Papers

Uncertainty in stratiform cloud optical thickness inferred from pyranometer measurements at the sea surface

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Abstract

The relative 'plane-parallel' error in a mean cloud optical thickness retrieved from ground-based pyranometer measurements is estimated. The plane-parallel error is defined as the bias introduced by the assumption in the radiative transfer model used in cloud optical thickness retrievals that the atmosphere, including clouds, is horizontally homogeneous on the scale of an individual retrieval. The error is estimated for the optical thickness averaged over the whole domain, which simulates the mean cloud optical thickness obtained from a time series of irradiance measurements. The study is based on 3D Monte Carlo radiative transfer simulations for non-absorbing, all-liquid, layer clouds. Liquid water path distributions in the clouds are simulated by a bounded cascade fractal model. The sensitivity of the error is studied with respect to the following factors: averaging time of irradiance used in an individual retrieval, mean cloud optical thickness, cloud variability, cloud base height and solar zenith angle. In the simulations presented in this paper, the relative bias in the domain averaged cloud optical thickness retrieved from pyranometer measurements varies from +1% for optically thin clouds to nearly –20%. The highest absolute value of the relative bias is expected for thick and variable clouds with high bases (e.g. 1 km) and retrievals based on long-term mean irradiances (averaging time of the order of several tens

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of minutes or hours). The bias can be diminished by using short-term irradiance averages, e.g. of one minute, and by limiting retrievals to low-level clouds.

1. Introduction

Cloud optical thickness is an important parameter for climate modelling. Methods for determining cloud optical thickness vary from the direct application of Mie theory to *in situ* measurements of droplet size distributions to retrievals based on ground-based (e.g. Raschke & Cox 1983, Ershov et al. 1988, Davis et al. 1997, 1999, Marshak et al. 2000, Barker & Marshak 2001) and satellite-based measurements (e.g. Nakajima & King 1990, Minnis et al. 1992, Hayasaka et al. 1994, Feijt 2000, Kuji et al. 2000, Platnick et al. 2001).

Surface-based pyranometer measurements have also proved useful for cloud optical thickness retrievals (Francis et al. 1991, Leontieva et al. 1994, Leontyeva & Stamnes 1994, Lubin & Simpson 1997, Pinto et al. 1997, Barker et al. 1998). The optical thickness of clouds can be inferred from surface-based broadband measurements of radiative fluxes by matching the observed fluxes with those obtained from the model. The UV and visible parts of the spectrum, without major absorption bands, are recommended for the retrievals (Leontyeva & Stamnes 1994, Lubin & Simpson 1997, Rozwadowska, in press). However, solar radiation totalled over the whole range of the solar spectrum is also used (Francis et al. 1991, Leontieva et al. 1994, Leontyeva & Stamnes 1994, Pinto et al. 1997).

One advantage of the pyranometric method is that pyranometers are widely available at meteorological stations, including on-board stations. This method is therefore an inexpensive and attractive means of obtaining information on the optical properties of clouds over the sea. A shortcoming of the method, however, is its limitation to layer clouds and an overcast sky. The pyranometer is a wide angle-of-view instrument, which makes the pyranometer method prone to errors due to the assumption in the retrieval model that the atmosphere is horizontally homogeneous. Recently, several methods have been developed which allow cloud optical thickness to be retrieved from ground-based measurements more accurately than with the pyranometric method. However, these methods need sophisticated instrumentation (e.g. off-beam lidar, Davis et al. 1997, 1999) and/or are inapplicable to clouds over the sea. For instance, very promising methods relying on spectral differences in surface albedo (Marshak et al. 2000, Barker & Marshak 2001) cannot be applied to conditions at sea because of the sea water's very low albedo.

The aim of the present study is to analyse the potential 'plane-parallel' error in cloud optical thickness retrievals from ship-borne irradiance measurements and to indicate the conditions under which the error falls to a minimum. The assumption in the retrieval algorithm that clouds are horizontally homogeneous is a considerable source of error. Although many researchers assume a plane-parallel atmosphere in retrievals of cloud properties, clouds are in fact inhomogeneous. Even an apparently homogeneous stratus cloud has an internal structure (e.g. Feigelson 1981, Cahalan et al. 1994a). For example, disregarding horizontal LWP (liquid water path) variability in marine stratocumulus may result in relative errors of more than 10% in the modelled mean albedo (e.g. Cahalan et al. 1994a). Similarly, inferring mean cloud optical thickness from radiation transmitted through cloud and averaged over time or space results in a considerable bias. As a first approach the bias can be explained by the non-linear relationship between the radiation and cloud optical thickness, so the mean value of one of those parameters is insufficient to estimate the mean value of the other. Higher-order statistics are necessary (e.g. Cahalan et al. 1994a). Boers et al. (2000) used a bounded cascade fractal model of cloud LWP distributions and a two-stream radiative transfer model to estimate uncertainties in cloud optical depth inferred from pyranometer irradiances. They found that if cloud cover is 100%, the mean bias is always negative, i.e. the mean cloud optical thickness retrieved is lower than the real one. Increasing the averaging time from 10 to 40 min reduces the scatter in the bias, although the mean bias in cloud optical thickness remains constant. Its value depends on the choice of fractal model, that is, on the cloud variability. Their analysis, however, was restricted to the two-stream radiative transfer model in the retrieval procedure and only selected cases of both irradiance averaging times (≥ 10 minutes) and clouds.

