GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 11, PAGES 1585-1588, JUNE 1, 1999

Horizontal radiative fluxes in clouds and accuracy of the Independent Pixel Approximation at absorbing wavelengths

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Abstract. For absorbing wavelengths, we discuss the effect of horizontal solar radiative fluxes in clouds on the accuracy of a conventional plane-parallel radiative transfer calculation for a single pixel, known as the Independent Pixel Approximation (IPA). Vertically integrated horizontal fluxes can be represented as a sum of three components: the IPA accuracies for reflectance, transmittance and absorptance. We show that IPA accuracy for reflectance always improves with more absorption, while the IPA accuracy for transmittance is less sensitive to the changes in absorption: with respect to the non-absorbing case, it may first deteriorate for weak absorption and then improve again for strongly absorbing wavelengths. IPA accuracy for absorptance always deteriorates with more absorption.

Introduction

In order to correctly interpret shortwave cloud radiation measured by satellites and ground-based radiometers, or by two aircraft flying above and below clouds, we need to better understand interactions between inhomogeneous clouds and solar radiation. The discrepancies between shortwave absorption inferred from measurements and predicted by models (e.g., Stephens and Tsay, 1990; Wiscombe, 1995), between cloud optical depths estimated from satellites and ground measurements (Min and Harrison, 1996), between single scattering albedo retrieved from in situ radiation measurements and computed from measured droplet size distribution (Pincus et al., 1997), amongst other examples, are strongly affected by cloud horizontal inhomogeneity.

Net horizontal photon transport (i. e., horizontal fluxes) are a direct consequence of the inhomogeneity in cloud structure. Horizontal fluxes and their effect on the accuracy of the pixel-by-pixel one-dimensional (1D) radiative transfer calculations has recently undergone close scrutiny for conservative scattering (Marshak et al., 1995; Barker, 1996; Davis et al., 1997a, b; Chambers et al., 1997; Titov, 1998; Zuidema and Evans, 1998). However, the properties and magnitude of horizontal fluxes in absorbing wavelengths are still poorly understood. As far as we are aware, only Ackerman and Cox (1981) and Titov (1998) discussed correlations between horizontal fluxes at absorbing wavelengths, though these were far from comprehensive.

This paper partly fills this gap. We discuss here whether the accuracy of the Independent Pixel Approximation (IPA), a 1D radiative transfer approximation for each pixel, is a better model for multiple scattering at conservative or at absorbing wavelengths. Issues addressed here are: (a) dependence of net horizontal fluxes on single-scattering albedo; and (b) connection between pixel-by-pixel accuracy of the IPA and net horizontal fluxes.

In contrast to the traditional understanding of IPA (Cahalan et al., 1994), we study IPA accuracies not only for reflectance but also for transmittance and absorptance at both conservative and absorbing wavelengths. In spite of the apparent similarity between the three processes, dependence of IPA accuracies on single-scattering albedo is completely different. As a result, cloud optical properties retrieved from high resolution satellite imagery and ground-based measurements using IPA at absorbing channels will have different accuracies. Understanding these differences helps us estimate the impact of horizontal fluxes on the interpretation of satellite and ground-based data as well as two-aircraft column absorption measurements (Ackerman and Cox, 1981).

Horizontal Flux and Its Components

To determine photon horizontal transport, we start with the radiative transfer equation

$$\Omega \bullet \nabla I = -\sigma(x) I(x,\Omega) + \sigma(x)\varpi_0 \int_{4\pi} p(\Omega' \to \Omega) I(x,\Omega') \mathrm{d}\Omega' \quad (1)$$

where $I(x,\Omega)$ is radiance at point $x = (x,y,z)$ in direction $\Omega = (\Omega_x,\Omega_y,\Omega_z)$, $P(\Omega' \to \Omega)$ is the scattering phase function, $\sigma(x)$ is extinction coefficient and ϖ_0 is a single-scattering albedo. Integrating Eq. (1) term-by-term with respect to Ω (over 4π) and z (from cloud base, z_b, to cloud top, z_t), we get relationship (Davis et al., 1997a; Titov, 1998) between vertically integrated horizontal fluxes $H(x,y)$, column absorption $A(x,y)$, reflectance $R(x,y)$ and transmittance $T(x,y)$.

