CO$_2$ Retrieval Using Thermal Infrared Radiation Observation by Interferometric Monitor for Greenhouse Gases (IMG) Onboard Advanced Earth Observing Satellite (ADEOS)

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(Manuscript received 19 October 2015, in final form 29 August 2016)

Abstract

CO$_2$ concentrations in the upper troposphere were retrieved from thermal infrared spectra as observed by the only spaceborne hyperspectral sounder launched in the 1990s: the Interferometric Monitor for Greenhouse gases (IMG) onboard the Advanced Earth Observing Satellite (ADEOS). First, the effective optical path difference of the IMG was evaluated because the actual instrumental line shape function of the interferometer component has not been evaluated for technical reasons in the orbit. The CO$_2$ retrieval method was based on the maximum a posteriori (MAP) retrieval method and on procedures to decrease errors that obstruct CO$_2$ signal detection. For the retrieval analysis, ERA-40 re-analysis meteorological data were used as temperature field data. A method of selecting effective channels for CO$_2$ retrieval was used to remove channels with a high temperature dependency and to reduce errors in estimating the water vapor, ozone, and surface temperature. Furthermore, uncertainties in temperature and other error factors, which cannot be removed through channel selection, were evaluated and optimized by treating them as components of measurement errors in the MAP retrieval. CO$_2$ retrieval noises of the MAP retrieval were estimated as 2.5 % and 2.0 % at pressure levels of 500 and 300 hPa, respectively. CO$_2$ concentrations retrieved from IMG data were compared with aircraft measurement data. Results showed that the random error in the IMG retrieval was smaller than that estimated as the a posteriori error of the MAP retrieval. No significant biases were shown compared with the margin of random errors. The CO$_2$ retrieval method was applied to IMG data measured in April, 1997. Although assuming a uniform CO$_2$ concentration as a priori, the latitudinal gradient of the zonal mean concentration was consistent with climatological features presented by previous studies at pressure levels of 500 and 300 hPa. These results suggest that thermal infrared observation by the IMG is effective for evaluating the upper tropospheric CO$_2$ concentration in the 1990s.

Keywords CO$_2$; satellite observation; thermal infrared radiation; maximum a posteriori retrieval; IMG; ADEOS
1. Introduction

Atmospheric carbon dioxide (CO2), a prevalent greenhouse gas, has shown an increasing atmospheric concentration because of anthropogenic emissions from fossil fuel combustion accompanying worldwide industrial development (Andres et al. 1996). The current knowledge of its spatial distribution and temporal variation has been accumulated over several decades using flask-sample monitoring from a global network of ground-based stations. Those efforts have revealed that only approximately half of the CO2 emitted by fossil-fuel combustion has been absorbed into the biosphere and uptaken by oceans from the atmosphere (Battle et al. 2000; Francey et al. 1995). Detailed investigation of CO2 sources and sinks and thorough elucidation of the global carbon cycle in the Earth system is important for a reliable prediction of future atmospheric CO2 concentration levels and of their impacts on climate systems.

To date, quantitative estimation of CO2 sources and sinks has been conducted using inversion techniques with current ground-based measurement data (Bousquet et al. 2000; Fan et al. 1998; Gurney et al. 2002; Tans et al. 1990). However, the sparse distribution of CO2 measurement sites (especially, in Africa, South America, and over the oceans) renders it difficult to reduce the estimation error of the source/sink strength below the present level. The extension of CO2 measurement locations is necessary to reduce the estimation error. Although the addition of new flask-measurement sites would be most effective in terms of high-precision CO2 measurement (Masarie and Tans 1995), satellite-based measurement is an attractive means that presents an important benefit—global coverage of measurement locations (Patra et al. 2003; Rayner and O’Brien 2001).

In general, high spectral resolution measurements of thermal infrared radiation, which resolve individual gaseous absorption lines, simplify the separation of signals for specific gases from noise arising from other error factors. Based on that fact, most recent satellite-based instruments are designed to have the highest probable spectral resolution. A typical high-resolution instrument is a Fourier transform spectrometer (FTS). Subsequent to the development of the InfraRed Interferometer Spectrometers (IRIS) used on the Nimbus 3 and 4 satellites (1969–1971), many FTS-type instruments for nadir measurement have been developed and planned. All of those instruments offer an important capability—measuring atmospheric trace gas concentrations.