Previous studies have demonstrated that in the case of cloud optical thickness retrievals based on (narrow-angle) satellite-based nadir radiance measurements and the independent pixel approximation approach (IPA) in radiative transfer, the domain averaged retrieval error (bias) falls with pixel size, decreasing to a certain scale when horizontal photon transport becomes significant and IPA cannot be applied. Further diminishing the pixel size does not improve the retrievals (Davis et al. 1997). An analogous situation may be expected in pyranometer retrievals, in which the IPA approach is also employed. However, in the case of the pyranometer, an instrument with a $2\,\pi$-angle of view, even an instantaneous measurement is spatially averaged with weights decreasing with distance from the zenith. In fact, a combined, spatial-temporal average of irradiance is measured. Assuming 'a frozen cloud field', temporal averaging is equivalent to additional spatial averaging. The effective averaging distance depends on the irradiance averaging time (which, in turn, is limited by the instrument's response time), wind speed (cloud field speed) and cloud base height. These factors are therefore expected to influence the retrieval error.

In the present paper the plane-parallel error of cloud optical thickness retrievals from ground-based pyranometer measurements is studied. Here, by 'plane-parallel error' is meant the error introduced by the assumption in the retrieval algorithm that clouds are horizontally homogeneous (on the scale of an individual 'pixel'). Later in this paper it is also referred to as the plane-parallel retrieval bias or bias by analogy to the plane-parallel biases in the cloud albedo defined by Cahalan (1994). The error is estimated for the optical thickness averaged over the whole domain, which simulates the mean cloud optical thickness obtained from a time series of irradiance measurements. The study is based on Monte Carlo simulations. A fully overcast sky is assumed because the pyranometric method is inapplicable in the case of broken cloud, when the retrieval error is excessively large. The dependence of the error is studied with respect to several factors, including the time of irradiance averaging used in an individual retrieval, real means of cloud optical thickness, cloud variability, cloud base height and solar zenith angle. The analysis of the impact of cloud variability, cloud base height, solar zenith angle as well as a wide range of averaging times on the bias expands our understanding of the process with respect to previous studies.

The outline of the paper is as follows: Section 2 describes the cloud models and the radiative transfer model employed in this analysis. Also in Section 2 the optical thickness retrieval method used in this study is given. Section 3, 'Results', presents and discusses estimated errors of cloud optical thickness retrieval based on pyranometric measurements, and the dependence of these errors on various factors. Section 4, 'Conclusions' summarises the findings and discusses the feasibility of minimising the 'plane-parallel' error in cloud optical thickness retrieval.

2. Methods

Cloud model

A cloud was simulated with a 300-m thick, vertically homogeneous, non-absorbing scattering layer. As the influence of the vertical structure of cloud on the solar irradiance at the sea surface is negligible (cf., e.g. Rozwadowska, in press), the assumption of vertical cloud homogeneity is sufficient in this study. The liquid water path (LWP) varied horizontally along a single direction (in 1D), as in stratocumulus undulatus. A 100% cloud cover was assumed. Further, if a constant droplet radius is assumed, the cloud optical thickness is related linearly to the LWP.

In this paper, the bounded cascade fractal model is used to simulate the cloud optical thickness τ or LWP variability in layer clouds. Although more sophisticated cloud generating algorithms have been developed recently, the simplicity and easy adjustability of the bounded cascade model remain its advantages. The model is characterised by two parameters: the variance parameter f, related approximately to the standard deviation of $\log_{10}$(LWP) as $\sigma_{\log(\text{LWP})} = 0.718\ f\ (1 - 0.556\ f^2)/(1 - 0.720\ f^2)$ (Cahalan 1994), and the scaling parameter c, related to the exponent of the power spectrum of the LWP α by the approximate equation $c^2{=}2^{(1-|\alpha|)}$ (Cahalan et al. 1994a). For given parameters c and f, at the cascade step n, each cell is divided into two equal parts and a fraction $0 \leq f \times c^n \leq 1$ of liquid water is randomly transferred from one half to the other. The concept and the properties of the cloud bounded cascade model are given in e.g. Cahalan (1994), Cahalan et al. (1994a), and Marshak et al. (1994). The bounded cascade model reproduces quite well the wave number spectrum, linear in the log-log scale, and the log-normal-like probability distribution of the liquid water path (LWP) in marine stratocumulus (Cahalan & Snider 1989, Cahalan et al. 1994a, 1994b). The wave number spectrum linear in the log-log scale was reported in e.g. ASTEX for scales from 60 m to 60 km (slope $\alpha = -1.43 \pm 0.08$, PVM-100 probe), FIRE 87 for scales from 20 m to 20 km ($\alpha = -1.36 \pm 0.06$, King LWC probe) (Davis et al. 1996) and in FIRE-ACE/SHEBA/ARM for scales of about 0.6 to 100 km ($\alpha = -1.40 \pm 0.06$, ground-based MWR LWP measurements) (Rozwadowska & Cahalan 2002). The slope may vary from realisation to realisation, also reaching –5/3 – the value for an 'upscale cascade' in 2D turbulence (Kraichnan 1967, Gage & Nastrom 1986, Cahalan & Snider 1989).

The log-term variance parameter f varies from about 0.6 in ASTEX and about 0.5 in FIRE (Cahalan et al. 1995) to 0.4 in the Arctic during FIRE-ACE/SHEBA/ARM (Rozwadowska & Cahalan 2002). For an individual 6-hour long MWR the LWP time series from FIRE-ACE/SHEBA/ARM, f ranges from 0.1 to 0.4 and usually does not exceed 0.4.

