RADIATION EFFECTS OF INHOMOGENEOUS STRATOCUMULUS CLOUDS: 2. ABSORPTION

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The influence of horizontal radiative transfer on the accuracy of absorption estimates as differences between the net fluxes measured above and below the clouds is studied. With such an absorption retrieval scheme, the horizontal transfer is interpreted as an apparent absorption and is the major source of uncertainty. If the measured net fluxes are averaged over intervals ~6 km *or longer, the horizontal transfer can be neglected, and reliable estimates of the average (over this interval) absorption can be obtained. Realization (*~200 km *long) average albedo, transmittance, and absorptance can be obtained, provided the interval between successive net flux measurements is not longer than* ~10 km. *Simultaneous net flux measurements of the visible and shortwave* (0.4–4.0 μm) *radiation allow one to substantially improve the absorption estimates and to study the absorption variability at small* (~0.1 km) *scales.*

1. INTRODUCTION

Solar radiation, absorbed by the atmosphere and underlying surface and transformed into other forms of energy, controls all dynamical processes in the earth's climate system. Cloud – radiation interactions are among most important yet least understood atmospheric processes governing the earth's climate. Most prominent example clearly illustrating our poor understanding of the radiative transfer in clouds is the problem of cloud absorption anomaly.[1–3] After more than 40 years of work, we are still far from answering the following questions, most important, in our opinion, to understanding the physics of interaction of solar radiation with clouds:

– Why does the cloud absorption as inferred from field measurements often exceed radiation model calculations?

– Is there any real unknown absorber, or is it just a consequence of uncertain field measurements and (or) input parameters in used radiative transfer models?

– How accurately do the radiation models, used for calculation, describe the radiative properties of real clouds?

Most atmospheric radiation models assume clouds to be homogeneous in horizontal direction (plane-parallel model). Optical parameters of real clouds fluctuate in space, and the scale of these fluctuations vary by several orders of magnitude. This horizontal inhomogeneity of clouds may be major source of discrepancy between field measurements and plane-parallel calculations.

This paper is a logical continuation of studies performed in Ref. 4, so we will use the same model of inhomogeneous stratocumulus clouds, method of solving radiative transfer equation, notations, etc. For convenience, for identification of formulas and figures, we will use two numbers, such as (4.6) stands for formula (6) from Ref. 4. Below we discuss the influence of horizontal transfer on the accuracy of absorption retrieval.

2. ABSORPTION AND RADIATIVE HORIZONTAL TRANSFER IN CLOUDS

According to Eq. (4.6), absorption of solar radiation by some cloud volume can be determined, provided that net fluxes leaving through its *closed* surface are known. In practice, however, only net fluxes above and below the clouds, F_0, $F^{\uparrow}(x, y, H)$ and $F^{\downarrow}(x, y, h)$ (see Fig. 4.1), are measured. Then, equation (4.6) contains two known (albedo and transmittance) and two unknown (absorptance and horizontal transfer) functions, hence the real absorptance $A(x, y)$ cannot be determined from it. When the horizontal radiative transfer is neglected and the balance equation (4.7) is used, instead of $A(x, y)$ one determines an inferred absorptance $A'(x, y)$ which is given by the formula

$$A'(x, y) = A(x, y) + E(x, y) = \\ = 1 - R(x, y) - T(x, y). \quad (1)$$

In this case, the horizontal transfer is considered as some apparent absorption. Since $e(x, y)$ may be either

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positive or negative, and be of the same order of magnitude as $A(x, y)$, the inferred absorptance $A'(x, y)$ may substantially diverge from the real one. Thus, the horizontal radiative transfer may be one of the main sources of uncertainty in cloud absorption measurement. We consider two possible approaches allowing this uncertainty to be removed and the absorption estimate to be improved.

1. Once net fluxes are spatially averaged, $\langle e \rangle = 0$, the radiative energy balance equation (4.8) contains one unknown, and the average absorptance $\langle A \rangle$ is uniquely calculated by the formula

$$\langle A \rangle = 1 - \langle R \rangle - \langle T \rangle. \quad (2)$$

Prior to using formula (2), one must answer the question: What is the minimum averaging area?

