Molecular Line Absorption in a Scattering Atmosphere. Part III: Pathlength Characteristics and Effects of Spatially Heterogeneous Clouds

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ABSTRACT

The paper analyzes the influence of horizontal variability of clouds on sunlight reflected in a narrow portion of the solar spectrum and how this influence affects the ability to estimate cloud properties from measurements of reflection. This paper is part of a series that examines the use of high-resolution measurements of absorption lines of the oxygen A band located between 0.763 and 0.773 μm as a way of deriving information on cloud structure presently unobtainable from other passive measurements. The effects of spatial heterogeneity on reflectances and pathlength distributions are examined for marine stratocumulus cloud fields derived from Landsat data. The results showed that for the marine stratocumulus fields studied, the radiance errors were on the order of 3%−20%, and the spectral radiance ratio (in-band to out-of-band) errors were on the order of 1%−5%. When these errors are too large, the retrieved quantities possess too much error to be useful. The errors due to horizontal transport of photons and subpixel variability are studied independently as a function of spatial scale. Using both the radiance and radiance ratios, a technique was developed that allows the plane-parallel forward model typically used in retrieval schemes to be able to predict when its retrievals are so influenced by spatial heterogeneity that the results are invalid. This ability would represent a significant step forward in the current abilities of passive retrievals, which cannot determine the effect of cloud spatial variability on their retrievals. Lastly, a method was demonstrated that used domain-averaged measurements of absorption formed by reflection along with plane-parallel theory to estimate the distribution of optical depth throughout the domain. The results for the four simulated cloud fields showed this technique to have significant promise in quickly classifying the level of cloud heterogeneity over a large area.

1. Introduction

This paper is concerned with the problem of estimating cloud properties from measurements of reflected sunlight. Inverting measurements of reflected sunlight to obtain cloud properties has become a popular approach over the last decade (e.g., Stone et al. 1990; Nakajima and King 1990; Nakajima and Nakajima 1995; Platnick and Valero 1995; and Han et al. 1994). However, the inversion methods developed generally lack quantitative error analyses and other information that can be used to determine the reliability of the retrieved information. In particular, retrieval methods developed to produce cloud information are based on crude assumptions about the vertical structure of clouds and assume that the radiative transport in each pixel occurs independently of the transport that takes place in neighboring pixels. This latter assumption is referred to as the independent pixel approximation (IPA; Cahalan et al. 1994a,b; Barker 1996). Model simulations of reflected sunlight from three-dimensional cloud fields (e.g., Duda and Stephens 1994) clearly point out that this assumption breaks down due to the effects of horizontal transport of photons from one pixel to another producing nonlocal influences on the measured radiances.

Unfortunately, our understanding of the 3D effects of clouds on radiative transfer is rudimentary, and we have yet to develop a method that can determine a priori whether these effects are likely to be large for any given scene. At this time, the satellite cloud retrieval schemes have not been able to account for this effect nor can these schemes provide clear estimates of uncertainty introduced by neglecting these effects. A method is required that, at a minimum, can determine when this assumption is violated and thus when cloud property retrievals become unreliable. This paper outlines the steps toward such a method.

This paper is the third in a series of papers dealing with the information content of absorption lines of mo-
lecular oxygen in a scattering atmosphere. Both the present topic and those addressed in the two earlier papers of this series (Stephens and Heidinger 2000; Heidinger and Stephens 2000, hereafter Parts 1 and 2, respectively) examine the use of high-resolution measurements of absorption lines of the oxygen A band located between 0.763 and 0.773 μm as a way of deriving information on cloud structure unobtainable from other passive measurements. Interest in this topic has been stimulated in part by the present measurements obtained from spectrometers currently flying on satellites (e.g., GOME and HRDI; Hays et al. 1993) and in part by the plans to fly A-band spectrometers in near-future satellite missions dedicated to the study of clouds and aerosol. This paper continues this interest and demonstrates how measurable signatures of three-dimensional transport are contained within molecular oxygen line absorption formed by the reflection of clouds. These signatures are distinct in the distributions of photon pathlengths, which can be diagnosed directly from the spectral radiances.