The bounded cascade model with scaling parameter $c = 0.8$ ($\alpha = -5/3$) and variance parameter $f = 0.5$ was applied in the error simulations presented in this paper. The bounded cascade cloud model in the version proposed by Cahalan (1994) will henceforth be referred to as BC. Apart from the BC cloud model, a modified bounded cascade model (denoted as MBC) was also used in the present error simulations. Boers et al. (2000) argued that the BC cloud model is slightly unrealistic and applied several modifications. The first adaptation was to restrict the variance at the first steps of the cascade and eliminate excessively high values of optical depth at small scales by using a lower parameter f for the first two cascades (scales down to about 12.5 km). The second modification concerns the behaviour of the variance of τ with increasing mean optical thickness. For the original fractal model with given parameters c and f, the variance of τ increases with the value of the average (the variance of $\log_{10}(\tau)$ is constant). Boers et al. (2000) suggested a restriction to the variance by allowing it to grow according to the fractal model with parameters f and c constant, while $<\tau>$ increases for the mean values of the optical depth below 12.8 (the angular brackets denote mean values in this paper). Thicker clouds were generated by adding a fixed optical depth value to all pixels generated by the MBC fractal model with $<\tau> = 12.8$. In the present paper, the modified bounded cascade model with the parameters $f = 0.24$ for the scales > 12.8 km and $f = 0.5$ for the lower scales, and $c = 0.8$ was adopted. The domain size is 102.40 km. In both versions of the bounded cascade cloud model, 11 cascades were applied, which made the pixel size, i.e. the width of a homogeneous cloud strip, equal to 50 m. The parameters of the cloud models are summarised in Table 1. Fig. 1 presents examples of the spatial distribution of cloud optical thickness generated by the pure (BC) and modified (MBC) fractal models for $<\tau> = 12$.

Table 1. Values of model input parameters used in the simulations of the plane-parallel biases in cloud optical thickness retrievals from ground-based irradiance measurements

Cloud model	Bounded cascade (BC)	Modified bounded cascade (MBC)
variance parameter f of cloud model	0.5	0.24 for scales $\geq$ 12.8 km 0.5 for scales $<$ 12.8 km
scaling parameter c of cloud model	0.8	0.8
mean cloud optical thickness	5, 12, 30	12, 30
cloud base height [m]	150, 1000	150, 1000
solar zenith angle [°]	0, 40, 70	40
solar azimuth with respect to cloud variability direction [°]	0, 90	0
irradiance averaging scales [km]	0.05–25.6	0.05–25.6

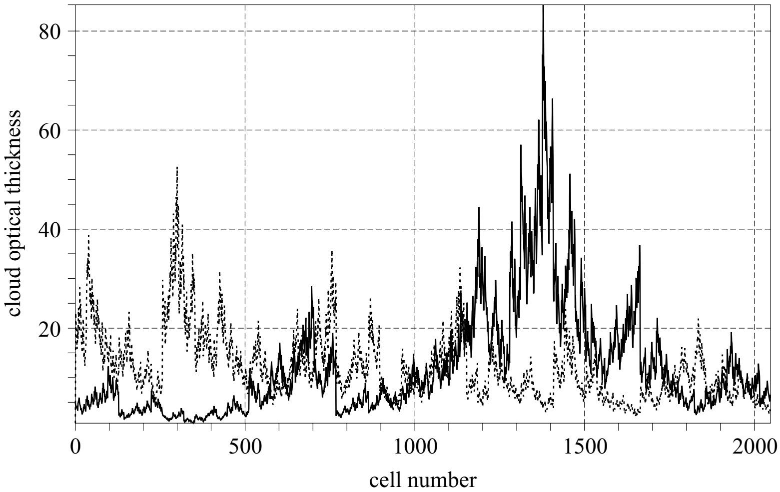

Fig. 1. Examples of the optical thickness distribution generated by the pure bounded cascade (solid line) and the modified bounded cascade (dashed line) models, $<\tau_{\rm real}> = 12$

Irradiance measurement simulations

Irradiance transmittance is defined in this paper as follows:

$$T = \frac{E_s}{E_\infty}, \tag{1}$$

where E_s and E_∞ are the irradiances measured at the sea surface and at the top of the atmosphere, respectively.

Radiative transfer was simulated by the 3D Monte Carlo code developed by Marshak (Marshak et al. 1995), using the 'maximum cross-section method' of Marchuk et al. (1980). All simulations were performed for $\lambda = 605$ nm. Because cloud optical properties are almost insensitive to λ throughout the VIS spectral range, the present error simulations are valid for cloud optical thickness retrievals from pyranometer measurements in the VIS part of the solar spectrum. Cloud thickness was assumed equal to 300 m. The cloud base ranged from 150 m to 1000 m above a non-reflective 'sea' surface. For comparison, the actual sea surface albedo for short-wave solar radiation, solar zenith angle $< 80°$ and atmospheric transmittance < 0.3 does not exceed 0.1 and typically takes a value of 0.06 (e.g. Payne 1972). The clouds and the sea surface were separated by a non-absorbing scattering layer with a scattering coefficient of 0.1 km^{-1} and an asymmetry factor of the scattering function of 0.68, which simulated an aerosol layer below the clouds. The clouds were also non-absorbing with an asymmetry factor of 0.85 (for $\lambda = 605$ nm). The mean cloud optical thickness, $<\tau>$, varied from 1 to 30. Variability in the LWP was simulated by the 'pure' (BC) and modified bounded cascade (MBC) fractal models with the variance parameters typically at $f = 0.5$ (0.24 for scales > 12.5 km in the MBC cloud model) and spectral parameter $c = 0.8$.