2. Suppose that data are available from albedo and transmission measurements in the visible (subscript "vis") and near IR (subscript "ir") wavelength ranges. In the visible range, there is no absorption, $A_{vis}(x, y) \equiv 0$, and so from equation (6) one can find the horizontal radiative transfer

$$E_{vis}(x, y) = 1 - R_{vis}(x, y) - T_{vis}(x, y). \quad (3)$$

Suppose we know the function $E_{ir}(x, y) = f(E_{vis}(x, y))$. According to Eq. (4.6), absorptance in the IR can be calculated as

$$A_{ir}(x,y) = 1 - R_{ir}(x, y) - T_{ir}(x, y) - f(E_{vis}(x, y)). \quad (4)$$

We note that this method of improving absorption estimate was proposed in Ref. 5 to study absorption of solar radiation by clouds of finite horizontal extents, by assuming that the horizontal transfer is the same at different wavelength intervals, i.e., $E_{ir}(x, y) = E_{vis}(x, y)$. Below we show that in inhomogeneous stratocumulus clouds this assumption, generally speaking, does not hold true.

To test both approaches, we use the one-dimensional cloud model with the slope of the power-law energy spectrum of optical depth $\beta = 5/3$, and the method of solving transfer equation, both described in Ref. 4. Other values are noted in the text and figure captions. For simplicity and better understanding of physics, in the IR we will account for the water droplet absorption alone and assume the single scattering albedo to be $\omega_{0,ir} = 0.99$. For each pixel, in addition to albedo and transmittance we calculated absorptance as well. At $\omega_{0,ir} = 0.99$, $\langle A \rangle = 0.18$, which approximately corresponds to the mean absorption by the cloudy atmosphere.[1,6]

Absorptance $A_{ir}(x_i)$ is shown in Fig. 1*a* as a function of the inferred absorptance, $A'_{ir}(x_i) = A_{ir}(x_i) + E_{ir}(x_i)$, $i = 1, \ldots, 4096$, calculated according to formula (1). We see that absorption depends strongly on the optical depth of a given pixel and neighboring ones and may vary by almost a factor of four. The parameters $A_{ir}(x_i)$ and $A'_{ir}(x_i)$ are not uniquely related, and, say, $A'_{ir}(x_i) = 0.20$ implies, for real absorptance, the range $0.08 \le A_{ir}(x_i) \le 0.32$. Situation is the same with different solar zenith angles and underlying surface albedos. Thus, from *individual* measurements of the net fluxes at the top and base of inhomogeneous clouds it is *impossible* to estimate absorption reliably.

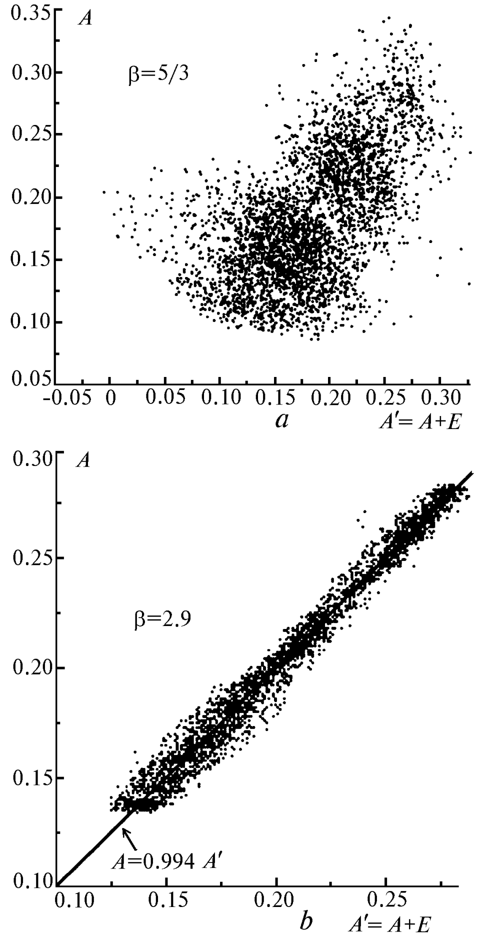

FIG. 1. Absorptance as a function of the inferred absorptance $A' = A + e$ *for* $\xi_{\odot} = 60°$, $A_s = 0$ *(ocean), and* $\omega_{0,ir} = 0.99$*:* $\beta = 5/3$ *(a) and* 2.9 *(b).*

Very few cases are conceivable when, due to the horizontal transfer, a pixel receives more radiation than it absorbs, and then $A'_{ir}(x_i) < 0$. That could be why negative absorption values were occasionally inferred from aircraft measurements of the net fluxes of solar radiation above and below the clouds.[1,6,7] Interestingly, the inferred absorptance $A'_{ir}(x_i)$ ranges from below zero to ~0.35, about just as absorption values measured *in situ* do.

