Retrieving profiles of atmospheric \( \text{CO}_2 \) in clear sky and in the presence of thin cloud using spectroscopy from the near and thermal infrared: A preliminary case study

M. J. Christi and G. L. Stephens
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA

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[1] The benefits and limitations of retrieving a typical source profile of \( \text{CO}_2 \) in the lower atmosphere employing high-resolution measurements from the 1.6 \( \mu \text{m} \) region in the near infrared (NIR) and moderate-resolution measurements from the thermal infrared (IR) are explored for clear-sky scenarios as well as scenarios containing thin cloud. With respect to \( \text{CO}_2 \) column-average values, the results of this study show that all errors in \( \text{CO}_2 \) column-average values were 1 ppmv or less for the cases considered. Retrievals using measurements from the NIR alone slightly outperformed those using measurements from the IR alone provided that atmospheric scatterers were properly constrained. It was also found that IR and NIR measurements complement one another in retrieving column \( \text{CO}_2 \) and potentially provide better retrievals than using either set of measurements alone. With respect to \( \text{CO}_2 \) surface values, the preliminary retrieved \( \text{CO}_2 \) profiles show the NIR measurements are the clear winner due to the fact that the NIR obtains its \( \text{CO}_2 \) information from the lower troposphere as opposed to the IR measurements which obtains its \( \text{CO}_2 \) information from the mid and upper troposphere. However, measurements in addition to the NIR measurements (such as provided by the \( \text{O}_2 \) A-band or by lidar) would be required to assist in constraining unwanted scattering.

INDEX TERMS: 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1640 Global Change: Remote sensing; 1610 Global Change: Atmosphere (0315, 0325); KEYWORDS: carbon dioxide, retrieval, remote sensing


1. Introduction

[2] Quantifying the distribution \( \text{CO}_2 \) surface sources and sinks is a subject of ongoing research. To date this has remained an elusive goal - in part due to lack of quantitative data on the carbon cycle. Current surface measurements of \( \text{CO}_2 \) are precise, but lack the necessary scope to meet the need [e.g., Gurney et al., 2002]. Aircraft can be used to measure \( \text{CO}_2 \), but the cost of getting the consistent needed coverage is also prohibitive. What is required is (1) a much more significant volume of quality data and (2) a more economical way of obtaining it.

[3] Perhaps the only way to obtain the required volume of data is to place an instrument aboard a space-borne platform. Rayner and O'Brien [2001] hold that remote sensing of \( \text{CO}_2 \) from space can be of benefit to retrieving \( \text{CO}_2 \) source and sinks for example if a precision of better than 2.5 ppmv (on an \( 8^\circ \times 10^\circ \) satellite footprint) for monthly averaged \( \text{CO}_2 \) column data can be achieved.

[4] To date, different studies have addressed the retrieval of the \( \text{CO}_2 \) column as a whole [e.g., Buchwitz et al., 2000; Tolton and Plouffe, 2001; O'Brien and Rayner, 2002; Kuang et al., 2002]. Each of these studies propose the use of NIR radiances from either the 1.6 \( \mu \text{m} \) or 2.0 \( \mu \text{m} \) \( \text{CO}_2 \) absorption band with Kuang et al. [2002] making use of both. The retrieval of mean values of \( \text{CO}_2 \) concentration in the 5–13 km region of the atmosphere using IR and microwave measurements from NOAA 10 has also been performed by Chédin et al. [2003].

[5] Efforts have also been made in retrieving profiles of \( \text{CO}_2 \) concentration at various levels. For example, Rinsland et al. [1992] focused on the region of the atmosphere between 70–120 km, Park [1997] on the region between 10–45 km, and Engelen et al. [2001] on the region between 0–20 km. In this last work, spectroscopic measurements from the IR were simulated to obtain profiles of \( \text{CO}_2 \) concentration in the 0–20 km region.

[6] The focus of this study is toward the retrieval of profiles of \( \text{CO}_2 \) concentration as near the surface as possible. One of the problems encountered in retrieving near-surface \( \text{CO}_2 \) using only the IR, as Engelen et al. [2001] illustrate, is the ambiguity introduced by surface emission: there is little contrast between the emission of infrared radiation from the lower atmosphere as opposed to that from the surface. As a
result, information extracted from IR emission in the 15 μm region originates largely from the atmosphere above 2 km with errors in retrieved CO$_2$ values increasing toward the surface.