The cloud optical thickness was variable in 1D. 1D variability was chosen to diminish the computation time necessary to achieve reasonable accuracy of the irradiance transmittance estimation for each individual pixel. Two extreme solar azimuths with respect to the cloud variability direction were simulated, azimuth $\phi = 0°$ (cloud variability direction parallel to the principal plane) and $\phi = 90°$ (cloud variability direction and the principal plane perpendicular to each other). Although the majority of the simulations were performed for a cloud variability direction parallel to the principal plane, the biases were estimated for selected 'perpendicular cases' to show the sensitivity of the bias to the assumption of cloud variability restricted to 1D. Moreover, stratiform clouds with nearly 1D variability are observed (stratocumulus undulatus).

Photons travel in 3D space. For each case from 1 to 4 runs with 2×10^8 photons each were performed, which results in the relative errors in the irradiance and transmittance estimates for an individual pixel ranging from about 3% for transmittance $T = 0.01$ to 0.03% for $T = 0.99$. The length of the domain is 102.4 km. The pixel size, i.e. the width of a homogeneous cloud strip, is 0.05 km. 50 m is much below the smoothing scale, where horizontal photon transport is important. Assuming a wind speed at cloud level of 5 m s^{-1} (i.e. its component which is parallel to the cloud variability direction), the scales of 0.05 and 102.4 km correspond to the respective irradiance averaging times of 10 s and 5.7 h. The variable irradiance averaging time was simulated by averaging the irradiance over different numbers of consecutive pixels. The simulations were performed for solar zenith angles of 0°, 40° and 70°. For the full list of input parameters used in the numerical experiments, see Table 1.

A Monte Carlo model based on the maximum cross-section method has been compared successfully with other radiative transfer models for several 3-dimensional stratiform and convective cloud fields as part of the International Intercomparison of 3-dimensional Radiation Codes (I3RC; see http: i3rc.gsfc.nasa.gov).

Optical thickness retrieval method

The optical thickness of clouds was inferred from ground-based broadband measurements of irradiance by matching the 'observed' irradiances with those obtained from the model. For each value of the solar zenith angle and cloud base height employed in the present error simulations (compare

Table 1), a lookup table was calculated to relate cloud optical thickness to atmospheric transmittance and irradiance for a uniform cloud separated from the non-reflective sea surface by a scattering 'aerosol' layer. The optical properties of the scattering layer were the same as in the simulations of irradiance fields under inhomogeneous clouds described in the previous section. For clouds of $\tau \leq 64$ the Monte Carlo code presented above was used to estimate the irradiance (transmittance) on the sea surface, while for cases of thick uniform clouds ($\tau \geq 32$) the irradiances were calculated by means of 8-stream DISORT (Stamnes et al. 1988, 2000). For the cases where both methods were used, the differences between the respective irradiances calculated by both methods were negligible. The computations were performed for the following values of τ: 0.0001, 1, 2, 4, 8, 16, 32, 64, 128, and 256. Cloud optical thickness values between the nodes were retrieved by the following interpolation formula (hyperbolic interpolation):

$$\tau = \tau_i + \frac{(\tau_i - \tau_{i+1})T_{i+1}}{(T_i - T_{i+1})}\left(1 - \frac{T_i}{T}\right), \tag{2}$$

where T is the 'measured' irradiance/cloud transmittance in a given pixel, $T_i < T_{i+1}$ are the values from a look-up table for the given conditions closest to T, and τ_i and τ_{i+1} are the corresponding cloud optical thicknesses.

3. Results

This section focuses on the biases in the mean cloud optical thickness retrieved from surface-based solar radiation measurements under the assumption of a horizontally uniform atmosphere at the time and place of measurements. The dependence of the biases on selected cloud properties and measuring conditions, including irradiance averaging time, is presented. Solar radiation reaching the sea surface is often measured as downward irradiance averaged over time periods ranging from seconds to hours. 15-minute up to 1-hour averages are typically employed in retrievals of cloud optical thickness (e.g. Pinto et al. 1997, Barker et al. 1998), although 6-hour means are also used (Leontieva et al. 1994). The plane-parallel bias in retrievals of cloud optical thickness is defined as the difference between the real domain-averaged cloud optical thickness $<\tau_{\text{real}}>$ and the domain averaged cloud optical thickness retrieved from irradiance measurements $<\tau_{\text{retr}}>$. The relative bias is defined as follows:

$$\varepsilon_\tau = \frac{\langle\tau_{\text{retr}}\,(\text{scale})\rangle - \langle\tau_{\text{real}}\rangle}{\langle\tau_{\text{real}}\rangle}, \tag{3}$$

where the scale is the averaging time (or, equivalently, the distance in the cloud) of the mean irradiance used in an individual retrieval.