As was already noted in Ref. 4, at $\beta = 2.9$ the cloud field is nearly homogeneous at the scales from 0.1 to 1–2 km, and so the horizontal radiative transfer can be neglected. In this case, there is close linear correlation between real and inferred absorptances (Fig. 1*b*). This is consistent with the results of analysis of field measurements[8]: models give correct values of cloud albedo in the near IR wavelength range when clouds "appear" more homogeneous.

2.1. Spatial averaging

To answer the above question of sufficient spatial averaging, we will use radiative fluxes averaged over different numbers of pixels,

$$R(nx) = \frac{1}{2^{nx}} \sum_{i=1}^{2^{nx}} R(x_i),$$

$$T(nx) = \frac{1}{2^{nx}} \sum_{i=1}^{2^{nx}} T(x_i), \quad A(nx) = \frac{1}{2^{nx}} \sum_{i=1}^{2^{nx}} A(x_i),$$

$$E(nx) = \frac{1}{2^{nx}} \sum_{i=1}^{2^{nx}} E(x_i), \quad nx = 0,\ 1,\ \ldots\ . \qquad (5)$$

The length $l(nx)$ of the averaging segment of realization is $l(nx) = \Delta x \cdot 2^{nx}$.

The effect of clouds on solar absorption is commonly quantified in terms of the ratio[3]

$$r = \frac{CRF_{\rm S}}{CRF_{\rm TOA}},\ CRF_{\rm S} = F_{\rm S}^{\rm all} - F_{\rm S}^{\rm clr},$$

$$CRF_{\rm TOA} = F_{\rm TOA}^{\rm all} - F_{TOA}^{\rm clr},\ r = -\frac{1 - A_s}{s}, \qquad (6)$$

where $CRF_{\rm S}$ and $CRF_{\rm TOA}$ abbreviate cloud radiative forcings at the surface level (S) and at the top of the atmosphere (TOA). The cloud radiative forcing is defined as the difference between the net flux F for the cloudy atmosphere (all) and that for the clear sky (clr). Also used to describe cloud absorption is the slope s of the linear regression between albedo and transmittance,[2] related to r by $r = (1 - A_s)/s$. Without any strict foundation, the slope s is claimed in Ref. 2 to be the direct measure of absorption.

When the surface albedo is zero, the ratio of radiative forcings is

$$r(nx) = \frac{1 - T(nx)}{R(nx)} = 1 + \frac{A(nx) + E(nx)}{R(nx)}. \qquad (7)$$

From Eq. (7) it follows that, for arbitrary nx, the ratio of cloud radiative forcings depends on both absorption and horizontal transfer. The ratio $r(nx)$ will *uniquely* determine cloud absorption only when $nx > nx_*$, where nx_* is given by the inequality $A(nx_*) >> E(nx_*)$.

The horizontal transfer $E(nx)$ and the ratio $r(nx)$, calculated for different single scattering albedos, are presented in Fig. 2. As seen, $r(nx)$ depends strongly on the number of pixels and, generally, is *not the direct measure* of cloud absorption. The same conclusion was reached in Ref. 9 which provided an analysis of four-year global solar flux data obtained using satellite and ground-based measurements. At $nx > nx_* \approx 2^7$, the horizontal transfer is negligible, while $r(nx)$ nearly levels off, truly characterizing cloud absorption. Thus, because of the horizontal radiative transfer, one can determine absorption averaged over intervals $l(2^7) \sim 6$ km or longer. The latter implies that one can divide a ~200 km long realization into ~30 nonoverlapping intervals and for each determine average absorption. By using net flux measurements for a *single* wavelength interval (no matter how wide), it is *impossible* to obtain reliable estimates of absorption averaged over shorter intervals, such as ~1 km or shorter. In other words, the absorption by inhomogeneous stratus clouds can be determined to *a maximum* spatial resolution of $\Delta l \sim 6$ km.