The paper begins with a discussion of the properties of A-band nadir radiances and photon path statistics for plane-parallel clouds. In this section, the relationship between the photon path distribution and the ratio of reflected radiances in and out of absorbing lines is clearly established. The equivalent properties are derived for 3D cloud distributions in sections 3 and 4. In these sections it is shown how the effects of cloud heterogeneity affects photon path distributions, spectral radiances, and radiance ratios. Section 5 analyzes errors in the plane-parallel, IPA treatment of clouds. This section quantifies errors that arise from the basic assumptions of the IPA, namely, errors due to the neglect of horizontal transport and errors due to the effects of subgrid variability. The differing effects of heterogeneity on radiances and radiance ratios are exploited in section 6. Here, we introduce a novel way of identifying the effects of cloud heterogeneity on retrievals of cloud optical depth. In addition, a description of the circumstances under which the spectral A-band measurements provide meaningful statistical information about the distribution of optical depth within a field of view of an instrument is presented. The paper concludes with a review of the key results reported in the paper and a summary of the main conclusions.

Recent related A-band works

Several important works concerning the use of A-band measurements to derive cloud properties have been recently published, and it is important to describe their relation to this work. In particular, the works of Pfeilsticker et al. (1998), Pfeilsticker (1999), Min and Harrison (1999), and Min et al. (2001, hereafter MHC) describe and present results of cloud geometric pathlength retrievals using ground-based A-band spectrometers. Both works clearly describe the difficulties in making highly accurate measurements of oxygen A-band spectra. The work of Pfeilsticker uses the Differential Optical Absorption Spectrometry method described by Platt (1994) to make measurements at roughly 0.33 cm⁻¹ resolution. In Pfeilsticker et al. (1998), these data were used to measure the pathlength distribution assuming the pathlength distribution is described by a Γ distribution. These results indicated that plane-parallel radiative models may overestimate the pathlengths through cloudy atmospheres. In Pfeilsticker (1999), similar data are analyzed to show the geometric distance between scatterings in cloudy atmospheres are governed by Lévy transport. Derived Lévy indices from the A-band data are in agreement with theoretical predictions. The consequence of Lévy distributed pathlengths is that the probability of mean geometrical paths is lowered in favor of shorter and much longer paths. This property of cloud radiative transfer may lead to a net increase of cloudy-sky shortwave heating (Pfeilsticker 1999). These findings are in agreement with theoretical predictions by Davis and Marshak (1997).

In the work of Min and Harrison (1999) and MHC, surface-based measurements from the Rotating Shadowband Spectroradiometer (RSS) located at the Atmospheric Radiation Measurement Program’s Southern Great Plains site (ARM-SGP) are used to observe A-band spectra (Harrison et al. 1999). The resolution of the RSS is roughly 40 cm⁻¹, which is sufficient to determine the mean of the pathlength distribution. In these studies, the data from the RSS were combined with the data from a zenith-viewing microwave radiometer to derive the mean pathlength, the cloud optical depth, and the mean particle size (Min and Harrison 1996). The data from several different cloudiness conditions are presented. One of the main conclusions from these interesting case studies is that the correlation of the mean pathlength with optical depth provides new insight on the radiative transfer through clouds not available with other passive techniques (MHC).

Both these studies clearly indicate the utility of measurements of A-band spectra in the presence of clouds. In Parts 1 and 2 the ability of using reflectance A-band spectra to derive cloudiness properties was explored. These papers and the observational works all exploit the unique properties of A-band spectra to derive cloudiness information. In this paper, we focus on the effects of cloud heterogeneity on the observed spectra and the consequences for cloud remote sensing. Unlike the observational studies described above, this work focuses solely on reflectance spectra as would be measured by a spaceborne A-band spectrometer. The observations of enhanced pathlengths in heterogeneous clouds are consistent with the results in this work based on simulations. This work attempts to infer from those enhanced pathlengths information about the inhomogeneities of the cloud field.
2. Photon pathlength properties in plane-parallel media

The distribution of photon paths associated with multiple scattering in clouds, and related statistics of this distribution, are sensitive to the three-dimensional distribution of clouds. This sensitivity, however, varies with the particular radiometric quantity of interest. The focus of this paper is the reflected radiances and the photon path properties considered are those relevant to these radiances.