Among these FTS instruments, the Interferometric Monitor for Greenhouse gases (IMG) on board the Advanced Earth Observing Satellite (ADEOS) was a first space-FTS developed for observing atmospheric gases. It measured thermal infrared radiation spectra emitted from the Earth at the highest spectral resolution in the 1990s (Kobayashi et al. 1999a, b). Those IMG spectrum data have been used for retrieval studies of several trace gases such as O3, CH4, CO, CFCs, and HDO (Clerbaux et al. 1998, 2003; Grieco et al. 2005; Lubrano et al. 2002; Zakharov et al. 2004). However, because of the uncertainty in its instrumental line shape (ILS) function and some other important parameters, data obtained using the IMG have not been fully analyzed to retrieve CO2 concentrations, although the spectral resolution and radiometric precision were sufficient to yield accurate trace gas profiles.

The extraction of the CO2 signal from actual satellite-measured radiation was first demonstrated by Chédin et al. (2002b) as the interannual and seasonal variation of the thermal infrared radiance recorded by the Television and Infrared Observation Satellite Operational Vertical Sounder/High-Resolution Infrared Radiation Sounder (TOVS/HIRS) over several decades. In that study, radiosonde data were used to reduce the error arising from the lack of an accurate description of the atmospheric state such as the temperature profile, which is the main error factor. Reducing this error is expected to support the extraction of CO2 information. A similar approach of using radiosonde data specifically addressed the annual and seasonal variation of CO2 concentrations (Chédin et al. 2002a), as deduced directly from the TOVS/HIRS data. A neural network approach was used with microwave radiance data (Chédin et al. 2003; Crevoisier et al. 2004) to ascertain the CO2 distribution over a wide area. However, when one seeks to avoid the uncertainty of ground surface conditions, the temperature information obtained using microwave data is limited to areas over the ocean.

In recent years, CO2 observations using thermal infrared radiation measurements have been conducted with hyperspectral sounders such as the Atmospheric Infrared Sounder (AIRS), the Tropospheric emission spectrometer (TES), and the Infrared Atmospheric Sounding Interferometer (IASI). Several CO2 retrieval methods for the AIRS have been developed. They have revealed CO2 concentrations in the mid-troposphere using thermal infrared radiation data obtained by the AIRS (Chahine et al. 2005; Crevoisier et al. 2004).
Similar approaches to CO₂ retrieval have been conducted for the TES (Kulawik et al. 2010; Nassar et al. 2011) and the IASI (Crevoisier et al. 2009). Those studies show the potential utility of thermal infrared radiation measurement for carbon source and sink estimations. However, CO₂ observations using thermal infrared radiation measurements have less impact on the uncertainty reduction of the estimates than the approach that measures solar reflected radiation in the CO₂ absorption band at near-infrared wavelengths because thermal infrared radiation is insensitive to CO₂ concentrations near the ground surface (e.g., Chevallier et al. 2007; Chevallier et al. 2009; Christi and Stephens 2004; Engelen et al. 2001). Therefore, the Greenhouse gases Observing SATellite (GOSAT) (e.g., Yokota et al. 2009; Yoshida et al. 2011) and the Orbiting Carbon Observatory (e.g., Crisp et al. 2008; Frankenberg et al. 2015), which are both satellites dedicated to observations of atmospheric CO₂ concentrations, measure solar reflected radiation in near-infrared CO₂ absorption bands that are sensitive to CO₂ concentrations near the ground surface. Those CO₂ concentration data retrieved from the near-infrared solar radiation measurement have recently been used in order to reduce the uncertainty of source and sink estimations (e.g., Maksyutov et al. 2013). Nevertheless, retrieving CO₂ concentrations from thermal infrared radiation measurements is important because those radiation data have been accumulated stably over many years using several space instruments, thereby enabling analyses of global long-term trends of mid-tropospheric CO₂ concentrations (Strow and Hannon 2008).