[7] The purpose of this preliminary work is to investigate the possible benefit of using space-based spectral measurements from both the NIR and IR to determine (1) if retrieved profiles of CO$_2$ concentration in the lower atmosphere reproduce the general characteristics of the corresponding true profiles under different conditions, (2) the nature of the synergy of the NIR and IR measurements, and (3) if the resulting column-averaged values of CO$_2$ are of sufficient precision to assist in bringing closure to the carbon cycle problem.

2. The Forward Models

[8] Two models were employed to simulate the measurements in this study: one model for the NIR and one for the IR. The model used to compute the monochromatic radiances at the top of the atmosphere (TOA) for the NIR portion of the spectrum was a new radiative transfer (RT) solver called Radiant. Radiant is a multistream, plane-parallel RT solver based on the Transfer Matrix Method that accounts for multiple scattering in the atmosphere and allows for the computation of radiances for different viewing angles. It allows for the stipulation of surface albedo and accounts for Rayleigh scatter by diatomic oxygen and nitrogen in the atmosphere, the scattering influence of thin cloud and aerosol, and the absorbing influence of atmospheric gases. In particular, gaseous absorption by CO$_2$ and water vapor was considered when generating the 1.6 μm measurements employed in this study.

[9] The accuracy of the radiances produced by Radiant’s algorithms were tested against tables from VandeHulst [1980], two doubling/adding schemes (used in Gabriel et al. [1990] and Miller et al. [2000], respectively), and the Discrete Ordinates Method for Radiative Transfer (DISORT) [Stammes et al., 1988] for the same optical parameters. One of the advantages of Radiant’s structure is the incorporation of atmospheric layer saving which allows Radiant to achieve a 14-fold increase in speed while computing the Jacobians required in the retrieval process used in this work.

[10] The forward model used to model the radiative transport in the IR portion of the spectrum to simulate the IR measurements is the same used by Engelen et al. [2001] with earlier versions given in Engelen and Stephens [1997] and Engelen and Stephens [1999]. The algorithm incorporates a Malkmus band model to obtain the optical depth and resulting transmission produced by different atmospheric gases. In this study, the influences of CO$_2$, water vapor, and ozone were considered in the IR. Unlike Radiant, the IR model only treats absorption and emission. In both the IR and NIR, nadir radiances are used for the retrievals in this study.

3. Retrieval Theory and Application to Retrievals of CO$_2$

[11] The numerical experiments performed to simulate the retrievals in this work utilized the method of optimal nonlinear inversion as set forth by Rodgers [2000]. Here, measurements are weighted along with a priori constraints according to estimated errors in the measurements and a priori.

[12] Using Bayes’ theorem and assuming that the a priori and the errors in the measurement and model are normally distributed, the solution to the CO$_2$ inversion problem can be obtained by minimizing the cost function (Rodgers [2000])

$$J = \|y - F(x)\|^2_S^{-1} + \|x - x_a\|^2_{S_a^{-1}}$$

(1)

where $y$ is a vector of measured radiances, $x$ a vector of atmospheric state variables to be retrieved, $x_a$ a vector containing a priori information about the state vector $x$, and $F$ is the RT model used to simulate the relationship established by the physics of nature between the measurements and the atmospheric parameters retrieved. $S$ is the covariance matrix associated with the measurement and model error and $S_a$ is the covariance matrix associated with the a priori. Using Newton’s method for nonlinear systems and assuming the problem is weakly nonlinear in $F$, one can obtain the following expression for iteration (Rodgers [2000]):

$$x_{i+1} = x_a + \left(S_a^{-1} + K_i^T S_i^{-1} K_i\right)^{-1} K_i^T S_i^{-1} \left[y - F(x_i) + K_i(x_i - x_a)\right]$$

(2)

where the $K$ matrix is the Jacobian and indicates the sensitivity of the measurements to the parameter(s) being retrieved at the measuring wave numbers. The $i$ notation on the $K$ matrix and $x$ vector indicate those associated with the $i$th iteration of the method.