The errors are analysed for averaging scales of irradiance ranging from 50 m to 25.6 km. Under the assumptions that the variations in cloud LWP are due mainly to advection of the spatial pattern of the turbulent liquid water field (Cahalan & Snider 1989) and wind speed of 5 m s^{-1}, these correspond to the respective time scales of 10 s and about 1.4 h. Dependences of the bias on the irradiance averaging scale for selected clouds (BC and MBC clouds, $<\tau_{\mathrm{real}}> = 5$, 12 and 30; cloud base height $h_{\mathrm{cl}} = 150$ and 1000 m) and solar zenith angles ($\vartheta = 40°$ and 70°) are presented in Fig. 2. For all the cases the bias is negative and its absolute value increases with an increase in the irradiance averaging scale. The negative bias is consistent with the plane-parallel biases found in cloud transmittance and albedo (e.g. Cahalan 1994, Cahalan et al. 1994a, 1995, Rozwadowska & Cahalan 2002) as well as with the findings by Boers et al. (2000). The negative bias in the cloud optical thickness results from the concavity of the relation between cloud transmittance and cloud optical depth: hence, $\tau((T_1 + T_2)/2) \geq (\tau(T_1) + \tau(T_2))/2$. Thin clouds, represented in the present paper by $<\tau_{\mathrm{real}}> = 5$, are an exception. For small irradiance averaging scales and thin clouds the optical thickness bias can be positive, as was also reported by Boers et al. (2000). This is due to horizontal photon transport, which can locally result in higher irradiances

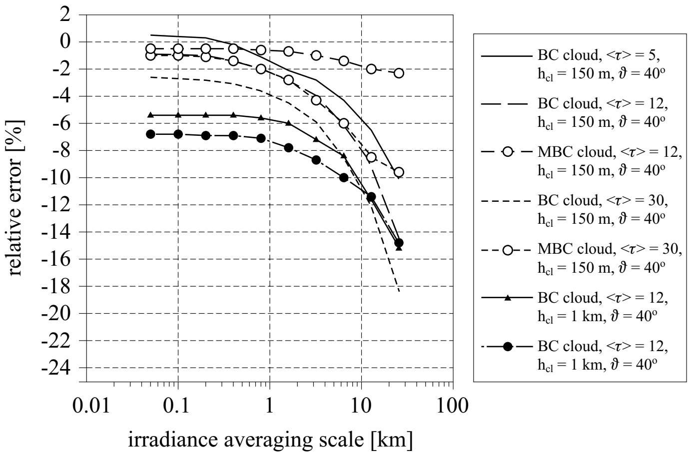

Fig. 2. Modelled dependences of the relative bias in domain averaged cloud optical thickness retrieved from pyranometer measurements on an irradiance averaging scale for selected bounded cascade clouds. BC and MBC respectively denote the pure and modified bounded cascade cloud model. $<\tau_{\mathrm{real}}>$, h_{cl}, and ϑ denote domain averaged cloud optical thickness, cloud base height and solar zenith angle, respectively. Computations were performed for a cloud variability direction parallel to the principal plane

than those in the respective cloudless case. In such cases the apparent cloud optical thickness is negative and a cloud optical thickness equal to 0 is assumed in the retrievals. This effect is strongest for small irradiance averaging scales (short averaging times) because such 'flashes' are of short duration (small-scaled). For larger scales (at least several hundred metres) horizontal photon transport becomes negligible in stratus clouds, therefore cloud transmittance >1 does not occur for a cloud cover of 100%. The shape of the bias plotted as a function of the irradiance averaging scale is characterised by a plateau for the smallest scales and an increase in the absolute value of the bias for larger scales, and depends mainly on the cloud internal variability, i.e. cloud type or cloud model (and model parameters), and cloud base height. The increase in bias with the irradiance averaging scale is least pronounced for the thick MBC cloud ($<\tau_{\mathrm{real}}> = 30$), and also for thinner MBC clouds and larger averaging scales, where the cloud optical thickness variabilities are weaker than those in analogous cases of the pure bounded cascade cloud. Fig. 3a shows the influence of the mean cloud optical thickness on the minimum error (minimum absolute value of the bias) for a solar zenith angle $\vartheta = 40°$ and a cloud base height $\mathrm{h_{cl}} = 150$ m. Both Figs. 3a and 2 indicate that for the pure bounded cascade clouds in which the model $\sigma_{\log 10(\tau)}$ is constant, that is, the variance of τ increases with increasing mean optical thickness $<\tau_{\mathrm{real}}>$, the optical thickness bias changes with a rise in $<\tau_{\mathrm{real}}>$ from about 1% for $<\tau_{\mathrm{real}}> = 5$ to about –3% for $<\tau_{\mathrm{real}}> = 30$. For the MBC cloud the bias is about –1%. In the case of the c. 40-minute averages of irradiance (averaging scale of 12.8 km) used in mean optical thickness retrievals the absolute value of the bias increases considerably for the BC cloud, reaching 13% for $<\tau_{\mathrm{real}}> = 30$, while for the thick MBC cloud it remains very low, c. 2% in our simulations (Fig. 3c). For comparison, the respective biases for BC cloud modified to obtain a cloud cover of 0.3 vary from $-20 - -30\%$ for instantaneous (10-second) irradiance measurements to over -70% for the 40-minute means (additional simulations, not shown in the figures).

The influence of cloud base height and solar zenith angle on the bias in mean cloud optical thickness for retrievals from 50-metre (10-second) and 12.8-kilometre (about 40-minute) mean irradiances are presented in Figs. 3 b and d, respectively. The real mean cloud optical thickness is set at 12. The increase in cloud base height results in an increase in the absolute value of the bias from about 0–3% for $\mathrm{h_{cl}} = 150$ m to typically 4–8% for $\mathrm{h_{cl}} = 1$ km and momentary irradiance measurements (50-m mean irradiances). When 40-minute averages of irradiance are used for the retrievals, the expected respective biases take values of $-8 - -10\%$ and $-10 - -12\%$ for