Most of the retrieval of CO₂ data from thermal infrared radiation measurements has been conducted using satellite-based instruments operating since the 2000s because those instruments measure high spectral resolution spectra. These measurements are necessary for accurate CO₂ retrieval, i.e., obtaining weak CO₂ signals that correspond to a small variation in concentration while avoiding several error contaminations. In the 1990s, the IMG was the exclusive instrument having high spectral resolution available for trace gas data retrieval. This study was undertaken to investigate the possibility of retrieving CO₂ concentrations from IMG spectrum data obtained in the 1990s. Instrumental properties of the IMG are described briefly in Section 2. Section 3 is devoted to a description of the forward model and retrieval principle used for this study. We assess the CO₂ retrieval noise arising from error factors as well as the temperature estimation error. Details of the CO₂ retrieval procedure along with error characterization are presented in Section 4. Results of the CO₂ retrieval are described in Section 5. Discussion related to the retrieval itself is presented in Section 6.

2. The IMG instrument

As its name implies, the IMG was an FTS developed to monitor greenhouse gases from space. After the IMG was launched aboard the ADEOS satellite in August 1996, it measured terrestrial upwelling infrared radiation by exact nadir looking until the unexpected malfunction of the ADEOS satellite in June 1997 ended its 10-month operation period. The IMG, equipped with three detectors (three bands), had a maximum optical path difference of 20 cm (10 cm mirror scanning). Band 3 data featured a spectral range of 600–2000 cm⁻¹ (5.0–16.7 µm). The instantaneous field of view (IFOV) was a horizontal square size of 8 × 8 km² in the nadir direction. Figure 1a shows a segment of the IMG spectrum in band 3, which is relevant to this study around the CO₂ band at 15 µm. Although the noise-equivalent spectral radiances differ at each wavenumber, they are almost less than approximately 0.030 µW (cm² sr cm⁻¹)⁻¹ in the spectral range, as presented by Kobayashi et al. (1999a). Radiometric calibration of the spectral data has been conducted along with interferometric phase corrections based on the method developed by Imasu et al. (2008).

The salient feature of the IMG instrument was its long optical path difference (OPD), which yields a high spectral resolution. However, the quantitative property of its ILS function is not well known because of the uncertain arrangement of detectors on the focal plane, rendering it unstable to acquire accurate interferograms in orbit. Furthermore, the ILS function of the IMG can differ among spectra because the phase error in the interferograms is variable for each interferogram. For this reason, an appropriate ILS function must be estimated for accurate analyses of the IMG spectrum data. A study by Ota and Imasu (2005) showed the influence of the ILS discrepancy between observed and calculated radiance spectra on temperature and water vapor profile retrieval using the IMG spectrum data. It also suggested an optimal ILS function for IMG data analysis of the upper tropospheric and lower stratospheric profiles. However, further analysis using least squares spectral fitting based on match-up sonde profile data of temperature and water vapor revealed the wavenumber dependence of the ILS function. Results of this analysis led to a more
optimal ILS function: effective OPD (EOPD). Actually, EOPD corresponds to the effective value of the maximum OPD as a function of the wavenumber (Fig. 1b). Consequently, the spectral resolution of IMG data is estimated as having half width at half maximum of approximately 0.060 cm\(^{-1}\) at 750 cm\(^{-1}\). The error variance of the estimated EOPD is approximately 0.25 cm for a wavenumber of 750 cm\(^{-1}\). The error in the EOPD estimation is caused mainly by the discrepancy between the temperature and the water vapor profile of match-up sonde data and those at the IMG observation. The number of match-up cases is 50. In wavenumber ranges of 780–800 cm\(^{-1}\) where absorption lines of water vapor are dominant, the error in the EOPD estimation is large because of the large spatiotemporal variation of water vapor. The error in the EOPD can be regarded as a random error, in conjunction with the error attributable to instability of interferogram measurements.