[13] Synthetic measurements used in the retrieval were taken from (1) the 6360.1–6389.9 cm$^{-1}$ spectral interval in the 1.6 μm region of the NIR at a resolution of 0.025 cm$^{-1}$ (1193 channels) and from (2) 500–2500 cm$^{-1}$ in the IR at a resolution of 1 cm$^{-1}$ (2000 channels) similar to the Atmospheric Infrared Sounder (AIRS). In the NIR, a measurement is also taken at 6429.3 cm$^{-1}$ in the continuum just outside the 1.6 μm CO$_2$ band as, according to HITRAN, this wave number is in the middle of a theoretical absorption “dead-spot” (a 5.8 cm$^{-1}$ region void of any gaseous absorption lines). This helps promote a more stable continuum reference.

[14] The portion of the 1.6 μm band was selected because it is desirable to use measurements that include one of the ends of the band so there is not too much spectral distance between measurements taken at absorbing wave numbers inside the band and the measurement taken in the continuum outside the band so that the surface albedo may be considered constant over that small spectral distance. The opposite end of the 1.6 μm band at 6180 cm$^{-1}$ is not used due to the contaminating presence of methane absorption lines outside the band.

[15] In the NIR, the ratio

$$R = I_a/I_c$$

(3)

was then formed where $I_a$ represents measurements taken at wave numbers inside the 1.6 μm band and $I_c$ is this measurement taken outside the band in the continuum. This ratio avoids a number of instrument calibration issues that might otherwise result. It is these ratios that constitute the measurement vector $y$ in the NIR for a retrieval.

[16] The instrument in the NIR is assumed to have a CO$_2$ continuum signal-to-noise ratio (SNR) of 400:1 at a surface albedo $\alpha = 0.06$ and solar zenith angle $\theta_{s0} = 22^\circ$ for nadir
viewing. This SNR is similar to that used in Kuang et al. [2002]. The instrument in the NIR is also taken to have a Gaussian filter response for this study. In the IR, the instrument SNR is 200:1 in each channel for nadir viewing as in Engelen et al. [2001].

Along with the CO2 profile, the water vapor and temperature profile were retrieved as well as the surface albedo. The surface pressure in this preliminary study is assumed known; however, this too will be retrieved in later studies which will add measurements from the O2 A-band. The atmospheric profiles of temperature and pressure as well as density of air, water vapor, and ozone in which the CO2 profile is embedded are from McClatchey et al. [1972] and correspond to midlatitude summer conditions. The underlying surface is assumed Lambertian with a surface temperature of 296 K. Different values of surface albedo are employed to observe the influence of these on the retrieval. In each scene, the surface albedo is treated as constant across the narrow NIR spectral band and the value of the IR emissivity is assumed to be unity.

The a priori profile of CO2 is the same as in Engelen et al. [2001] and is shown in panel (a) of Figure 1 as the dotted curve. The a priori profiles of water vapor concentration and temperature were constructed by taking the respective midlatitude summer profiles from McClatchey et al. [1972] and shifting the profile values upward by 10% and 1 K, respectively. The magnitude of these adjustments are compatible with typical error characteristics used for data assimilation in the European Centre for Medium-Range Weather Forecasts (ECMWF) and are the same used in Engelen et al. [2001]. The a priori values of surface albedo were constructed by taking the true values and shifting upward by 2%. This is compatible with the accuracies that are now beginning to be attained by instruments such as the Multi-angle Imaging Spectroradiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Lucht and Schaaf [2000]).

The actual variances employed in the a priori covariance matrix $S_a$ were determined as follows. Those for CO2 from the top of the atmosphere (TOA) down to 500 mb are based on the work of Schmidt and Khedim [1991]. The variances used for CO2 concentrations in the lower atmosphere below 500 mb were designed to reflect the larger variations of CO2 in this region. In particular, the variance estimated for the surface is based on CO2 measurements taken from tall towers [e.g., see Bakwin et al., 1995, 1998]. In these studies, CO2 demonstrates highly variable behavior in the boundary layer. Diurnal variations of 50 ppmv are not uncommon with variations near the surface up to 85 ppmv reported from one of these studies. In light of this information, 15 ppmv was chosen as a reasonable standard deviation for CO2 at the surface. Of course, in an operational framework, the error statistics of the a priori profile could be tuned for each locale in which measurements are made and thus yield a more precise a priori for that locale. The standard deviations for water vapor and temperature at each level are 10% and 1 K, respectively, and for the surface albedo is 2% to maintain consistency with the a priori utilized for these parameters.