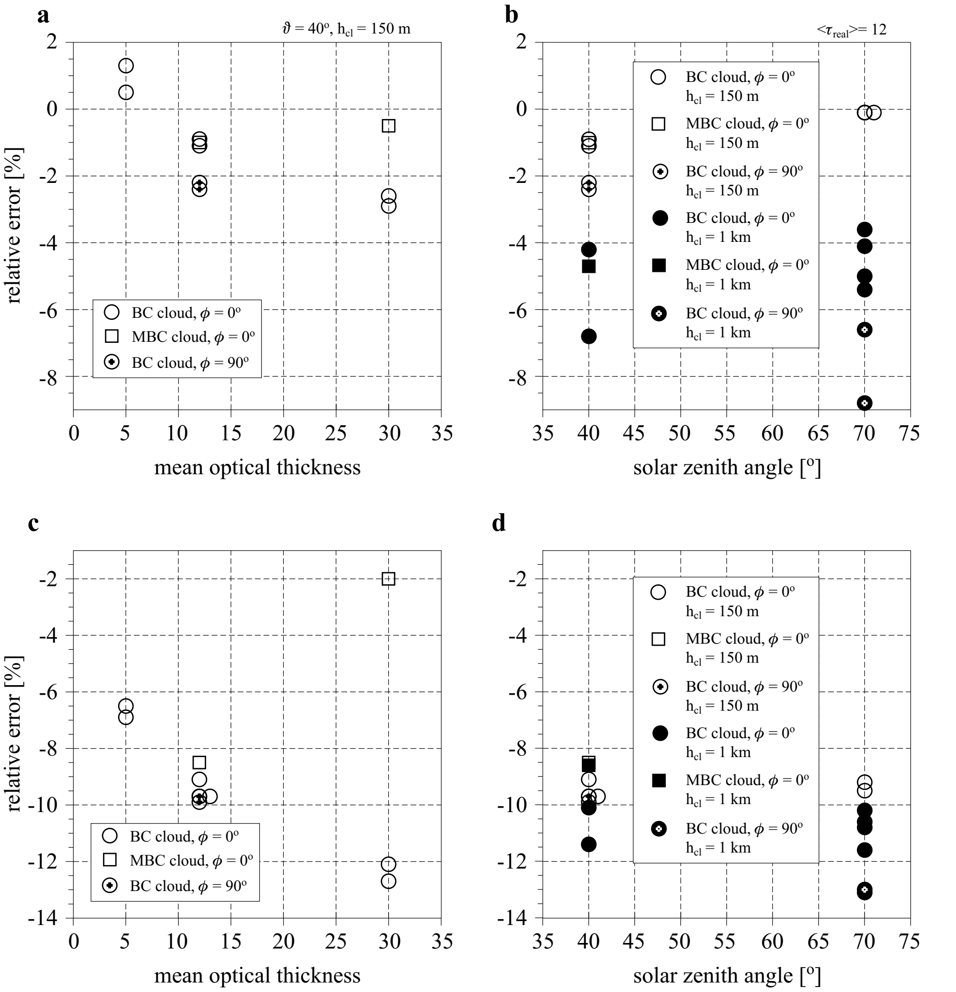

Fig. 3. Modelled dependences of the relative bias in domain averaged cloud optical thickness retrieved from pyranometer measurements on (left panel: a and c) mean optical thickness and (right panel: b and d) cloud base height and solar zenith angle for irradiance averaging scales of (upper row) 50-metre (10-second) and (lower row) 12.8-kilometre (about 40-minute). $<\tau_{\mathrm{real}}>$, $\mathrm{h_{cl}}$, and ϑ denote domain averaged cloud optical thickness, cloud base height and solar zenith angle, respectively. Computations were performed for a cloud variability direction parallel $\phi = 0°$ and perpendicular $\phi = 90°$ to the principal plane. Overlapping points are shifted to the right

$<\tau_{\mathrm{real}}> = 12$. The impact of the solar zenith angle on the retrieval error is of less importance. In general, an increase in solar zenith angle diminishes the bias. For BC cloud, $<\tau_{\mathrm{real}}> = 12$ and $\mathrm{h_{cl}} = 150$ m the absolute value of the bias in the retrievals based on instantaneous irradiance measurements drops from 2.2% for $\vartheta = 0°$ (not shown in the figure) and about 1% for $\vartheta = 40°$ to become negligible for $\vartheta = 70°$ (0.1%). The bias based on 40-minute mean irradiances is practically constant with respect to the solar zenith angle.

Although the majority of the simulations were performed for a cloud variability direction parallel to the principal plane, biases were also estimated for selected cases with the cloud field variable along a direction perpendicular to the principal plane in order to show the sensitivity of the bias to the assumption of cloud variability restricted to 1D. For the perpendicular cases the absolute values of the bias are higher by 1–2% than the respective biases for the parallel cases (Figs. 3 a–d).

In the simulations presented in this paper the bias in the domain averaged cloud optical thickness retrievals varies from +1% to nearly –20%. The highest absolute value of the bias is expected for thick and variable clouds, retrievals based on long-term mean irradiances and clouds with higher bases. 1-hour averages of irradiance typically used in cloud optical thickness determination are likely to introduce a bias in excess of −10%. Because the bias is sensitive to internal cloud variability, and real stratus clouds are likely to be less variable than the bounded cascade clouds analysed in this paper, the biases estimated in this study can be taken as the upper limit of the biases due to the plane parallel assumption in the cloud optical thickness retrievals. For comparison, uncertainties in cloud optical thickness retrievals due to: (1) model assumptions concerning, among other things, atmospheric gases and aerosols, vertical cloud structure and droplet size distributions and (2) measurement errors of retrieval input parameters result in a total error of several to about 100 percent for an individual retrieval (e.g. Leontyeva & Stamnes 1994, Pinto et al. 1997, Boers et al. 2000, Rozwadowska, in press). However, because these uncertainties are mainly of a 'statistical' character, the respective error for the mean cloud optical thickness is considerably lower.

