assume that interactions between photons and inhomogeneous clouds are strongly correlated for conservative and absorbing wavelengths. Then, if we subtract point-by-point the apparent absorption for conservative scattering from the apparent absorption for absorbing spectral bands [as in Eq. (1)], we obtain a better approximation to A_{true}. The effect of this procedure is the most pronounced in case of complex geometry and oblique illumination (see energy spectra for gappy clouds in Figure 1). Indeed, the more geometrically complex cloud shapes are the more horizontal fluxes are correlated because first order of scattering plays a dominant role in tracking geometrical structures.

Figure 2 shows the entire wavenumber spectrum for gappy clouds and θ_0 = 60°. We see that the subtraction method removes strong fluctuations at intermediate scales and makes A_{sub} *a smoothed version* of A_{true}. This statement is valid for any solar angle complex cloud structure.

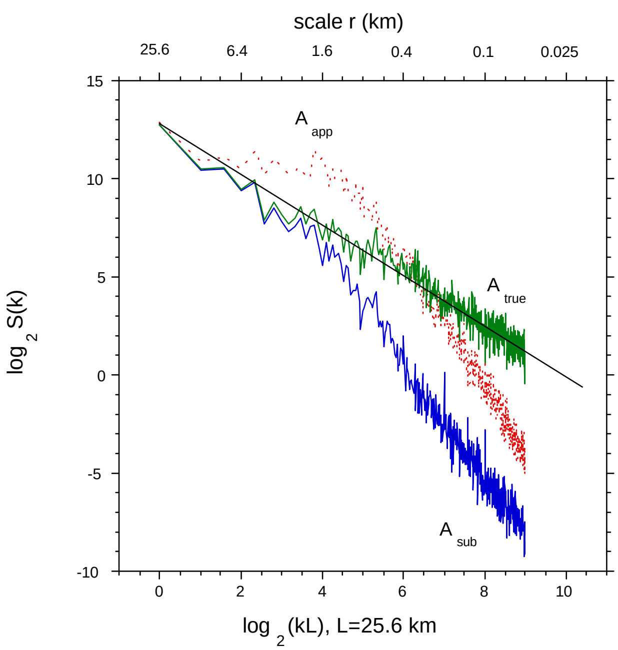

Figure 2. Spectra of three absorption fields, gappy clouds with ϖ_0 = 0.99 and θ_0 = 60°. Scale-invariance of true absorption is illustrated by a linear fit. (For a color version of this figure, please see *http://www. arm. gov/docs/documents/technical/conf_9803/wiscombe-98. pdf*.)

From a Smooth Field to a Rougher One

As we see from Figure 2, A_{sub} field is too smooth to be a good point-by-point approximation to A_{true}. To further improve A_{sub}, we have to "roughen" both small and intermediate scales. The smoothing of a scale-invariant radiation field like A_{true} can be grounded in the theory of radiative smoothing (Marshak et al. 1995, Davis et al. 1997). In that framework, there is a two-parameter family of G-type distributions that can used in convolutions with A_{true} to approximate A_{sub}, i.e.,

$$A_{sub}(x) = A_{true}(x) * G(\alpha, \eta; x) \qquad (9)$$

where $G(\cdot)$ is a parameterized approximation to the reflected Green function for radiative transfer, η is the characteristic radiative smoothing scale and α determines the small-scale behavior.

It follows from Eq. (9) that, to retrieve A_{true} from A_{sub}, one has to solve the integral equation

$$A_{sub}(x) = \int G(x-y; \alpha, \eta)\, A_{ret}(y)\, dy \qquad (10)$$

for $A_{ret}(x)$, which will approximate $A_{true}(x)$. Note that Eq. (10) is an "ill-posed" problem that requires regularization, as described in Marshak et al. (1998b).

Figure 3 illustrates the effects of solving Eq. (10). With threshold E* = 3.5 %, the new averaging scale r* = 0.4 km is 4 to 5 times smaller than for the subtraction method alone. So we obtain at least four times more statistically reliable data points with estimates of true absorption to better than ≈3.5 %.

Conditional Sampling

Even in a "worst-case" configuration of complex geometry and oblique illumination (resulting in large horizontal fluxes) there are many points that lie on the diagonal when one plots $A_{app}(x)$ vs. $A_{true}(x)$ for each x ε [0,L]. At these points, we have good agreement between $A_{true}(x)$ and $A_{app}(x)$.

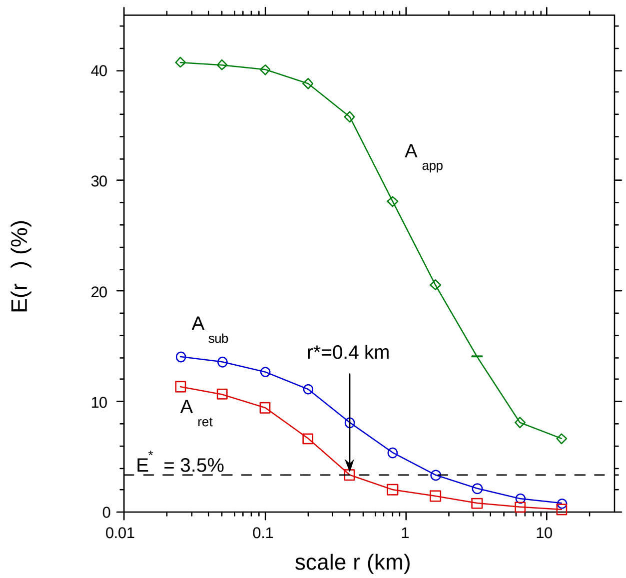

Figure 3. Discrepancy E(r) after applying the subtraction procedure and then deconvolution (10). Clouds had variable top, ϖ_0 = 0.99 and θ_0 = 60°; Γ-distribution parameters were η = 0.175 km and α = 1.2, regularization parameter (see Marshak et al. 1998b) γ = 0.0075. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/wiscombe-98.pdf*.)