The measurement and model error covariance $S_m$ in clear sky is assumed diagonal (i.e., measurement error at one wave number is assumed independent of measurement error at other wave numbers); however, an additional factor was added to this matrix for CO2 retrievals performed in the presence of thin cloud to estimate the cloud’s influence on the retrieval as in these cases prior cloud information is provided to the forward model, but is not a retrieved parameter. In these cases, the error covariance matrix can be rendered

$$S'_m = S_m + K_0 S_0 K_0^T$$

(Rodgers [2000]) where $S_m$ is the covariance matrix associated with uncertainty in cloud optical depth at each altitude in the atmosphere and $K_0$ the Jacobian quantifying the sensitivity of the measurements to these cloud uncertainties. For the cases containing thin cloud in this study (“thin” defined as an optical depth $\tau \leq 0.15$), information on the cloud’s altitude and optical depth is assumed to be provided from other sources (e.g., by spaceborne lidar). In the covariance matrix $S_m$, the height of the cloud is treated as accurately determined by the lidar, but with a 20% uncertainty in optical depth at that height.

To assist in accounting for model error in these and future retrievals, a multiplier was applied to $S_m$ during the retrieval process and was adjusted by comparing the results of a $\chi^2$ test (described below) with the total number of degrees of freedom in the retrieval. In this study, since the same forward models are employed to generate both the measurements for the scene as well as those during the retrieval, this multiplier remained near 1; however, when CO2 retrievals are performed on actual measurements, this will assist in giving an indication of the trueness of the forward models as they approximate the processes that occur in nature.

For testing the quality of the retrieval, a $\chi^2$ test was employed to test the assumption that the retrieved vector $\hat{x}$ belonged to a normal distribution with the assumed error covariances used. From the expression for the cost function $J$, we have

$$\chi^2 = (\hat{x} - x_a)^T S_a^{-1}(\hat{x} - x_a) + [y - F(\hat{x})]^T S_x^{-1}[y - F(\hat{x})]$$

By a theorem of statistics, if $\hat{x}$ follows a normal distribution with the error covariances $S_a$ and $S_x$, then $J$ should be $\chi^2(N) - \chi^2$ distribution with $N$ degrees of freedom; thus a value of $N$ for $\chi^2$ is obtained if $\hat{x}$ is normally distributed and the assumed error covariances are accurate.

To provide a reference with which to compare the $\chi^2$ results, the total number of degrees of freedom (DF) can be determined for a given retrieval by summing the number of elements in the measurement vector $y$ with the number of elements in the a priori vector $x_a$. Comparing $\chi^2$ with the DF helps provide a sense of how reasonable the assumptions are that the errors are normally distributed with the magnitudes and correlations assigned in the covariance matrices $S_a$ and $S_m$. In this study, the iterative method was performed until $\chi^2$ was within 1% of the DF for each retrieval.

4. Preliminary Retrieval Results

The CO2 profile used in the retrieval simulations is meant to typify the kind of profile one would expect to find
downwind of a source of atmospheric CO₂. It was generated by the Colorado State University GCM and corresponds to the eastern coast of the United States and is the same as used in Engelen et al. [2001].

The retrieval results are presented in figures containing three sets of results. For example, see Figure 1. The three sets correspond to retrieval results using measurements from the IR only (upper set), NIR only (middle set), and both IR and NIR measurements (lower set).

Figure 1. Retrieved source profile of CO₂ in clear sky with associated profiles of error statistics for measurements with α = 0.05 and θ₀ = 30°. (a, d, g) Real (thin solid), retrieved (thick solid), and a priori (dashed) CO₂ profiles; (b, e, h) a priori error (dotted), and actual error (dashed); (c, f, i) Averaging kernels for retrieval (left) and their sums at each level (right). See text for details. The retrievals are the result of using only infrared (IR) measurements (upper set), near infrared (NIR) measurements (middle set), and both IR and NIR measurements (lower set).
and both (lower set). In each set, the lefthand plots display the actual CO₂ profile being retrieved as the thin solid line, the retrieved profile as the thick solid line, and the a priori profile as dotted. In the center plots, the a priori error profile is dotted and the actual retrieval error profile dashed. Of course, during normal operation the actual error is unknown, but since we know the profile the retrieval is supposed to be returning, this will be used to see how much the measurements improved our knowledge of the CO₂ profile over the a priori. Last, the righthand plots display the averaging kernels of the retrieval on the left with every 5th kernel given as a thick line to assist viewing. These provide a measure of the vertical resolution of the measurements in the observing system. Also, the sums of each of the averaging kernel curves for each of the retrieved values of CO₂ at each level are given to the right in these righthand figures. For a retrieved value of CO₂ at a given height, the corresponding value on this righthand curve should exceed \( \approx 0.5 \) if its value is being derived primarily from the measurements with values moving toward 0 indicating more and more reliance on the a priori information of the atmospheric state provided to the retrieval.