3. Forward model and inverse method

3.1 Forward model

The relation between the measurement vector \(y\) (e.g., radiance spectrum measured from the satellite) and a state vector to be retrieved \(x\) (e.g., atmospheric profiles or surface parameters) can be written as

\[
y = F(x, b) + \varepsilon, \tag{1}
\]

where \(y\) and \(x\) comprise \(m\) and \(n\) elements, respectively, and where \(F(x, b)\) is the forward radiative transfer model that relates a given \(x\) to \(y\). In addition, \(b\) is a forward model parameter that is not retrieved but influences the measurement of \(y\); and \(\varepsilon\) represents the measurement error, which includes both the random instrumental noise and systematic biases. For cases in which systematic biases are properly corrected, the measurement error can be characterized statistically by the error covariance matrix \(S_\varepsilon\) on the assumption that it has a Gaussian distribution.
Absorption and emission are principal processes of the radiative transfer of the terrestrial thermal infrared radiation in the atmosphere and ground surface system. Upwelling monochromatic radiance, which is measured by nadir looking at the top of the atmosphere under cloud-free conditions, can be written as

\[
R = \beta \tau_{\text{total}} B(T_s) + \int_{\tau_{\text{total}}}^{1} B(T(p))d\tau + (1-\beta) \tau_{\text{total}} \int_{\tau_{\text{total}}}^{1} B(T(p))d\tau^*,
\]

where \( p \) stands for the atmospheric pressure, \( B(T) \) signifies the Planck function at atmospheric temperature \( T(p) \) or at surface skin temperature \( T_s \), and \( \tau \) denotes the atmospheric transmittance from any vertical level to the top of the atmosphere. In addition, \( \tau^* \) is the atmospheric transmittance from any vertical level to the ground surface, \( \tau_{\text{total}} \) is the total atmospheric transmittance, and \( \beta \) is the surface emissivity. The contribution of reflected solar radiation in the thermal infrared region, which can be safely neglected for wavelengths longer than approximately 4.0 \( \mu \text{m} \), is not incorporated. In this study, monochromatic radiance was calculated using the optical depth function computed with a line-by-line calculation code LBLRTM (ver.9.4) (Clough et al. 2005) with the HITRAN 2004 database (Rothman et al. 2005). Recently, the updated HITRAN 2008 and 2012 databases are available but the updates of the CO2 line parameter after HITRAN 2004 are mainly in the near-infrared region rather than the thermal infrared region. Accordingly, it is not particularly necessary to consider the radiative transfer error associated with the line parameter database.

To simulate the radiance spectrum obtained from satellite-based instruments, the monochromatic radiance must be convolved with the appropriate ILS function of the spectrometer as

\[
\hat{R}(\hat{k}) = \int_{-\infty}^{\infty} R(k)f(\hat{k}-k)dk,
\]

where \( k \) stands for the wavenumber, \( f(k) \) denotes the normalized ILS function, and \( \hat{R}(\hat{k}) \) represents the radiance at the wavenumber channel \( \hat{k} \). In this study, the functional shape of the ILS for the IMG retrieval was presumed to be a Norton–Beer function (medium) (Norton and Beer 1976). The EOPD and its spectral dependency (Fig. 1) were introduced as a functional parameter of the Norton–Beer function to describe the actual ILS function of the IMG, as explained in Section 2.

### 3.2 Retrieval principle

The Bayesian approach described carefully by Rodgers (2000) is introduced herein to solve the inverse problem associated with Eq. (1). It is designated as the maximum a posteriori (MAP) retrieval method, which selects the state of maximizing the posterior probability density function of \( x \), given the measurement of \( y \). The MAP solution is obtainable by minimizing the cost function as

\[
J(x) = [y - F(x, \hat{b})]^T S_e^{-1}[y - F(x, \hat{b})] + [x - x_0]^T S_e^{-1}[x - x_0],
\]

where superscript T denotes the transpose, \( x_0 \) is the a priori state, and \( S_e \) is the a priori error covariance matrix assuming a Gaussian probability density distribution around \( x_0 \). In Eq. (4), \( b \) is the optimal estimation of \( b \), which is presumed to be the baseline for retrieval. The optimal estimation \( \hat{x} \) is given in the iterative form as

\[
\hat{x}_{i+1} = x_0 + G_i[y - F(\hat{x}_i, \hat{b}) + K_i(\hat{x}_i - x_0)],
\]

where subscript \( i \) denotes an iterative index, and \( x_0 = x_0 \) in this study. Matrices \( K \) and \( G \) are the Jacobian and retrieval gain matrices, respectively, defined as

\[
K(x) = \nabla_x F(x, b),
\]

and

\[
G = (S_e^{-1} + K^T S_e^{-1}K)^{-1} K^T S_e^{-1}.
\]