In order to understand how photon path distributions change as cloud geometry varies, it is convenient to begin with a discussion of the photon path properties of plane-parallel cloud layers. As shown in Parts 1 and 2, a key parameter in the definition of the photon path is the absorption line parameter

$$s_c = \frac{I_c}{I_n},$$

where $I_c$ is the radiance measured in the continuum defined as a region of minimal gaseous absorption and $I_n$ is the radiance measured at a frequency located within the absorption line. Photon path properties are related to this profile property through the equivalence theorem (e.g., Irvine 1964) according to

$$s_c = \int_0^\infty p(l) e^{-\sigma l} \, dl,$$

where $l$ is the geometric photon pathlength, and $\sigma$ is the volume extinction coefficient taken to be constant for convenience. Thus measurements of $s_c$ are related formally to the photon pathlength distribution $p(l)$ through an inverse Laplace transform (e.g., van de Hulst 1980). Pfeilsticker et al. (1998), Pfeilsticker (1999), and Min and Harrison (1999), and MHC make use of this transform procedure to estimate $p(l)$ from A-band measurements. Monte Carlo models also explicitly compute $p(l)$. This information derived from such models can be used with (2) and applied to those spectral regions over which the particle scattering properties can be assumed constant to determine a spectra of arbitrary spectral resolution for any cloud geometry. This technique was used in Part 1 to compute line-by-line A-band spectra and is used here to compute A-band spectra in the presence of spatially heterogeneous clouds. This technique has been extended to the broadband computation of fluxes in 3D cloud fields in the recent work of Partain et al. (2000).

a. Pathlength distributions of plane-parallel clouds

For a vertically uniform plane-parallel medium, the optical pathlength $\lambda$ differs only from the geometric pathlength $l$ by a constant multiplicative factor

$$\lambda = \sigma_c l,$$

where the $\sigma_c$ factor is the extinction coefficient of the continuum scatterers. Any heterogeneity in $\sigma_c$ causes a degree of decorrelation between $\langle \lambda \rangle$ and $\langle l \rangle$. For example, in the limit where the heterogeneity in $\sigma_c$ is so extreme that all scatters condense to a single point, $\langle \lambda \rangle \to \infty$ and $\langle l \rangle \to 0$.

The mean optical pathlength can be written as (van de Hulst 1980)

$$\langle \lambda \rangle = \frac{\partial \ln I}{\partial \omega_o} - \frac{\partial \ln I}{\partial \tau},$$

where $\omega_o$ is the single scatter albedo and $\tau$ is the optical depth. While (2) applies to any scattering media, (3) applies only to homogenous media. For the case of the oxygen A band, the continuum scattering properties (i.e., those properties associated with the particle scattering) are constant across the absorption band so the only spectral variation is that associated with molecular oxygen absorption characterized by the oxygen optical depth $\tau_{O_2}$ in the cloud layer. In this case, (3) becomes

$$\langle \lambda \rangle = -\frac{d \ln I}{d \tau_{O_2}}.$$

Figure 1 illustrates numerical evaluations of (4) as a func-
tion of \( \tau_{\text{eq}} \), using the multiple scattering model described in Part 1. The results of these simulations, displayed as \( \langle \lambda \rangle \) normalized by the domain mean optical depth \( \langle \tau \rangle \), were derived for both an isotropically scattering layer and an anisotropically scattering layer with the phase function being given by a single Henyey–Greenstein representation with an asymmetry parameter \( g = 0.85 \). The quantity \( \langle \lambda \rangle / \langle \tau \rangle \) in this case is identical to the ratio of the mean geometrical pathlength \( \langle l \rangle \), to mean geometrical thickness of the layer \( H \). A similar analysis, including the mean pathlength for fractal (heterogenous) clouds, is given by Davis et al. (1997) for \( \tau > 2 \).

We now provide the mean photon path properties under the optically thin and thick limits. The behavior under these limits offers a useful guide to interpreting the results of Fig. 1.

**b. Optically thin limit**

In the optically thin limit (\( \tau \to 0 \)), the reflected radiance is defined by those photons that experience single scattering only. This radiance, hereafter denoted as \( I_{\text{n}} \), can be written as

\[
I_{\text{n}} = \frac{\omega F_{\text{p}} P}{m\mu \frac{4\pi}{r}}(1 - e^{-\mu r})
\]

(refer to Part 1 for details). It follows by substitution of (5) in (4) and evaluation of this expression that the mean optical pathlength is

\[
\langle \lambda \rangle_{\text{n}} = 1 - \frac{m\tau e^{-\mu r}}{1 - e^{-\mu r}},
\]

and in the limit as \( \tau \to 0 \),

\[
\langle \lambda \rangle_{\tau \to 0} = \frac{m}{2}.
\]

Thus, in ratio form,

\[
\frac{\langle \lambda \rangle_{\tau \to 0}}{\tau_{\text{e}}} = \frac{\langle l \rangle_{\tau \to 0}}{H} = \frac{m}{2\tau_{\text{e}}}.
\]

The single scatter limit is confirmed in Fig. 1, which shows the predictions from the numerical multiple scattering model introduced in Part 1. It is also relevant to note that this thin limit to the mean pathlength is independent of the properties of the scattering phase function.