We assume here that the extinction field varies only in the x-direction, i.e., $\sigma(x) \equiv \sigma(x)$. This assumption is for simplicity only; all results reported below are valid for at least an x-y variable extinction. In the case of vanishing surface reflection and unitary (normally) incident flux, we have (Ackerman and Cox, 1981; Marshak et al., 1998),

$$H(x) = \int_{z_b}^{z_t} \frac{\partial}{\partial x} \int_{4\pi} \Omega_x I(x,z;\Omega) \mathrm{d}\Omega \mathrm{d}z =$$

$$-\int_{z_b}^{z_t} \frac{\partial}{\partial z} \int_{4\pi} \Omega_z I(x,z;\Omega) \mathrm{d}\Omega \mathrm{d}z - (1-\varpi_0)\sigma(x) \int_{z_b}^{z_t} \int_{4\pi} I(x,z;\Omega) \mathrm{d}\Omega \mathrm{d}z$$

Paper number 1999GL900306.
0094-8276/99/1999GL900306$05.00

The first term in the right-hand side of the above equation is the difference between two net fluxes at z_t and z_b, while the second one is column absorption. In other words,

$$H(x) = \{[1-R(x)] - [T(x)-0]\} - A(x),\ 0 \le x \le L, \qquad (2)$$

i.e., vertically integrated horizontal fluxes $H(x)$ is determined as a difference between "true" column absorption $A(x)$ and its "apparent" counterpart, $1-R(x)-T(x)$. Note that Eq. (2) is simply an energy balance statement that defines horizontal fluxes.

Let us relate vertically integrated horizontal fluxes $H(x)$ to pixel-by-pixel accuracy of the IPA which treats each pixel as an independent plane-parallel medium, neglecting any *net* horizontal photon transport. If we replace unity in Eq. (2) by $R_{\text{IPA}}(x)+T_{\text{IPA}}(x)+A_{\text{IPA}}(x)$, we get,

$$H(x) = H_R(x) + H_T(x) + H_A(x). \qquad (3)$$

Each component in Eq. (3) is a pixel-by-pixel IPA accuracy,

$$H_F(x) = F_{\text{IPA}}(x) - F(x),\ F = R, T \text{ and } A. \qquad (4)$$

We will call H_R, H_T and H_A horizontal fluxes for photons reflected from cloud top, transmitted to cloud base, or absorbed by cloud column, respectively.

To measure the magnitude of horizontal fluxes, we will use the norm,

$$\|H_F\| = [\int_0^L |H_F(x)|^2\, dx]^{1/2} \qquad (5)$$

where L is the outer scale or the size of the basic cloud cell. Equation (3) and the norm definition (5) yield

$$\|H\| \le \|H_R\| + \|H_T\| + \|H_A\|. \qquad (6)$$

Note that IPA accuracies H_F are the average pixel-by-pixel absolute differences between the full 3D calculations of reflectance (transmittance or absorptance), through the solutions of Eq. (1), and 1D computations of the same quantities independently performed at each pixel.

Next we study the dependence of each component in Eq. (3) on single-scattering albedo. We also examine how close the left and right parts of (6) are for two different solar angles.

IPA accuracy on a per-pixel basis

Since the behavior of the above horizontal fluxes varies with scale r, we introduce the coarse-grained flux,

$$H_F(r,x) = \frac{1}{r}\int_x^{x+r} H_F(x')\, dx' \quad (0 \le x \le L-r,\ 0 < r \le L). \qquad (7)$$

It is natural to expect that, as r increases, the IPA becomes more accurate and horizontal fluxes $\|H_F(r)\|$ smaller. Figures 1a, 1b, and 1c show that this is true for H_R, H_T and H_A, i.e.,

$$\|H_F(r)\| \to 0,\ r \to L;\ \ F = R, T, \text{ and } A. \qquad (8)$$

It follows from (6) that (8) is valid for H as well. The effect of single-scattering albedo ϖ_0 on horizontal fluxes is, however, different for reflected, transmitted and absorbed photons.