4.1. Retrievals of a CO₂ Profile in Clear Sky

[26] Figure 1a reveals the results of retrieving CO₂ in clear sky using only IR measurements. One observes from the figure that the retrieved profile matches the real profile down to about 2 km, but diverges below that level towards the surface as the IR measurements have difficulty distinguishing between thermal emission from the surface and that of the lower atmosphere and as a result are insensitive to CO₂ in this region.

[27] Panel (b) shows a different view of the actual error in the retrieved profile from panel (a). The actual error (dashed) is 1 ppmv or less down to about 2 km with error increasing significantly as one approaches the surface. Again, this is due to the insensitivity of the IR measurements to CO₂ in this region. However, the figure also indicates that the measurements have provided a good deal of information about the CO₂ profile as indicated by the smallness of the actual error in relation to the uncertainty of the a priori CO₂ profile (dotted) throughout most of the troposphere.

[28] We observe from panel (c) that most of the information about the CO₂ profile arises from the 1–11 km region of the atmosphere. In this region, the sum of the averaging kernels on the righthand side of the panel is 0.5 or better indicating that the retrieval relies more on the measurements than on a priori knowledge. Above and below this region, the retrieval relies mostly on the a priori profile as indicated by the lower averaging kernel sums. In the region 11–20 km, the a priori was accurate due to the small variations in CO₂ that take place in this region of the atmosphere and the retrieval did well as a result even though the IR measurements are not sensitive to CO₂ at these altitudes. As alluded to earlier, use of the IR to discern the presence of CO₂ as one approaches the surface becomes difficult due to a lack of contrast between the temperature of the surface and that of the lower atmosphere. The retrieval again converges to the a priori as a result, but here the a priori was not as accurate as it was for the higher altitudes and the retrieval errors are largest in this region with an error at the surface of about 10 ppmv.

[29] The middle set of panels in Figure 1 show the CO₂ profile retrievals for clear sky using only the NIR measurements. The profiles in each panel are denoted the same as in the IR set just discussed. Since the NIR radiances are largely due to reflection of the sun’s radiation from the underlying surface, the solar zenith angle \( \theta_s \) and surface albedo \( \alpha \) are also specified. For the NIR simulations of this study, the solar zenith angle is 30° while the surface albedo takes on the values of 5% and 20%. The results of Figure 1 are for a surface albedo of 5%.

[30] Panel (d) shows the retrieved CO₂ profile that results from using only measurements from the NIR. The retrieved CO₂ profile matches the true profile tightly in the region from the surface to 2 km with some loosening in the region 2–12 km. Upon looking at the averaging kernel sums on the righthand side of panel (f) we see the reason for this: the NIR derives information about the CO₂ profile from the surface up to 8 km with the most of this information coming in the region from the surface to 4 km. The overall effect of this is a retrieved profile that possesses the general character of the true profile all the way down to the surface. The retrieved profile error is 2 ppmv or less from 3–12 km with errors of 1 ppmv or less from 3 km to the surface (Figure 1e). The errors above 12 km are also small due to the quality of the a priori profile in this region.

[31] The lower set of panels represent retrieval results for which both the IR and NIR measurements are used. The combined retrieval produces a profile that is better than the “NIR only” profile at mid levels due to the contribution by the IR measurements and is also closer to the true profile near the surface than the “IR only” profile due to the contribution provided by the NIR. This example provides a clear demonstration of the value of combining NIR and IR measurements in CO₂ retrievals. As panel (h) reveals, the retrieval error in CO₂ is approximately 1 ppmv or less down to 1 km with larger errors still occurring near the surface. These are not as large as when using the IR alone, but larger than when the NIR alone is used due to some reliance of the retrieval on the IR. Looking at the averaging kernel sums on the righthand side of panel (i), we see the retrieval has a curve similar to the “IR only” case with some modification near the surface due to the presence of the NIR.