**c. Optically thick limit**

In the optically thick limit as \( \tau \to \infty \), the ratio of the mean optical pathlength to the optical depth is independent of the phase function and asymptotes to the value of 1.66 (Fig. 1). This value is consistent with the well-known diffusivity constant commonly used in infrared radiative transfer models, which ignore scattering. According to the numerical results given, the nadir radiance pathlength is sensitive to the phase function under moderate values of \( \tau_{\text{e}} \). The most important region is the relative maximum in \( \langle \lambda \rangle / \langle \tau \rangle \) near \( \tau \approx 4 \) for the
anisotropically scattering case. This behavior is shown later to be important in the detection of heterogeneity in absorption line spectra.

3. Effect of cloud heterogeneity on photon pathlengths

The effect of the three-dimensional spatial variability of cloud on the reflected radiances is now examined in relation to the effects of this variability on photon pathlengths. The effects are studied using results obtained from the 3D Backward Monte Carlo Model described in Part 1. This model simulates the reflection of sunlight in the oxygen A band from a few selected cloud distributions that are derived from two different Landsat images of marine stratocumulus. The particular dataset used for this purpose is described by Harshvardhan et al. (1994) and Barker et al. (1996) and consists entirely of single-layered marine stratocumulus. One of the images is of a relatively homogeneous cloud field (Fig. 2; cloud field 2) and the other (Fig. 3; cloud field 2) is a more complex field containing regions of clear sky amid denser portions of the cloud.

Fields of cloud optical depth are constructed from these cloud images using a simple reflection-based retrieval approach. The details of this retrieval are unimportant. The optical depth fields so derived are shown respectively in Figs. 2 and 3. The spatial resolution of the data (pixel size) is 28.5 m over a 58 × 58 km domain defined by 2048 × 2048 pixels. Table 1 summarizes relevant statistical properties of the two cloud fields. The properties listed are the cloud fraction $N$, the domain mean optical depth $\langle \tau_c \rangle$, and the width parameter $a$ of the distribution of $\tau$ assuming a $\Gamma$ distribution. In section 6b, a methodology and numerical examples are presented for retrieving $\langle \tau \rangle$ and $a$ from A-band measurements.

The distributions of optical depth as shown in Figs. 2 and 3 were used in the 3D model to simulate the reflected A-band radiances. Only the results for nadir radiances are presented. Model simulations of these radiances include the following assumptions: (i) an underlying dark surface, (ii) one solar zenith angle $\mu_s = 0.8$, (iii) a cloud thickness of 500 m and no horizontal variations in cloud geometrical thickness, (iv) that the cloud droplets conservatively scatter across the spectral region of the oxygen A band, and (v) scattering phase function for the cloud droplets is approximated as a Henyey–Greenstein phase function with an asymmetry parameter of 0.85, as used previously in Part 1. Since

![Fig. 3. (left) A 58-km Landsat-derived field of optical depth (cloud field 2). (right) A 4-km subsection (cloud field 2a).](image)

**Table 1.** Properties of cloud fields shown in Figs. 2 and 3. $N$ is the cloud fraction, $\langle \tau_c \rangle$ is the domain-averaged continuum optical depth, and $a$ is the width parameter of $\tau$ distribution.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Field 1</th>
<th>Field 1a</th>
<th>Field 2</th>
<th>Field 2a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>0.99</td>
<td>1.00</td>
<td>0.36</td>
<td>0.90</td>
</tr>
<tr>
<td>$\langle \tau_c \rangle$</td>
<td>14.5</td>
<td>19.9</td>
<td>2.2</td>
<td>8.4</td>
</tr>
<tr>
<td>$a$</td>
<td>1.58</td>
<td>21.5</td>
<td>0.12</td>
<td>0.74</td>
</tr>
</tbody>
</table>
these simulations are concerned only with relative errors, lack of the inclusion of effects of surface reflection will not alter the conclusions of this study. Furthermore, the purpose of the model simulations is not to provide a systematic and detailed account of the effects of 3D geometry on reflected radiances under a variety of conditions. Rather the goal is to illustrate errors associated with interpretation of these radiances for conditions that might be considered typical of the spatial variability expected in low-level boundary layer cloud.