This subset of data points occupies the whole diagonal and map to a variety of cloud optical depths and different local geometrical shapes. If one can discriminate these points, the harvest of reliable data will be substantially increased. So the question is "How can we recognize these points in the observations?" Based on Eq. (4), these points correspond to the locations with vanishing horizontal fluxes:

$$H_{abs}(x) = 0 \qquad (11)$$

Now we assume that where horizontal fluxes vanish in the absorbing spectral region are close in space to points having zero horizontal fluxes in the spectral bands with conservative scattering:

$$U_\varepsilon = \{ x : |H_{no\_abs}(x)| \le \varepsilon \} \qquad (12)$$

Taking into account that $H_{no\_abs}(x)$ can be measured, we propose a conditional-sampling method: sample only those data-points that belong to U_ε. The apparent absorption in those points should be an improved local estimate of the true absorption.

Figure 4 is a scatter plot of $A_{app}(x)$ vs. $A_{true}(x)$ for both x ε [0,L] and x ε $U_{0.01}$. The set $U_{0.01}$ contains about 6% of all points, with cloud optical depths from 0 (clear sky) to over 100; these points are located all along the flight leg from 0 km to 256 km.

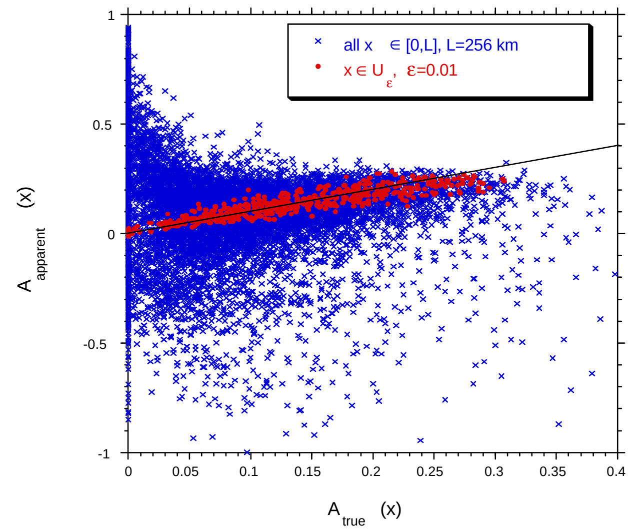

Figure 4. Scatter plot of $A_{app}(x)$ vs. $A_{true}(x)$ for x[0,L] (crosses) and x$U_{0.01}$ (bold circles), respectively. For notations, see Eq. (12). Gappy clouds with ϖ_0 = 0.996 and θ_0= 60°. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/wiscombe-98.pdf*.)

In general, the above assumption is not strictly valid. Even the set $U_{0.01}$ plotted in Figure 4 has outliers with $|H_{abs}(x)| > 0.1$ and, of course, $A_{app}(x)$ at these points is not a good estimate of $A_{true}(x)$. However, most of x ε $U_{0.01}$ (60 % in our case) have $|H_{abs}(x)| \le 0.02$ and, there, $A_{app}(x) \approx A_{true}(x)$.

Summary

Cloud absorption is difficult to measure. If inferred from the difference between net fluxes at fixed altitudes (below and above clouds), as in a stacked aircraft experiment, then horizontally inhomogeneous cloud structure will invariably affect the column absorption estimates. So, if spatial averaging is insufficient, it is impossible to distinguish between enhanced cloud absorption and natural variability in cloud structure (Francis et al. 1997, Barker and Li 1997, Marshak et al. 1997).

Severe averaging requirements on stacked aircraft measurement campaigns (Evans 1997, Marshak et al. 1997) lead to a meager "data harvest" from quite expensive experiments. This paper describes two ways of increasing the data harvest by removing 3-D effects in absorption estimates. Both methods use the assumption—first articulated by Ackerman and Cox (1981)—that 3-D effects in absorbing wavebands are similar to those in a non-absorbing band.

The first ("subtraction") method subtracts point-by-point horizontal fluxes measured in a transparent band from the apparent absorption A_{app} measured in the absorbing bands. As a result, we obtain A_{sub}, which is far less affected by the cloud's horizontal inhomogeneity than the original A_{app}. The resulting field A_{sub} is, however, much smoother than the true absorption field A_{true} that we ultimately want to retrieve. To roughen A_{sub}, we used a deconvolution operation with the radiative transfer Green function (approximated by a two-parameter Γ-distribution). To estimate the amount of averaging required to receive a given accuracy of the retrieval, a scale-dependent bias E(r) defined in Eq. (7). We show that, even in the case of complex cloud structure and oblique illumination, the data-harvest can be substantially increased. For instance, averaging over 0.4 km of the retrieved absorption field gives a 3% to 4% error; the same level of accuracy can be achieved only by averaging the differences in the raw net-flux datastreams over more than 10 km.

The second ("conditional sampling") method consists in using only those data points that have vanishingly small horizontal fluxes in nonabsorbing wavebands. Turning to absorbing bands, apparent absorption at these points will, in most cases, be a good estimate of true absorption. This increases the data harvest beyond overall time and space averages.

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