Figure 1a illustrates the dependence of H_R on both r and ϖ_0. We see that the more absorption the shorter photon horizontal transport for reflected photons. As a result, the IPA pixel-by-pixel accuracy for reflectance improves with the decrease of ϖ_0. Note that, for $\varpi_0 = 0.9$, IPA is almost accurate even on a per-pixel basis. This is expected since the contribution of multiple scattering to the reflectance field decreases and very few photons travel between pixels.

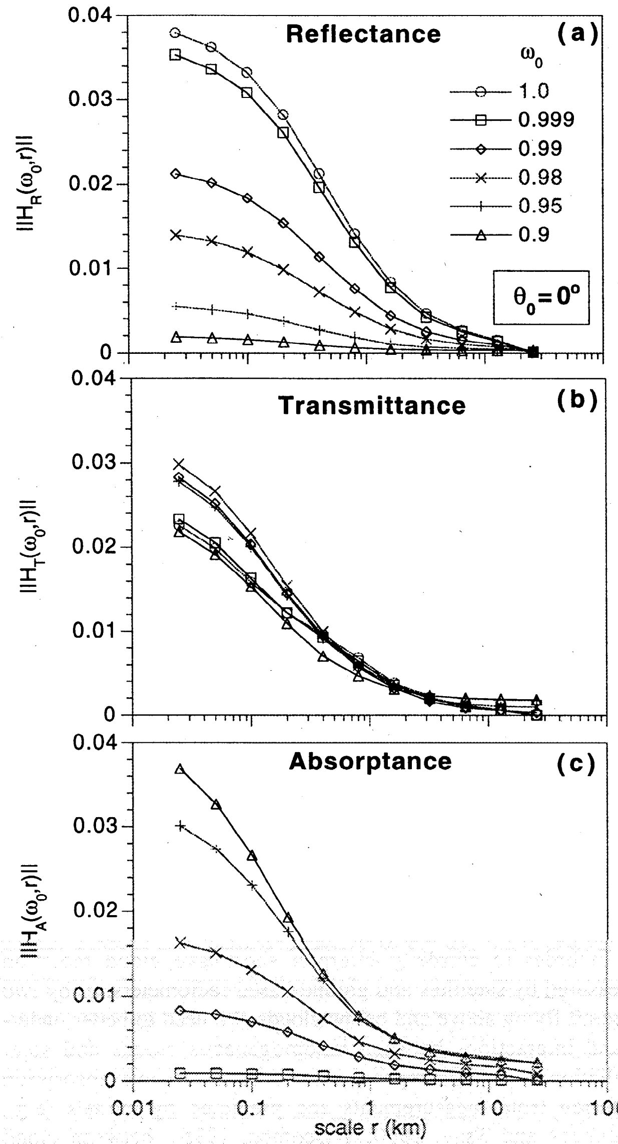

Figure 1. Dependence of pixel-by-pixel IPA accuracy on averaging scale r and single-scattering albedo ϖ_0. Horizontal distribution of cloud optical depth is simulated with 10-step bounded cascades model (Cahalan et al., 1994) where $p = 0.3$, $H = 1/3$, $\langle\tau\rangle = 13$, pixel size = 25 m. Flat cloud top and cloud base, geometrical thickness h = 300 m. Henyey-Greenstein phase functions with asymmetry parameter $g = 0.85$ is used. Solar zenith angle $\theta_0 = 0°$, surface is absorbing. The results are averaged over 10 independent realizations. **(a)** Reflectance; **(b)** Transmittance; **(c)** Absorptance.

The situation with transmitted photons (at least for high Sun) is surprisingly different: the uncertainty of the IPA on a per-pixel basis first decreases (from $\varpi_0 = 1.0$ down to $\varpi_0 = 0.98$) and only for strongly absorbing wavelengths ($\varpi_0 > 0.98$) does it increase again (Fig. 1b) reaching the accuracy level of the conservative scattering in case of $\varpi_0 = 0.9$.