The Jacobian matrix associated with the absorbing gas constituent is defined as the brightness temperature derivative with respect to gas perturbation per unit logarithmic concentration (or relative concentration) as

\[
K = \frac{\partial T_B}{\partial \ln q},
\]

where \( T_B \) is the measurement vector of the brightness temperature and \( q \) is the state vector of the gaseous volume mixing ratio. The MAP retrieval method has the benefit of describing the retrieval error analytically, which simplifies the evaluation of sorts of retrieval error arising from various error factors. For instance, the total retrieval error (a posteriori error) of optimal estimation \( \hat{x} \) can be expressed as

\[
\hat{S} = (S_e^{-1} + K^T S_e^{-1}K)^{-1}.
\]

The error characterization of the MAP retrieval method is described in Appendix A.
4. Retrieval characterization

4.1 A priori state and auxiliary data

The retrieval state obtained using the MAP retrieval method includes not only the true state but also the a priori state. To facilitate interpretation of the retrieval state, the a priori state should be fixed for all retrievals. WMO Global Atmosphere Watch (GAW) has reported that the global monthly mean mole fraction of CO₂ was approximately 364 ppmv in April, 1997 (e.g., Tsutsumi et al. 2009). The concentration value has been estimated mainly based on ground-based flask measurements. Therefore, the diffusion effect of the CO₂ concentration from the surface to the upper troposphere should be considered. For this study, the a priori profile of the CO₂ concentration was set as a vertically uniform distribution of 360 ppmv for all retrievals. The CO₂ a priori covariance of 1 % (3.6 ppmv), which is also vertically uniform, was assumed for diagonal elements of the a priori covariance matrix (e.g., Niwa et al. 2011). In addition, a Gaussian correlation of which the standard deviation of decay was 1 km between vertical layers was introduced into the off-diagonal elements.

The European Center for Mid-Range Weather Forecasting (ECMWF) re-analysis data, designated as ERA40 (Uppala et al. 2005), were used to reduce CO₂ retrieval biases attributable to those error factors, thereby ensuring an accurate baseline comprising temperature, water vapor, and ozone. Cloud contamination in the IFOV is a severe error factor. Therefore, a set of cloud-free IMG spectra was used for the CO₂ retrieval. It was identified through cloud analysis using the IMG and the Ocean Color and Temperature Scanner (OCTS), which was on board the ADEOS satellite, providing visible-spectrum day-time images in and around the IFOV of the IMG (Imasu et al. 2000; Imasu and Ota 2003).

4.2 Vertical sensitivity and error sources

The vertical sensitivity of the IMG measurement can be characterized using a Jacobian matrix. Figure 2 shows the Jacobian matrix of the CO₂ 15 µm band calculated on the basis of instrumental characteristics (i.e., EOPD) of the IMG using the climatological profile of middle latitudes in April. The Jacobian matrix shows that the radiance in this spectral region is sensitive to CO₂ variations that occur mainly in the upper troposphere. In addition, the CO₂ retrieval sensitivity for the upper troposphere is higher than that for the lower troposphere.

Thermal infrared radiation in the 15 µm band comprises radiation emitted from the atmosphere and from the ground surface under a cloud-free condition. The principal factors affecting it are the CO₂ concentration, temperature, water vapor, ozone, and surface skin temperature (surface emissivity). The spectral response of radiance attributable to the perturbation of

![Fig. 2. The CO₂ Jacobian matrix in Kelvins. The CO₂ profile is vertically uniform as 360 ppmv. The atmospheric state, except for CO₂, is the climatological profile of middle latitudes in April.](image-url)
these factors is given as

$$S_R = K_b S_b K_b^T,$$  \hspace{1cm} (10)

where $S_b$ and $K_b$ represent the covariance matrix and the Jacobian matrix of each perturbation factor, respectively. Figure 3 shows the square root values of the diagonal element of Eq. (10) for each factor. Those values indicate that the temperature variation of 0.5 K at all vertical levels in the atmosphere is almost comparable to the CO2 concentration variations of 3 %. Furthermore, the spectral response of CO2 resembles that of temperature, rendering it difficult to separate the CO2 signal from the temperature estimation error. Even the water vapor and ozone variation of 10 % show the spectral response as not negligible, with a surface skin temperature variation of 0.5 K.