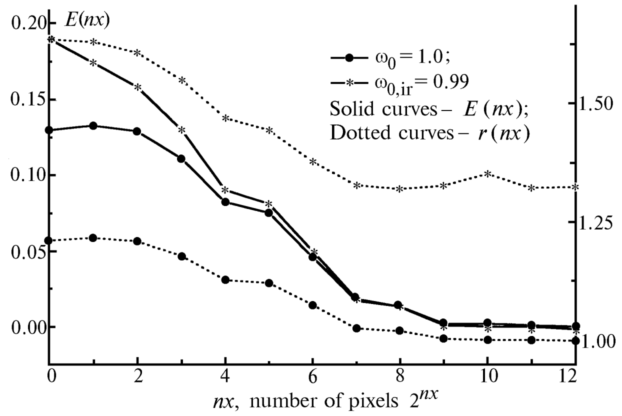

FIG. 2. The horizontal transfer and the ratio of cloud radiative forcings as functions of the number of pixels over which the average is taken: $\xi_\odot = 60°$ *and* $A_s = 0$ *(ocean).*

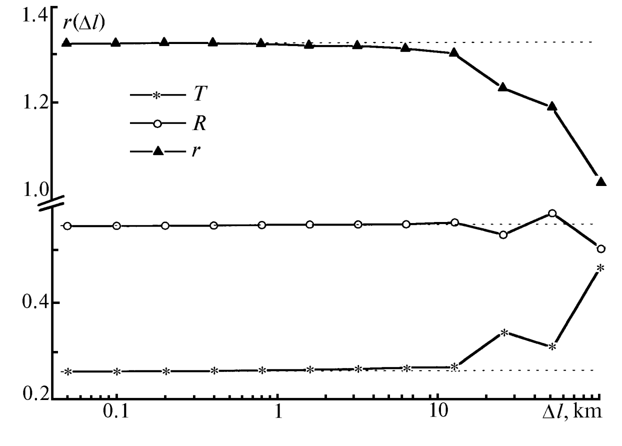

FIG. 3. Albedo, transmittance, and the ratio of cloud radiative forcings as functions of spatial resolution used: $\xi_\odot = 60°$, $\omega_0 = 0.99$ *and* $A_s = 0$ *(ocean).*

To test radiation codes of atmospheric general circulation models (GCMs), one has to measure albedo, transmittance, and absorptance averaged over a GCM cell. The use of a set of detectors for collocated and simultaneous measurements within the