[32] The results presented in Figure 2 reveal the effect of retrieving the CO₂ profile in the presence of an increased surface albedo of 20%. In this case, the “IR only” retrievals are the same as in the previous figure and are provided only for comparison purposes. Comparing the “NIR Only” set of panels in this figure with those in the previous figure, we observe that the primary benefit of the increased surface returns has been to improve the retrieval at midlevels compared to the 5% albedo case. In the “IR/NIR” lower set, the retrieval has roughly the same nature as before with some tightening in the upper troposphere and near 1 km and some loosening between 2 and 6 km as the retrieval has adjusted to the increased signal-to-noise in the NIR due to the increased surface returns.

4.2. Retrievals of a CO₂ Profile in the Presence of a Thin Cirrus Cloud

[33] The results of retrieving the CO₂ source profile in the presence of a thin cirrus layer are given in Figures 3 and 4. For this part of the study, a cirrus cloud was placed at 13 km
in the atmospheric scene with an optical depth of $\tau_c = 0.10$ in the 1.6 $\mu$m region of the NIR. The cloud was chosen to have an asymmetry factor of $g = 0.77$ and a single scatter albedo of $\omega_o = 0.97$ in the NIR. This corresponds to a cirrus cloud with ice crystals with a mean effective size of 10 $\mu$m (Lynch et al. [2002]). The Henyey-Greenstein phase function was prescribed to characterize the cloud’s pattern of scatter in the NIR. Although the Henyey-Greenstein is not totally adequate to describe the scattering pattern of an ice cloud, which possess complex phase functions, the Henyey-Greenstein was chosen as in O’Brien and Rayner [2002] to provide a reasonable upper bound on the scattered radiance. In the IR, the reflectivity of cloud particles can reach values as high as 6% for very thick clouds [e.g., Paltridge and Platt, 1976], but (1) the clouds considered in this study are thin and (2) gaseous absorption greatly reduces the scattering in the strongly absorbing 15 $\mu$m CO$_2$ band in the IR. Thus in this preliminary study, the cloud was approximated in the IR.

Figure 2. The same as Figure 1 except $\alpha = 0.20$ in middle and lower rows where NIR measurements are in use (IR results in upper row repeated from Figure 1 to assist in comparing with these results).
as a totally absorbing layer. A more comprehensive treatment of IR scattering will be a topic of future study. The optical depth of the cloud in the IR was assigned based on the ratio of absorption to extinction efficiency as one moves into the IR portion of the spectrum ($\approx 1/2$). Using this approximation, $\tau_c$ is assigned a fixed value of 0.05 across the IR. 

[35] In their work in the NIR, O'Brien and Rayner [2002] and Kuang et al. [2002] each treat the scattering of NIR photons caused by thin cloud and aerosol. In particular, O'Brien and Rayner [2002] demonstrate that errors in retrieved CO$_2$ column values can be 0.5% or greater if cloud height information for an atmospheric scene is not available but is assumed. 

[36] Since the measurements used here are not geared to retrieving properties of thin clouds, information about the cloud’s height and optical depth could be provided from other sources, such as from a spectrometer taking measurements in the O$_2$ A-band (e.g., Heidinger and Stephens [1996]).

Figure 3. The same as Figure 1 except retrievals performed in the presence of a cirrus cloud at 13 km with $\tau_c = 0.10$ in the NIR and $\tau_c = 0.05$ in the IR.
or by a space-borne lidar for example. Here, a lidar was assumed to provide the information regarding the thin cloud in this scene. Specifically, we assume that the lidar provides the correct cloud height (13 km) and a value of $\tau_c = 0.08$ for its optical depth in the NIR (i.e., representing a 20% bias in $\tau_c$). For the other optical properties of the cloud, namely the asymmetry factor $g$ and single scatter albedo $\omega_o$, we assumed we had fairly good but not perfect understanding of the nature of this cloud. During the retrieval process for this scene, we assigned the cloud an asymmetry factor of $g = 0.75$ and a single scatter albedo of $\omega_o = 0.95$ in the NIR forward model. The Henyey-Greenstein phase function was also used to characterize the cloud's pattern of scatter during the retrieval process.

[37] Figure 3a reveals the CO$_2$ profile retrieved in the presence of the thin cloud using only the IR. The affect of
Table 1. Column Average Values of CO2 Volume Mixing Ratio in ppmv ($\tilde{q}$) for Real, a Priori, and Retrieved Profiles Along With Associated Error Expressed in ppmv ($\Delta \tilde{q}$) and as a Percentage Error (%).