4.3 Characterization of CO2 retrieval error

Inaccurate temperature, water vapor, ozone, and surface skin temperature produce CO2 retrieval noises. In the retrieval procedure, those error factors are regarded as the forward model parameters which influence CO2 retrieval. They can be evaluated quantitatively using the error covariance, as described in Eq. (A6) in the Appendix A. For this evaluation, climatological monthly covariance matrices were constructed from ERA40 during 1986–1995, which corresponded to the 10 years preceding the launch of the IMG in 1996. Figure 4 shows the CO2 error variance in terms of the climatological variation of temperature, water vapor, ozone, and surface skin temperature at middle latitudes in April. In the figure, values of CO2 error variances in percentages denote the relative values to a constant concentration of 360 ppmv (vertically uniform). Dotted lines represent the cases using all channels in the CO2 band, as presented in Fig. 2 (700–765 cm⁻¹). Solid lines show those of CO2 channels described in Section 4.4. The sensitivity of CO2 retrieval is low in the stratosphere and lower troposphere. Therefore, the corresponding CO2 error variance attributable to those error factors is also small for each factor.

4.4 Channel selection

The strong influence of the temperature error on the CO2 retrieval is based fundamentally on the fact that, in the 15 µm band, radiance variations resulting from temperature variations cause similar spectral responses to those resulting from CO2 concentration variations. However, the spectral responses are not completely identical to those of CO2 variations in some spectral channels, which indicates the possibility of a separate detection of CO2 signals against the temperature error using appropriate channels. The information content (IC), whose definition is briefly summarized in Appendix B, is useful as an effective measure for such an objective. Figure 5 shows that the IC ranks each channel in order of priority to be used in retrieval. It is noteworthy that the order of priority of channels for CO2 retrieval differs from that for temperature retrieval. However, to ensure a sufficient number of channels for each vertical level, each channel must be characterized using the vertical position at which the CO2 Jacobian has its peak because the IC does not reflect the vertical sensitivity of each channel to CO2 retrieval.

For this study, channels were selected for each vertical level based on the IC figures of merit. Channels that were selected as the maximum permissible number of 30 for each vertical level, designated as CO2 channels, were used in these analyses. Solid lines in Fig. 4 show the CO2 retrieval noise for cases using only CO2 channels. Comparison of the cases of all channels (dotted lines) shows that the channel selection yields a decrease of retrieval noise because of an inaccurate “baseline” of temperature. By adopting the CO2 channels, it is also possible to reduce the CO2 retrieval noise arising from climatological variations of water vapor, ozone, and surface temperature.

4.5 Error conversion

Although ERA40 was used for reducing the CO2 retrieval bias attributable to inaccurate baseline values, the time and sub-grid scale uncertainties in ERA40 compared with the time and location of the IMG measurement produce errors in the retrieved CO2 concentration. Furthermore, IMG data have uncertainty in the EOPD of the ILS function. Accordingly, to avoid those random errors in the CO2 retrieval, an error conversion method was introduced along with the use of CO2 channels. When the temperature and the EOPD of the ILS function have a random error that can be described by Gaussian error covariances $S_{\text{temp}}$ and $S_{\text{ILS}}$, respectively, they yield the forward model parameter error in the retrieved state, as shown in Eq. (A6). This error can be converted to and regarded as a component of the measurement error $S_e$ as

$$S_e \rightarrow S_e + K_{\text{temp}} S_{\text{temp}} K_{\text{temp}}^T + K_{\text{ILS}} S_{\text{ILS}} K_{\text{ILS}}^T,$$  \hspace{1cm} (11)