The model-derived optical and geometrical path distributions, \( p(l) \) and \( p(l') \), respectively, of photons reflected along the zenith direction from the two cloud fields are shown in Figs. 4 and 5. The geometric path-lengths are normalized by the layer geometric thickness \( H \), and the optical path-lengths are normalized by the domain mean optical depth \( \langle \tau \rangle \). Displaying the path-length distributions in this manner allows them to be plotted on the same scale. Also shown in both figures for comparison are the pathlength distributions obtained for plane-parallel clouds of equivalent \( \langle \tau \rangle \).

The comparisons provided in Figs. 4 and 5 reveal how cloud spatial variability directly affects the photon path distributions. The results suggest that the greater the degree of spatial heterogeneity, the larger the difference in these path-length distributions. Cloud field 2 has characteristically greater variability than cloud field 1, which has properties close to the equivalent plane-parallel distribution. For cloud field 1, the photons that comprise the nadir reflectance travel an average of 2.1 times the layer optical thickness compared to 2.0 times the layer thickness in the plane-parallel cloud. Alternatively, photons from cloud field 2 travel an optical path that is 9.0 times the average optical thickness of the field compared to 2.2 times the layer thickness in the plane-parallel cloud. These results in Figs. 4 and 5 indicate that cloud spatial heterogeneity causes the photons that comprise the nadir reflectance to experience more scattering events but to travel less distance than an equivalent-in-optical-depth plane-parallel cloud.

The results presented in Figs. 4 and 5, as well as the results presented in Part 1, both indicate that the mean optical pathlength of photons scattered in a heterogeneous cloudy layer exceeds the optical pathlength of an equivalent-in-optical-depth plane-parallel cloud. Thus larger mean optical depths must be used in plane-parallel models to reproduce the actual mean pathlength of the heterogenous cloudy medium. This produces a positive bias in the optical depth–photon path relationship in contrast to the better known albedo–optical depth negative bias (refer to Part 1). The importance of the difference in behavior of albedo and photon path to varying cloud geometry is explored in further detail in the next section.

4. Effect of heterogeneity on A-band reflection spectra

The photon path characteristics describe above are significantly affected by cloud heterogeneity. These characteristics, in turn, are encoded in the spectrum of \( s_n \). In this section, the effects of heterogeneity on both \( s_n \) and radiance \( I_n \) are examined by comparing the spectra of these quantities to spectra derived using IPA. The relevance of this exercise stems from the universal use of the IPA in current passive methods (e.g., Minnis et al. 1992) and the overwhelming need to assess any errors that might arise from this widespread application of IPA. In this study, we make this assessment using full 3D simulations of both \( s_n \) and radiance \( I_n \) and compare these spectra with spectra produced under the IPA. The resulting errors in the retrieved optical depth associated with IPA errors are discussed in the next section.

The error that results from the use of IPA for estimating properties of three-dimensional cloud fields has two components. The first error component is that due to unresolved subpixel variability within the pixel of the IPA and is often referred to as the plane-parallel bias error (Cahalan et al. 1994b). The subpixel error varies according to the pixel dimension assumed in the IPA, and this dimension is determined by the resolution of the given satellite instrument. The spatial resolution of satellite image data ranges from 28.5-m Landsat data
to the typical 1–4-km resolution currently used for Geostationary Operational Environmental Satellite (GOES) and Advanced Very High-Resolution Radiometer (AVHRR) retrievals. The spatial resolution of state of the art imagers such as a moderate-resolution imaging spectroradiometer (MODIS) varies between 250 and 1000 m. These pixel dimensions typically do not resolve all scales of variability in cloud fields. Figures 6 and 7 provide a visual comparison of the effect of this spatial resolution on the perceived structure of the two sample cloud fields. The 28.5-m Landsat data shows spatial structure much smaller than the resolution of most satellite sensors. The comparisons presented in these figures qualitatively suggest that resolution of the order of 100 m is required to resolve the structures seen in both cloud fields. Results shown below indicate that the effect of subpixel variability on the cloud field 2 calculations is also significant.