<table>
<thead>
<tr>
<th>Profile</th>
<th>Scene</th>
<th>$\alpha$</th>
<th>$\tilde{q}$</th>
<th>$\Delta \tilde{q}$</th>
<th>%</th>
</tr>
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<tr>
<td>Real</td>
<td>–</td>
<td>–</td>
<td>373.43</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
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<td>372.43</td>
<td>372.67</td>
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</tr>
<tr>
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<td>0.05</td>
<td>372.76</td>
<td>372.84</td>
<td>–0.59</td>
</tr>
<tr>
<td>NIR only</td>
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<td>373.51</td>
<td>373.05</td>
<td>–0.38</td>
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<tr>
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<td>373.75</td>
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<td>–0.65</td>
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<tr>
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<td>373.51</td>
<td>373.44</td>
<td>–0.01</td>
</tr>
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</table>

Retrieved profiles are indicated by the measurements used, the scene (clear or with cirrus cloud), and surface albedo $\alpha$ given in which the profile was retrieved.

the cloud is to slightly increase the emission from the atmosphere which is interpreted by the retrieval process as enhanced levels of CO2 concentration in the 2–4 km region compared to the clear sky case (e.g., compare Figure 3a with either Figures 1a or 2a).

As in the clear-sky cases, NIR radiances for these cloudy cases were created for scenes with surface albedos of 5% and 20%. In comparing the “NIR only” retrieval results shown in the middle panels of Figure 3 to the companion clear-sky case in Figure 1, we observe that the retrieved CO2 profile obtained in the presence of the thin cloud is slightly degraded from the equivalent clear-sky profile; however, the general character of the retrieved profile remains good. When both IR and NIR measurements are used (lower set of panels in Figures 1 and 3), the most significant changes in the retrieved CO2 profile are in the region between the surface and 6 km where the NIR measurements play a larger role. Here, the sensitivity of the IR measurements to the cloud are somewhat greater than those in the NIR due to the cloud’s location at 13 km and the fact that the IR primarily derives its information about the CO2 profile from higher up in the troposphere. Since this effect is accounted for in the modified error covariance matrix $S_{\tilde{q}}$, the retrieval leans a little more heavily on the NIR at lower levels. What results is a retrieved profile that is slightly degraded in the 1–5 km region (since the NIR measurements are influenced somewhat by scatter caused by the thin cloud), but where some improvement is observed near the surface due to the NIR’s increased influence over the IR.

Figure 4 shows the effect of retrieving the CO2 profile in the presence of the thin cloud, but with a surface albedo of 20%. Again, since the CO2 retrieval using the IR is thermally based, the results in the upper set are the same as in Figure 3 and are provided solely for comparison with the CO2 retrievals using the NIR alone and the IR and NIR together. Comparing the “NIR Only” middle set in this figure with that of Figure 3, we observe that the main byproduct of the increased surface returns has been to move the NIR averaging kernel curve slightly higher into the atmosphere (this also occurred in the clear-sky case, but was not as obvious). The result is a retrieved CO2 profile that is slightly better in the 3–13 km region and slightly worse between 3 km and the surface than panel (d) in Figure 3. In the “IR/NIR” lower set, the retrieval is basically unchanged with an improvement in the CO2 concentration at the surface of $\approx 0.5$ ppmv.

4.3. CO2 Column Average Values

For the cases shown in Figures 1 through 4, the column-average value of CO2 volume mixing ratio ($\tilde{q}$) for the real, a priori, and retrieved CO2 profiles are shown in Table 1 along with associated error expressed in ppmv ($\Delta \tilde{q}$) and as a percentage error (%). The retrieved profiles are indicated by the measurements used in the retrieval, the scene in which it was retrieved (clear sky or in the presence of thin cloud), and the scene surface albedo.

We observe that the “IR only” CO2 retrievals performed well in clear sky or the presence of thin cloud where the magnitudes of the column-average error $\Delta \tilde{q}$ were both under 1 ppmv. Except for the clear-sky case when the albedo was 5%, the “NIR only” CO2 retrievals were comparable to or slightly outperformed the “IR only” retrievals with $|\Delta \tilde{q}| \leq 1$ ppmv. However, the column-average values $\tilde{q}$ obtained via the “IR/NIR” CO2 retrievals had the lowest errors for each scene as they took advantage of the strengths that both the IR and NIR had to offer. The resulting CO2 column-average percentage errors given in the last column of Table 1 are comparable to those obtained in O’Brien and Rayner [2002] when cloud height information was also available.