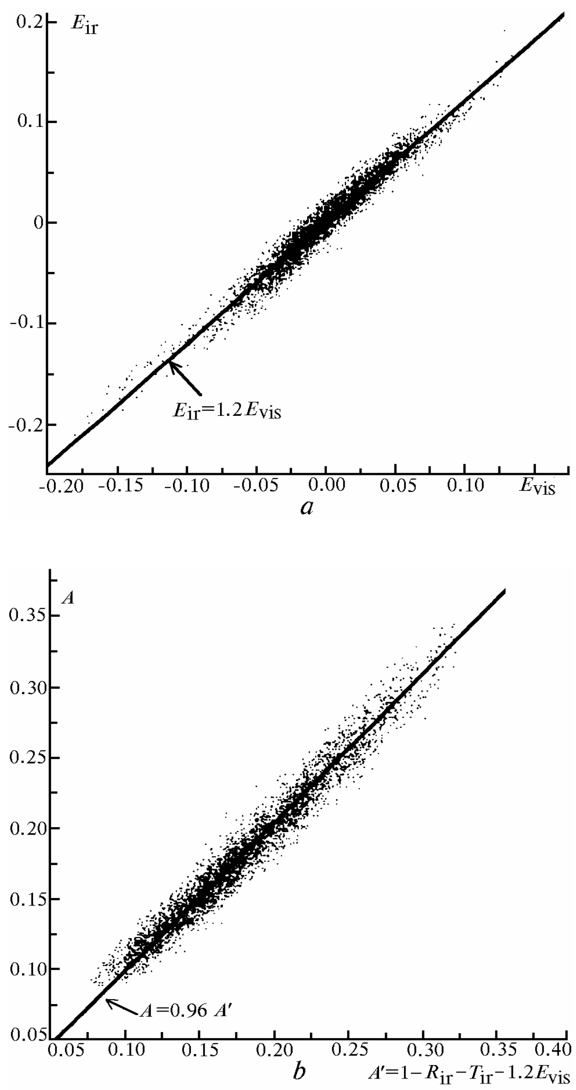

FIG. 4. Linear regression between E_{ir} and E_{vis} and the absorptance A as a function of the improved absorption estimate A′ with $\xi_{\odot}$ = 60° and A_s = 0 (ocean).

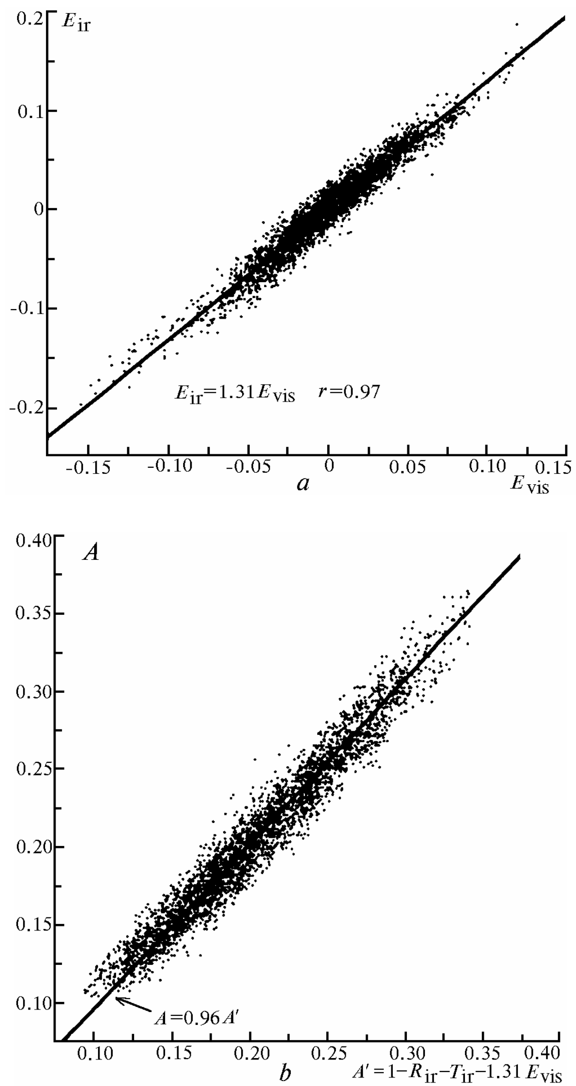

FIG. 5. The same as in Fig. 4, but for A_s = 0.4 (desert).