To explain this, let us go back to homogeneous clouds and calculate the standard deviation

$$s_F = \{\int_0^\infty [F(\tau)]^2 p(\tau)\, d\tau - [\int_0^\infty F(\tau)p(\tau)\, d\tau]^2\}^{1/2} \qquad (9)$$

for reflectance ($F = R$) and transmittance ($F = T$). In Eq. (9), $p(\tau)$ is the probability density of the optical depth distribu-

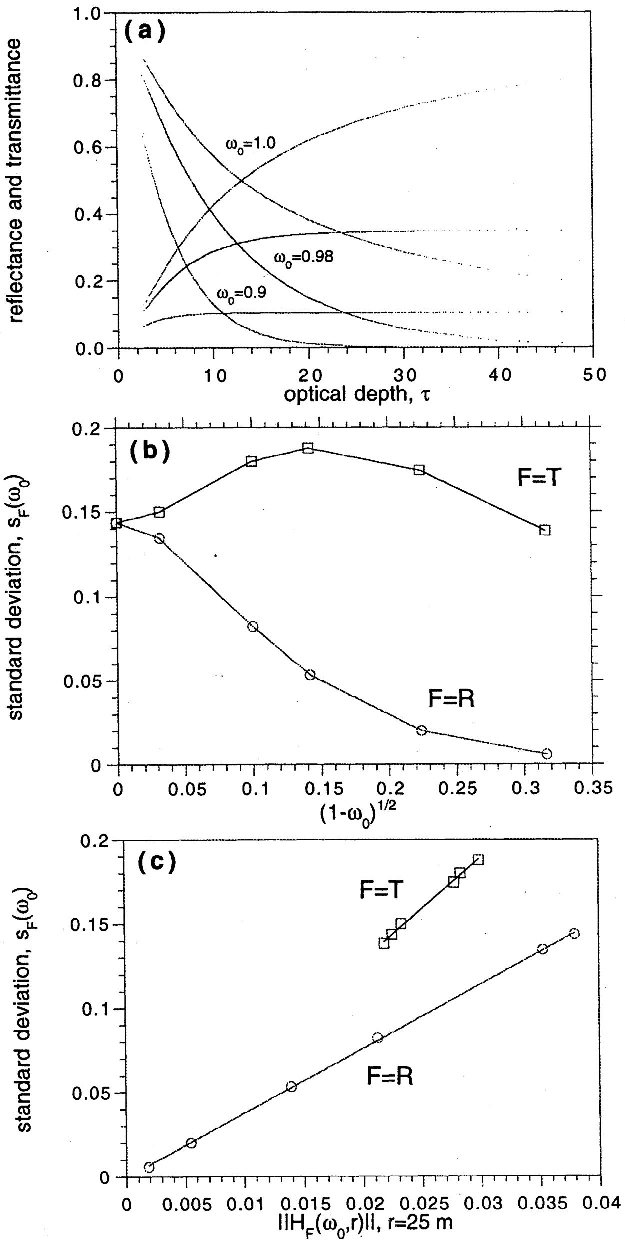

Figure 2. Standard deviation s_F and pixel-by-pixel IPA accuracy for reflectance and transmittance. Illumination and scattering conditions are the same as in Fig. 1. **(a)** 1D reflectances (increasing curves) and transmittance (decreasing curves) calculated using DISORT for ϖ_0 = 1.0, 0.98, and 0.9. Distribution of optical depth, $p(\tau)$, is defined by a bounded cascade model and is close to log-normal (Cahalan et al., 1994). **(b)** Standard deviations s_R and s_T defined in Eq. (9) vs. $(1 - \varpi_0)^{1/2}$. **(c)** Standard deviations $s_R(\varpi_0)$ and $s_T(\varpi_0)$ vs. IPA accuracies $\|H_R(\varpi_0)\|$ and $\|H_T(\varpi_0)\|$ at pixel scale r = 25 m.