The second source of error associated with the IPA occurs when the effects of horizontal transport between neighboring pixels outside the immediate field of view of the sensor are neglected. This transport influences the reflectance measured over that pixel. In plane-parallel models, there is no net horizontal transport of photons. In three-dimensional clouds, photons tend to migrate from denser regions of clouds to more tenuous regions of the cloud thus effectively smoothing the radiation field (e.g., Stephens 1988; Stephens and Preisendorfer 1984).

Figure 8 illustrates the combined effect of these factors on the spatial variability of both $I_\gamma$ and $s_\gamma$. The left panels of Fig. 8 are the horizontal distributions of $I_\gamma$ and the radiance ratio $s_\gamma$ defined at a frequency for which $\tau_0 = 2.0$, whereas, in Parts 1 and 2, $\tau_0$ refers to the total column oxygen optical depth. These quantities were calculated using the optical depth distribution of cloud field 2a and at the full Landsat resolution. The right panels show the errors in each respective quantity using the IPA applied to pixels of 300-m resolution. The errors are the differences between the quantities derived from the full 3D calculation at full resolution averaged to 300-m pixel sizes and the IPA calculation.

The radiance errors in Fig. 8 (upper right panel) show how the IPA tends to overestimate $I_\gamma$ in the optically thicker regions, while underestimating in the optically thin regions. This error in the spatial pattern of radiance occurs because the IPA cannot account for the horizontal diffusion of photons from the thicker regions to the thin
regions of the cloud field. Similar but reversed patterns of error occur for $s_n$ (lower right panel). The effect of horizontal transport causes the photons that compose the nadir reflectance in the optically thick regions to have traveled shorter paths than if no horizontal transport occurred as for the IPA simulations. The reduction in the pathlengths increases $s_n$ relative to the IPA results, producing the negative errors. Conversely, the effect of horizontal transport increases the pathlengths of photons within the thinner portions of the clouds, resulting in a decrease of $s_n$ and thus positive IPA errors in these regions.

5. IPA errors

Figure 9 shows the variation of the total error (subpixel error plus horizontal transport error) as a function of the pixel dimension (hereafter referred to as resolution) for three values of the total column optical depth of oxygen $\tau_0^o$. These values of $\tau_0^o$, as shown in Part I, represent the range of opacities needed to retrieve the optical depths of low clouds. The left panels show the errors in the nadir reflected radiance $I_n$, and the right panels show the errors in the radiance ratio $s_n$ derived using cloud field 2a. The total error was computed by comparing the true pixel value of the given quantity to the IPA estimate for that pixel. The lower dashed curves trace the errors due to subpixel averaging and were computed using the 3D model with horizontal transport but assumed a uniform value of optical depth in the pixel. The shaded region between these two curves thus represents the errors due to horizontal transport. A similar analysis for a cloud field similar to cloud field 1 is given by Davis et al. (1997). The results of Davis et al. (1997) present the variation errors with spatial scale arising from using the IPA for optical retrieval and indicate errors ranging from 2%–12%.

In Fig. 9, the subpixel averaging error increases almost linearly with the resolution. The errors due to subpixel averaging range from 7% for 100-m resolution to over 15% for a 1-km resolution. Total radiance errors, however, are much less sensitive to resolution and appear to be about 20% for cloud fields under consideration. This reduced sensitivity of the total error to resolution occurs as a result of the near balance of the increase subpixel error and the decrease in the horizontal transport error with increasing resolution.

It is also relevant how the errors change in character
as the oxygen optical depth is increased. Multiply scattered photons become increasingly attenuated as the amount of absorption in a cloud layer increases. The scattering becomes more localized and horizontal transport between neighboring pixels is reduced. Thus significant reductions in radiance errors can be achieved with accurate measurements deep in absorption lines.

The right panel of Fig. 9 shows the errors in the spectral radiance ratio $s_n$. Since $s_n$ is a ratio of radiances, many of the errors due to spatial variability cancel as they did in the case of phase function errors discussed in Part 2. The errors in $s_n$ appear to be on the order of only 1%-2% for cloud field 2a.