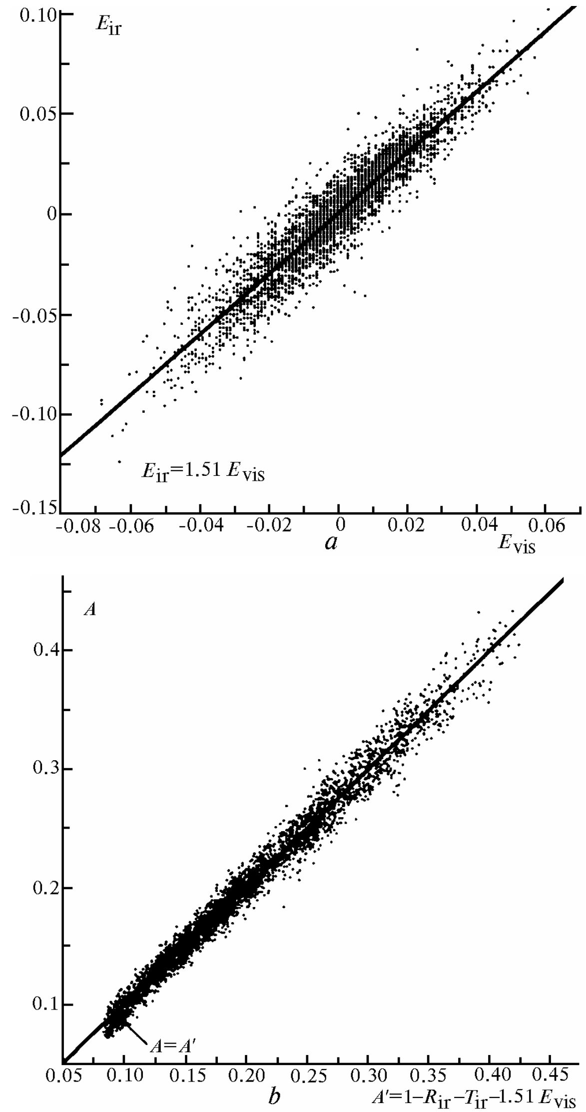

FIG. 6. The same as in Fig. 4, but for $\xi_{\odot}$ = 0°.

cell would remove the effects of solar zenith angle and temporal variability of cloud field, e.g., on transmittance. What is the minimum spatial resolution Δl required for flux measurements? How many detectors will be optimum? Mathematical simulation provides answers to these questions. Let us calculate (realization) average albedo and transmittance with different resolutions $\Delta l = 2^i \Delta x$, $i = 0, ..., nx - 1$, using the formulas

$$R(\Delta l) = \frac{1}{2^{nx-i}} \sum_{j=1}^{2^{nx-i}} R_{n_{ij}},$$

$$T(\Delta l) = \frac{1}{2^{nx-i}} \sum_{j=1}^{2^{nx-i}} T_{n_{ij}}, \quad n_{ij} = j2^i, \tag{8}$$

while the ratio of radiative forcings is $r(\Delta l) = [1 - T(\Delta l)]/R(\Delta l)$. According to Eq. (8), $R(\Delta l)$ and $T(\Delta l)$ are calculated either using all points ($i = 0$) or points with numbers 2, 4, 6, ..., 2^{nx} ($i = 1$), and so forth.

Figure 3 presents $R(\Delta l)$, $T(\Delta l)$, and $r(\Delta l)$ as functions of Δl. At a realization length of ~200 km, the minimum spatial resolution is $\Delta l \sim 10$ km, and for transmittance measurements one needs ~20 detectors. This result is important because it clearly illustrates the potentialities of mathematical simulation when planning costly experiments.

2.2. Measurements in the visible and near IR wavelength range

Suppose that data are available from collocated (above- and below-cloud) measurements of the net fluxes of visible and near IR radiation. Note that instead of infrared data one can use measurements of the net fluxes of shortwave (0.3–4.0 μm) radiation.

From Eq. (4) it follows that absorption estimate can be improved if the function $E_{ir}(x,y) = f(E_{vis}(x,y))$ is known, that can be found by mathematical simulation. Using linear regression between E_{ir} and E_{vis}, we get $E_{ir} = 1.2E_{vis}$ (Fig. 4). Substituting this result in Eq. (4) yields an improved estimate of the absorptance A' that well agrees with the real absorptance ($\max|A - A'| \leq 0.05$). From comparison of the results shown in Figs. 1 and 4, we conclude that the use of the simple "measurement" scheme considered here allows significant improvement in the cloud absorption estimate. This conclusion also holds true with different values of surface albedo and solar zenith angle (see Figs. 5 and 6).

An important advantage of the coincident visible and near-IR measurements is that they relieve one of having to average, provide reliable absorption estimates of high spatial resolution, and, thereby, enable the study of small-scale (~ 0.1 km) fluctuations of absorption of solar radiation by inhomogeneous clouds.