As mentioned earlier, for the smallest irradiance averaging scales the bias is almost constant. The scales of the constant bias in cloud optical thickness retrievals with respect to the mean cloud optical thickness (h_{cl} = 150 m), and the solar zenith angle and the cloud base height are given in Figs. 4 a and b, respectively. The constant bias scale is defined here as the maximum scale of irradiance averaging used in retrievals for which the relative bias changes no more than 0.5% when compared to the respective bias for the instantaneous irradiance, that is, the maximum averaging scale for which the difference between the minimum relative bias and a given bias

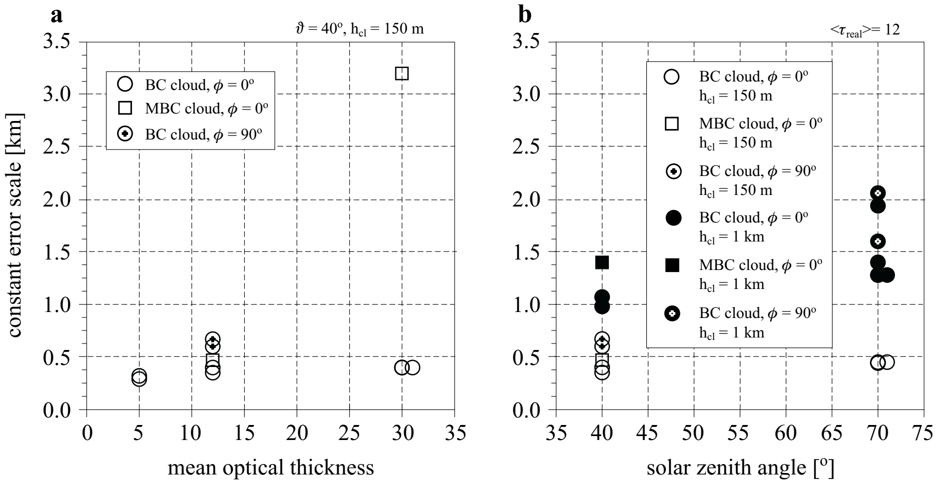

Fig. 4. Modelled dependences of maximum averaging scales of irradiance to obtain minimum biases (constant bias scale) on (a) mean optical thickness and (b) cloud base height and solar zenith angle. The same notation as in Fig. 3

does not exceed 0.5%. The constant bias scale varies from several hundred metres for clouds with their bases at 150 m (time scales of 1–2 minutes) to 1–2 km (4–7 minutes) for clouds with bases at 1 km. However, for thick MBC cloud this scale is over 3 km owing to the nature of this cloud model. The simulations indicate that short-term mean irradiances (up to 1–2 minutes) are more suitable in cloud optical thickness retrieval than 1-hour or 15-minute averages, which are often used.

The influence of the cloud base height, and $<\tau_{\mathrm{real}}>$ on the bias can be explained by Fig. 5, which presents the domain averaged contribution of cloud areas of different radius centred at the zenith to the total irradiance measured at the sea surface. The simulations were performed for BC clouds. While for low-level cloud (h_{cl} = 150 m) over 90% of solar energy measured at a given point comes from a cloud area 500 m in radius, in the case of a 1-kilometre-high cloud the same area contributes to only slightly more than 20% of the irradiance. Therefore, for higher clouds angular averaging is very important and at smaller scales dominates the retrieval bias (when compared to time averaging). The increase in the solar zenith angle also results in the higher contribution of cloud pixels further from the zenith, although to a much smaller degree than in the case of the cloud base height. With respect to the influence of mean cloud thickness, a difference is perceptible only for thin clouds, when direct solar radiation can occasionally reach the sea surface.

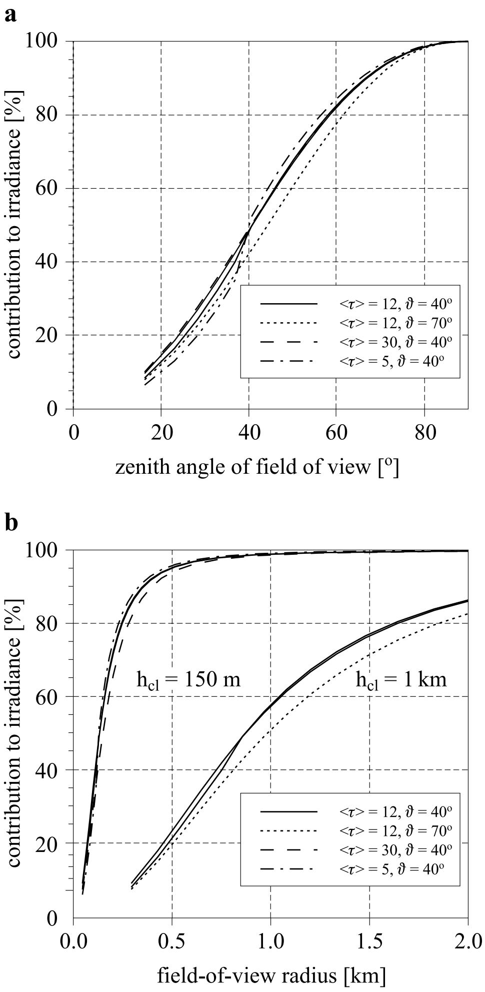

Fig. 5. Domain averaged contribution of the radiation from a cloud area centred at the zenith to the total irradiance measured at the sea/land surface, with respect to (a) the zenith angle of the field of view and (b) the radius of the area at cloud level. The simulations were performed for BC clouds

The biases discussed here were estimated for a dark sea surface. In the case of a reflective surface such as sea ice, the biases could be different, diminished if the underlying surface is uniform or enhanced if the surface is both highly reflective and highly variable (cf. Rozwadowska & Cahalan 2002).