6. Optical depth retrievals in spatially varying clouds

This section introduces two approaches to retrieving cloud properties under conditions of cloud variability. The first is a novel technique that diagnoses when estimates of optical depth retrieved using a conventional plane-parallel forward model are affected by cloud heterogeneity. The second approach explores the utility of using pixel-averaged A-band spectra to retrieve information on the pixel-level probability density function (PDF) of optical depths. Knowledge of this distribution $p(\tau)$ is important for a number of applications.

a. Detecting effects of spatial variability

The method of detection builds on the results of Fig. 9, which emphasizes the different ways heterogeneity affects both $I_n$ and $s_n$. As discussed above, the effect of heterogeneity causes the domain-averaged optical depth inferred directly from radiances to be underestimated, and the optical depth inferred directly from radiance ratio data to be overestimated. Figure 10 shows the results of applying both radiance and radiance ratio retrievals to pixel-level data of cloud fields 1a and 2a. For this example, the pixel resolution is 100 m. The abscissa
Fig. 9. Variation with satellite spatial resolution and with column absorption optical depth of oxygen, τ_{O_2}, of the average pixel error in A-band observables computed for cloud field 2a.

of Fig. 10 is the ratio of the optical depth retrieved using the radiance ratio s, to the optical depth retrieved using the radiance I. The ordinate is the ratio of the radiance-derived optical depth to the true value of optical depth obtained by averaging the 28-m Landsat data over the pixel. The departure of the value of this ratio from unity thus represents the errors incurred by the conventional radiance retrievals such as performed using the AVHRR and GOES visible channels.

Perfect plane-parallel cloud fields, with no spatial variability, are represented by the (1.0, 1.0) point, and near-plane-parallel conditions will cluster around this point. This is exemplified in the case of cloud field 1a, being the more uniform of the two cloud fields. The more spatially heterogeneous cloud field 2a has points that deviate significantly from the plane-parallel value. Thus the spread of the values from the (1.0, 1.0) point is a clear indication of the amount of variability in the cloud field. We propose that the value of the (τ_{O_2}^a)/(τ_{O_2}^p) provides a diagnosis of when the effect of cloud heterogeneity is too great to allow an accurate retrieval of optical depth using a plane-parallel model. It is important to note that this ratio comes entirely from measurement of A-band spectra and does not assume any further a priori information about the value of the optical depth other than that assumed for the retrievals performed in the low cloud retrievals in Part 2. It appears that once this ratio exceeds 2, errors in the retrieved optical depths exceed 10%–20%.

The two branches of points derived for cloud field 2a in Fig. 10 indicates how the optical depths retrieved from radiances data alone can be less than or greater than the true value. The physical reason for this behavior is that photons tend to migrate from optically thick regions to optically thin regions (Marshak et al. 1995; Davis et al. 1997). Optically thick regions therefore appear less reflective compared to a plane-parallel cloud of equivalent optical depth. Conversely, the optically thinner portions appear more reflective than the equivalent plane-parallel cloud. To illustrate this point, Fig.
Fig. 10. Variation of the optical depth retrieval errors using radiance $I_s$ and the radiance ratio $s$ for cloud fields 1a and 2a.

11 shows the variation of the ratio of optical depth retrieved from radiances alone to the true pixel optical depth as function of the pixel optical depth for cloud field 2a. As this figure shows, the optical depths of thin cloud tend to be overestimated and the optical depths of thick cloud are underestimated.

b. Retrieval of cloud optical depths probability distributions

The IPA is valid for some types of radiation problems. Duda and Stephens (1994), for example, pointed out that the use of the IPA results in domain-averaged quantities that possess much smaller errors than those associated with individual pixels. Barker et al. (1996), using the same Landsat dataset adopted in the present study, also show how the IPA is able to produce accurate estimates of domain-averaged fluxes in heterogeneous media. The ability of the IPA to produce fluxes averaged over large domains arises from the tendency of the IPA errors to cancel in the domain averaging.