Figures 4–6 present paradoxical, at first sight, result: horizontal radiative transfer with absorption, $|E_{ir}|$, may be greater than without it, $|E_{vis}|$. Since $\langle E_{ir} \rangle = \langle E_{vis} \rangle = 0$, the distribution of E_{ir} is broader than that of E_{vis} (Fig. 7). This effect can be explained as follows. Consider a segment of photon trajectory between nth and $n + 2$th collisions. Let nth and $n + 2$th collisions belong to the pixel with number i, while $n + 1$th collision belongs to either pixel $i + 1$ or $i - 1$. In other words, the photon exits a pixel, suffers a collision in a neighboring one, and then returns back. In the pure scattering case, statistical weight of the photon, proportional to its radiative energy, does not change upon collision, therefore, such a trajectory segment contributes nothing to the horizontal transfer. Unlike, with the water droplet absorption present, the photon leaves the pixel having one statistical weight, and returns back with other, less one; thus, the horizontal transfer is not zero. This means that, switching to absorptive case, the number of trajectories contributing to E_{ir} increases, thus the E_{ir} distribution broadens. If the above argument is valid, the allowance for atmospheric gaseous absorption should further broaden the distribution of E_{ir}.

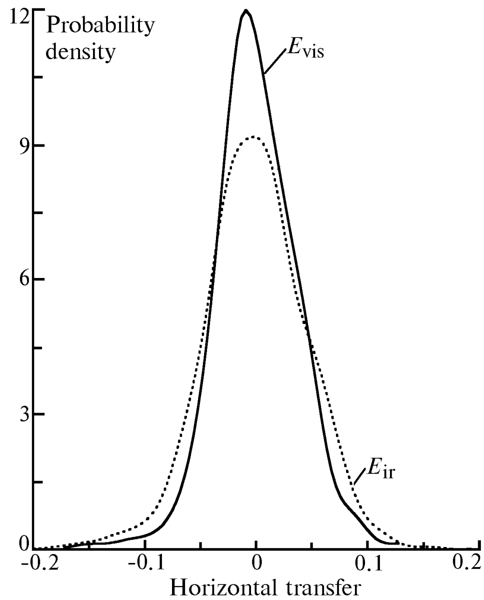

FIG. 7. Probability densities of horizontal transfer with and without absorption: $A_s = 0$ (ocean) and the solar zenith angle $\xi_\odot = 60°$.

3. CONCLUSION

When absorption is determined as the difference between net radiative fluxes measured above and below clouds, the horizontal transfer is interpreted as an apparent absorption and is a major source of uncertainty. The presence of this apparent absorption in both *visible* and near-IR is confirmed by the field measurements in broken stratocumulus clouds.[7] Owing to the radiative horizontal transfer, some pixels may receive more radiative energy from nearby pixels than they inherently absorb. Such pixels have negative inferred absorption as deduced by interpreting field data.[1,6,7]

From *individual* net flux measurements it is *impossible* to estimate cloud absorption accurately. After the measured net fluxes are averaged over realization fragments ~ 6 km or longer, the horizontal radiative transfer can be neglected, and (fragment) average absorption can be reliably estimated. Such an averaging can be made, provided net flux measurements of much finer spatial resolution (~ 0.1 km) are available. To estimate (~ 200 km long) *realization average* albedo, transmittance, and absorptance, solar radiation fluxes should be measured with spatial resolution ~10 km.

Using simultaneous measurements of the net fluxes in the visible and shortwave (0.4–4.0 μm) wavelength range, along with the linear correlation between the horizontal transfer of shortwave ($E_{\rm ir}$) and visible ($E_{\rm vis}$) radiation, it is possible to substantially improve the estimate of absorption by inhomogeneous clouds. In this case, we can obtain reliable absorption estimates of high spatial resolution and, therefore, study the variability of absorption at small (~ 0.1 km) scales. One-point distribution of $E_{\rm ir}$ is broader than that of $E_{\rm vis}$, and the coefficient of the linear regression between $E_{\rm ir}$ and $E_{\rm vis}$ is greater than unity. This is because, with absorption present, more photon trajectories contribute to horizontal radiative transfer. With allowance for atmospheric gaseous absorption and stochastic boundaries of stratocumulus clouds, $|e|$ will be greater, i.e., the one-point distribution of E will be even broader. For this reason, here we have considered just the minimum influence of horizontal transfer on the accuracy of determining cloud absorption.

The results presented above provide quite firm grounds to think that, in terms of the radiative effects of inhomogeneous clouds and primarily the horizontal radiative transfer, the cloud absorption anomaly can be successfully explained. The main reason for discrepancy between theory and experiment lies in the incorrect interpretation of data of field measurements.

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