tion. As shown in Fig. 2a, for a log-normal type of $p(\tau)$, the range of reflectance, $R(\tau_{max})$–$R(\tau_{min})$, sharply decreases with more absorption. At the same time, the range of transmittance, $T(\tau_{max})$–$T(\tau_{min})$, increases, at least for weakly absorbing wavelengths. As a result, s_T first increases (down to ϖ_0 = 0.98) and then decreases for strongly absorbing wavelengths, while s_R decreases monotonically (Fig. 2b). These results are almost independent of $p(\tau)$, unless it has an unrealistically long tail. Moreover, similar trends are found for all solar zenith angles within the 2-stream approximation, even for an uniform (but truncated) distribution of τ. Note that the behavior of s_R and s_T is very similar to what is shown in Fig. 1a and 1b for the IPA accuracies H_R and H_T, respectively. Indeed, Fig. 2c illustrates a surprisingly good linear correlation between $s_F(\varpi_0)$ and $\|H_F(\varpi_0)\|$ for both $F = R$ and $F = T$. This completes the explanation of both Figs. 1a and 1b.

Finally, the increase of pixel-by-pixel IPA absorption errors, $\|H_A(\varpi_0)\|$, with more absorption (Fig. 1c) is easily understandable; it follows directly from both the natural increase of $A_{IPA}(\tau)$ itself and its standard deviation with increasing of co-albedo $1-\varpi_0$. Besides that, the magnitude of $\|H_A(\varpi_0)\|$ monotonically increases with stronger cloud variability and more oblique illumination for any $\varpi_0 < 1$.

Figures 3a and 3b illustrate the joint effect of all horizontal fluxes for both high ($\theta_0 = 0°$) and low ($\theta_0 = 60°$) Sun. The general tendencies of horizontal fluxes are similar for both solar angles. However, the vertically integrated horizontal fluxes $\|H\|$ are much closer to the sum $\|H_A\|+\|H_T\|+\|H_R\|$ in case of slant illumination than in case of high Sun (Figs. 3a and b).

To interpret this, note that for high Sun horizontal fluxes for reflected and transmitted photons are mostly anticorrelated, while for low Sun they are mostly correlated. This is a direct consequence of radiative "channeling" around the dense regions into the tenuous ones (Davis et al., 1997b, 1998). As a result, for the majority of pixels, H_R and H_T have opposite signs if $\theta_0 = 0°$ and the same sign if $\theta_0 = 60°$. Thus

$$\|H\| \equiv \|H_R + H_T + H_A\| \ll \|H_R\| + \|H_T\| + \|H_A\|, \ \theta_0 = 0°; \tag{10a}$$

$$\|H\| \approx \|H_R\| + \|H_T\| + \|H_A\|, \ \theta_0 = 60°, \tag{10b}$$

as we see in Figs. 3a and 3b. (Note that "≪" is used only to emphasize the contrast between high and low Sun.)

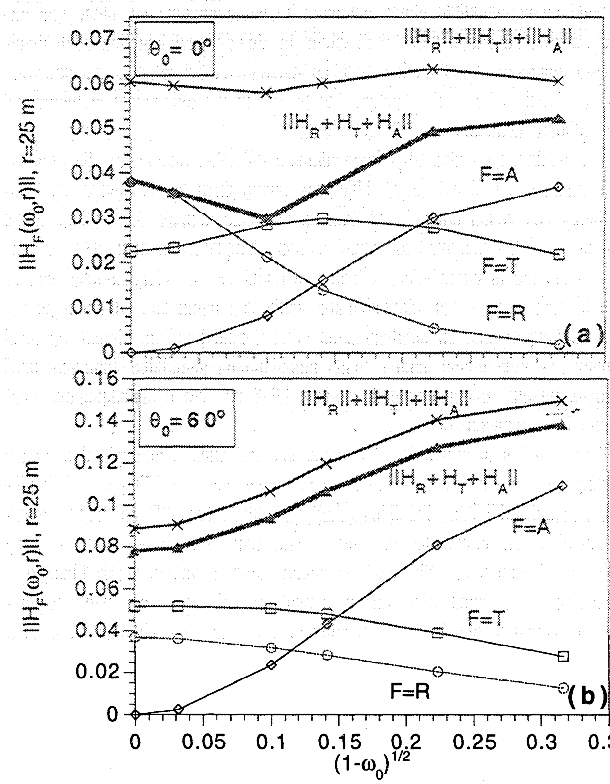

Figure 3. Pixel-by-pixel IPA accuracy for reflectance, transmittance, absorptance, their sum, and the total horizontal fluxes H. Cloud model and scattering conditions are the same as in Fig. 1. **(a)** $\theta_0 = 0°$; **(b)** $\theta_0 = 60°$.