4. Conclusions

Optical thicknesses of clouds can be inferred from ground-based broadband measurements of irradiance by matching the observed irradiances with those obtained from a model. For an individual retrieval the atmosphere is typically assumed to be horizontally uniform, which introduces a considerable uncertainty into the retrievals. In the present paper the relative plane-parallel error in cloud optical thickness retrievals from ground-based (shipborne) pyranometer measurements was analysed. The error was estimated for an optical thickness averaged over the whole domain, which simulated the mean cloud optical thickness obtained from a time series of irradiance measurements. The analysis was based on Monte Carlo simulations. The 3D Monte Carlo code developed by Marshak (Marshak et al. 1995), using the 'maximum cross-section method' of Marchuk et al. (1980), was employed. A fully overcast sky was assumed. Non-absorbing liquid water clouds with their bases at 150 and 1000 m were used in this study. Clouds were modelled by two bounded cascade models: the 'pure' bounded cascade (referred to as BC, e.g. Cahalan 1994) with the scaling parameter $c = 0.8$ ($\alpha = -5/3$) and the variance parameter $f = 0.5$, and the modified bounded cascade (referred to as MBC) (Boers et al. 2000) with $f = 0.24$ for scales > 12.8 km and $f = 0.5$ for smaller scales, and $c = 0.8$. The cloud thickness was set at 300 m. Clouds and the underlying non-reflective 'sea' surface were separated by a non-absorbing scattering layer. The cloud optical thickness was variable in 1D in directions both parallel and perpendicular to the principal plane. Typical model parameters were as follows: wavelength $\lambda = 605$ nm, scattering coefficient of the scattering layer under the cloud 0.1 km^{-1}, asymmetry factor of the scattering layer 0.68, cloud asymmetry factor 0.85, mean cloud optical thickness 5, 12, and 30, solar zenith angle 0°, 40° and 70°, domain length 102.4 km, minimum cell size 0.05 km. For each case from 1 to 4 runs with 2×10^8 photons each were performed.

The dependence of the error was studied with respect to several factors, including the time of irradiance averaging used in an individual retrieval, mean cloud optical thickness, cloud variability, cloud base height and solar zenith angle. The bias was analysed for irradiance averaging scales ranging from 50 m to 25.6 km, which for a wind speed of 5 m s^{-1} corresponds to the time scales of 10 s and 1.4 h, respectively.

The findings are summarised as follows:

1. For all cases the plane-parallel error is negative. Thin clouds, represented in the present paper by $<\tau_{\text{real}}> = 5$, are an exception. For small irradiance averaging scales and thin clouds the optical thickness bias can be positive. This is consistent with the findings of Boers et al. (2000).
2. The absolute value of the error is at a minimum for small irradiance averaging scales (short averaging times) and increases as the averaging scale does so. The minimum absolute value of the bias depends mainly on cloud internal variability (cloud type/cloud model) and cloud base height. The impact of the solar zenith angle on the retrieval error

is of less importance in mid-latitudes, but may become considerable in the tropics where the Sun's position ranges from the zenith to the horizon. In the present simulations the minimum bias varies from about 1% for $<\tau_{\mathrm{real}}> = 5$ and $h_{\mathrm{cl}} = 150$ m to $-4 - -8$% for $<\tau_{\mathrm{real}}> = 12$ and $h_{\mathrm{cl}} = 1$ km. For thick and highly variable middle-level clouds the error can be higher.

3. For small irradiance averaging scales the bias is almost constant. The constant bias scale varies from several hundred metres for clouds with their bases at 150 m (time scales of 1–2 minutes for wind speed 5 m s^{-1}) to 1–2 km (4–7 minutes) for clouds with bases at 1 km. However, for thick MBC clouds this scale is over 3 km owing to the nature of the cloud model.

4. The increase in the plane-parallel error with irradiance averaging scale is least pronounced for thick MBC clouds ($<\tau_{\mathrm{real}}> = 30$) and also for thinner MBC clouds and larger irradiance averaging scales, where the variability in cloud optical thickness is weaker than in analogous cases of pure bounded cascade clouds.

5. In the simulations presented in this paper, the plane-parallel error in the domain averaged cloud optical thickness retrievals varies from +1% to nearly –20%. The highest absolute value of the bias is expected for thick and variable clouds, retrievals based on long-term mean irradiances (tens of minutes and hours) and a higher cloud base. Because the bias is sensitive to internal cloud variability, and real layer clouds are likely to be less variable than the bounded cascade clouds analysed in this paper, the biases found can be taken as the upper limit of the biases resulting from the plane parallel assumption in the retrievals.

6. The bias can be reduced by using short-term irradiance averages, i.e. of one minute. One-hour averages of irradiance, typically employed in cloud optical thickness retrievals, are not recommended. They are likely to introduce a bias in excess of 10%. In addition, the retrievals should be limited to fully overcast cases (see also Boers et al. 2000) and low-level clouds.

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