We also observe that regardless of the combination of measurements used to retrieve the CO2 source profile, there is a tendency to underestimate the CO2 column. It will be interesting to see if this effect will be seen in these retrievals in general when retrieving CO2 sources and if the opposite effect may occur when retrieving sinks, whereby making the sources and sinks less potent than reality. We will be looking for any behavior such as this in further studies as biases may be introduced into the modeling of CO2 surface sources and sinks if such behavior is not properly taken into account.

Figure 5 Variation in column average CO2 error $\Delta \tilde{q}$ for a thin cloud at two different heights for the optical depths indicated.
Lastly, Figure 5 indicates the influence of thin cirrus cloud on the CO₂ column-average error $\Delta q$ as cloud optical depth is varied between 0.03 and 0.15 when located at a height $h$ of 7 and 13 km, respectively. Here, both IR and NIR measurements are in use, $\theta_0 = 30^\circ$, and $\alpha = 0.05$. We observe that the thin cloud located at the lower altitude has less influence on the column-average error than the cloud at greater altitude (i.e., there is less variation in $\Delta q$). This can be understood by considering that, for a thin scatterer of given optical depth, the scatterer at higher altitude leads to more variable photon path lengths as it tends either to deny photons entry into the region below the scatterer where they can be absorbed by CO₂ or to trap photons within the region below it once they are there. 

Whether the cloud acts more like a barrier or a trap depends on such factors as the cloud’s optical depth, the solar zenith angle, and the surface albedo. For example, in Figure 5, where the cloud’s optical depth is varied, we observe that when the optical depth of the thin cloud at 13 km is increased to a point, the increased scatter and resulting CO₂ absorption below the cloud can give the illusion of a somewhat increased CO₂ abundance in that region. In this study, the retrieved values of $q$ are less than the true value in clear sky (i.e., $\Delta q < 0$ to start). The increasing optical depth of the thin cloud thus leads to an actual decrease in $\Delta q$ as the optical depth is increased from 0.03 to 0.09. As the optical depth is increased further, however, the cloud starts behaving more and more like a barrier to the region below and this leads to less photons penetrating into that region where they are subjected to CO₂ absorption. This results in the increasing column-average error beyond $r_{cloud} = 0.09$.

5. Conclusions

A preliminary study was performed to investigate the possible benefits and limitations of retrieving profiles of CO₂ by employing high-resolution measurements from the 1.6 µm region in the NIR and moderate-resolution measurements in IR. Two groups of experiments were performed to begin to assess these benefits and limitations - one group in clear sky and one group with a thin cloud present.

With respect to CO₂ column-average values, the results of this study show that retrievals using measurements from the NIR can slightly outperform those in the IR (provided that atmospheric scatters are properly constrained) and particularly that IR and NIR measurements complement one another in retrieving CO₂ thereby producing results that are potentially better than using either set of measurements alone. With respect to CO₂ surface values, the preliminary retrieved CO₂ profiles show the NIR measurements are in use, particularly that IR and NIR measurements are more variable photon path lengths as it tends either to deny photons entry into the region below the scatterer where they can be absorbed by CO₂ or to trap photons within the region below it once they are there.

Additional work is planned to examine the behavior of retrieved CO₂ profiles and their resulting column-average values over a greater climatological range (including thin cloud and aerosol with more complex phase functions and more complex surfaces) and to include the retrieval of surface pressure along with the retrieval of CO₂, water vapor, temperature, and surface albedo currently done here. Nevertheless, due to the greater sensitivity of the NIR to CO₂ in the lower troposphere and of the IR to CO₂ in the middle and upper troposphere, it would appear wise to consider utilizing them together in future satellite missions for measuring CO₂ so that the best results may be obtained as the measurements are subjected to the variety of conditions experienced in earth’s atmosphere.

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References


Lucht, W., and C. B. Schaaf (2000), An algorithm for the retrieval of albedo and aerosol with more complex phase functions and conditions experienced in earth’s atmosphere.


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M. J. Christi and G. L. Stephens, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA. (mick@atmos.colostate.edu)