Finally, the increase in vertically integrated horizontal fluxes $\|H(\varpi_0)\|$ with the increase of co-albedo $1-\varpi_0$ is entirely determined by the increase of $\|H_A(\varpi_0)\|$. In the case of slant illumination, this is true for all ϖ_0 and, in case of high Sun, only for strongly absorbing wavelengths. To conclude, horizontal flux H defined in Eq. (2) is not directly related to IPA accuracy for either reflectance or transmittance; for strongly absorbing wavelengths, the IPA errors H_R and H_T can be sufficiently small but nevertheless horizontal fluxes H are large because of the absorptance error H_A.

An original explanation of the increase of vertically integrated horizontal fluxes with co-albedo was advanced by Titov (1998). He stated that, with no absorption, photons traveling between neighboring pixels do not contribute to the increase of net horizontal fluxes; in absorbing cases, a photon traveling back and forth horizontally changes its "weight" after each order of scattering. As a result, the more absorption, the larger the changes in photon weight, and the bigger its contribution to net horizontal fluxes.

Summary and Discussion

Vertically integrated horizontal fluxes, defined as the difference between "true" and "apparent" (measured) absorption in Eq. (2), can be represented as the sum of three "horizontal fluxes" for reflected, transmitted and absorbed photons [see Eq. (3)]. These fluxes are also pixel-by-pixel IPA accuracies for reflectance, transmittance and absorptance, respectively.

We showed that in general, the magnitude of vertically integrated horizontal fluxes increase with the increase of single scattering co-albedo $1-\varpi_0$. However, the increase of their magnitudes is not correlated with a pixel-by-pixel accuracy of IPA for reflectance and transmittance but is due to the increase in the error of IPA absorption. The accuracy of IPA for reflected and transmitted radiation is described by the net horizontal transport of reflected or transmitted photons, respectively; both are just components of the vertically integrated horizontal fluxes.

We found that the ϖ_0-dependence of IPA accuracy for transmittance is qualitatively different from that of reflectance, especially for high Sun. While the IPA accuracy for reflectance monotonically improves with more absorption, the IPA accuracy for transmittance is less sensitive to single-scattering albedo and may even deteriorate with the increase of co-albedo. This is important to understand when comparing cloud optical properties retrieved from high resolution satellite images and ground-based measurements using IPA for both transparent and absorbing channels.

The results summarized above are robust. Indeed, the same tendencies in horizontal fluxes are observed in 2D vs. 1D horizontal variabilities, in presence vs. absence of vertical inhomogeneity, in variable vs. flat cloud top and base, with strong surface albedo vs. a "black" surface, and, finally, with Henyey-Greenstein vs. realistic phase function. Of course, the magnitude of horizontal fluxes increases with the gradients in cloud structure. Stronger cloud variability, clear sky gaps in cloud structure and oblique illumination may substantially enhance the magnitude of horizontal fluxes as additional sources for photon horizontal transport. Therefore, there is a need for new methods that can distinguish between radiative signatures of cloud inner variability and horizontal fluxes using both absorbing and nonabsorbing wavelengths.

Acknowledgments. This work was supported by the Department of Energy (under grant DE-A105-90ER61069 to NASA's GSFC) as part of the Atmospheric Radiation Measurement (ARM) program, and by NASA's EOS Project Science Office at GSFC (under grant NAG5-6675) as part of the EOS Validation Program. We thank R. Pincus, S. Platnick, and G. Titov for stimulating discussions. We also appreciate the comments and suggestions of the anonymous reviewer that have helped to improve the paper.

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(Received October 15, 1998; revised February 19, 1999; accepted April 8, 1999.)