Domain-averaged A-band spectra of reflected radiances contains information on the probability distributions of optical depths $p(\tau)$ under certain circumstances and given certain assumptions. This fact can be demonstrated in the following way. The measured domain-averaged A-band spectra are related to $p(\tau)$ as

$$\langle I_s \rangle = \int_0^\infty p(\tau) I_s(\tau) \, d\tau, \quad \text{and} \quad \langle s \rangle = \int_0^\infty p(\tau) s(\tau) \, d\tau, \quad (9)$$

where $p(\tau)$ is determined over a domain of specified size. For boundary layer clouds considered in this study, this distribution can be conveniently approximated as a gamma function (Barker et al. 1996):

$$p(\tau) = \frac{1}{\Gamma(a)} \left( \frac{\tau}{\langle\tau\rangle} \right)^{a-1} e^{-\tau/\langle\tau\rangle}, \quad (11)$$

where $\langle\tau\rangle$ is the domain-averaged optical depth and $a$ is a parameter governing the width of the distribution. The width parameter $a$ is related to the standard deviation of the optical depth distribution $\sigma_\tau$ by the following definition:

$$a = \left( \frac{\langle\tau\rangle}{\sigma_\tau} \right)^2.$$

From the above relation it is seen that, for homogeneous cloud fields where $\sigma_\tau$ is small, the value of $a$ is large and the resulting $p(\tau)$ is narrow. As described by Barker
et al. (1996), the mean value of $a$ derived for several case studies of broken stratocumulus and scattered cumulus clouds is 1.21 and 0.70, based on a series of Landsat-derived distribution of optical depths. For the overcast stratocumulus case studies, a mean value for $a$ of 7.98 was reported.

The goal then is to use simulated domain-averaged A-band spectra along with independent pixel theory to produce estimates of $P(\tau)$, which can then be compared to the distributions shown in Figs. 2 and 3. Figure 12 shows the variation of the continuum radiance $I_c$ (left panel) and the variation of the radiance ratio $s_n$ (right panel) as a function of the $\langle \tau \rangle$ and $a$. The multiple scattering model used was a discrete ordinates radiative transfer model and was run with $\mu_w = 0.8$ and $\alpha_{sc} = 0.00$ to generate Fig. 12. Radiance ratio $s_n$ corresponds to the radiance ratio computed for $\tau_o^5 = 2.0$. Regions where the contours in Fig. 12 are not parallel to each other allow for simultaneous estimations of $\langle \tau \rangle$ and $a$ from observations of $I_c$ and $s_n$. This simulated retrieval ignored the effects of variations in surface reflectance and surface elevation. The effects will influence the observed distributions of $I_c$ and $s_n$. However, the inclusion of these effects into the radiative transfer model is possible if these variations are known. The results from these simulations are therefore most relevant to the remote sensing of clouds over the ocean.

The Monte Carlo model is used to compute domain-averaged quantities $\langle I_c \rangle$ and $\langle s_n \rangle$. These averaged radiances were used in a retrieval of the corresponding PDF of $\tau$ based on the results of Fig. 12. The resulting PDF along with the true PDFs of $\tau$ are shown in Fig. 13 for each of the four cloud fields in Figs. 2 and 3. The defining parameters for the retrieved distributions are shown in Table 2.

The retrieved PDFs demonstrate that domain-averaged spectra can yield information on the distribution of optical depth over a large area. While comparison of
The mean photon pathlength contains clear signatures of the 3D variability of the scattering medium. Relative to plane-parallel clouds, the optical pathlength is extended in reflection. When viewed as an equivalent plane-parallel cloud, the mean optical depth of a heterogeneous cloud appears to be larger than in reality.

2) There are two main sources of error in applying the IPA to modeling radiances reflected from heterogeneous media: errors due to the neglect of horizontal transport, and errors due to the the effects of subgrid variability. The results showed that for the marine stratocumulus fields studied, the radiance errors were on the order of 3%–20% and the radiance ratio errors were on the order of 1%–5%. These errors were found to be dominated by the error due to horizontal transport for satellite resolutions less than 200 m while the error due to subpixel variability was dominant for satellite resolutions on the order of 1 km and greater. These findings are consistent with those of Davis et al. (1997).

3) The differing effects of heterogeneity on radiances and radiance ratios provides a way of judging whether or not retrievals contain acceptably small biases from three-dimensional effects.

4) Circumstances, expected to occur in reality, exist for which the spectral A-band measurements averaged over a domain provides meaningful statistical information about the probability distribution of optical depth defined over that domain, which is larger than the field of view of an instrument. The results for the simulated cloud fields considered in this study suggest that this technique has significant promise in quickly classifying the level of cloud heterogeneity over a large area. More extensive research on this topic is required.

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