which enables the optimal treatment of random errors of temperature and the ILS function in the retrieval.
Fig. 3. The spectral response of the brightness temperature caused by the perturbation of several parameters in the CO$_2$ 15 mm band. Figures show (a) CO$_2$ perturbation of 3 % at all vertical levels in the atmosphere, (b) temperature of 0.5 K, (c) water vapor of 10 %, (d) ozone of 10 %, and (e) surface temperature of 0.5 K.
Fig. 4. The CO₂ error variances corresponding to climatological variations of (a) temperature, (b) water vapor, (c) ozone, and (d) surface temperature. The values of CO₂ error variances in percent denote relative values to a constant concentration of 360 ppmv (vertically uniform). Solid lines represent cases employing CO₂ channel selection. Dotted lines show those of all channels in the CO₂ band.
procedure. This approach produces an analytically identical a posteriori error covariance matrix of the CO$_2$ profile to that of the simultaneous retrieval of CO$_2$, temperature, and EOPD. Therefore, it is as optimal as simultaneous retrieval in terms of estimating the a posteriori state. Using the gain matrix, the CO$_2$ retrieval noise corresponding to Eq. (11) can be expressed as

$$S_M = G S_e G^T.$$  \hfill (12)

Figure 6 shows the CO$_2$ retrieval noises described by Eq. (12), as estimated presuming a temperature error variance of 1 K and the EOPD error variance of 0.25 cm. The magnitude of the temperature error was estimated considering the random error of ERA40 data evaluated by Uppala et al. (2005) and cloud contamination error which were unidentifiable by OCTS, so that the temperature error might be estimated larger than the inherent error in ERA40 data. Because the CO$_2$ retrieval noise associated with the EOPD error was below 1 %, the most of the CO$_2$ retrieval noise shown in Figure 6 was attributable to temperature error. For instance, CO$_2$ retrieval noises were estimated as 2.5 % and 2.0 % at pressure levels of 500 and 300 hPa, respectively. The maximum error variance was approximately 3 % (11 ppmv) at pressure levels of 700 hPa. Small errors in the lower troposphere and stratosphere are attributable to their low sensitivity to CO$_2$ variation.

4.6 Vertical resolution of retrieval

The information contents of CO$_2$ retrieval and vertical resolution are depicted by the averaging

Fig. 5. Channel rank (order of priority), respectively based on IC-figures of merit for retrieving CO$_2$ (blue) and temperatures (red).

Fig. 6. Error variances of CO$_2$ retrieval that comprise the radiance measurement error, temperature error, and the error attributable to the ILS function. The solid line shows the case employing CO$_2$ channel selection. The dotted line shows those of all channels. The temperature variance is presumed to be vertically uniform of 1 K. Uncertainty of the ILS function is 0.25 cm of the EOPD.
kernel functions portrayed in Fig. 7. The averaging kernel functions indicate that IMG measurements bring information related to the CO2 retrieval in the pressure range of approximately 200–700 hPa, which corresponds to the vertical sensitivity shown by the Jacobian matrix. The degrees of freedom for the trace of the averaging kernel matrix were approximately one for this case.

5. Retrieval results

Based on the channel selection method and the error treatment presented in previous sections, CO2 concentrations were retrieved from IMG spectrum data in the CO2 15 μm band at 700–765 cm\(^{-1}\). The retrieved CO2 concentration must be compared with in situ observations for validation. However, in the 1990s, most knowledge related to atmospheric CO2 concentration data came from flask-sampling measurements at ground-based networks. The only data available for the comparison with IMG retrievals were aircraft observations taken during Japan Airlines (JAL) commercial airliner flights between Japan and Australia (Matsueda et al. 2002). Those data were taken using flask-sampling measurements at altitudes of 8–13 km. They have been accumulated since April 1993. Although the IMG measured approximately 138,000 spectra during its lifetime, only two cases coincided with the aircraft observations satisfying a requirement that the data were obtained on the same day and the fairway of the aircraft observation intersected with the orbit of the IMG observation. Figures 8 and 9 present a comparison of the IMG-retrieved CO2 volume mixing ratio with the aircraft observations. The altitude differences between the IMG retrieval and aircraft observations were matched within 500 m. Error bars in those figures represent the a posteriori error of CO2 retrieval expressed by Eq. (9), comprising smoothing error and measurement error, in which forward model parameter errors of temperature and the ILS function are incorporated, as described in Appendix A. In the latitude domain shown in Figs. 8 and 9 and especially in the upper troposphere, because the effect of the temperature lapse rate on CO2 retrieval is very small (Saitoh et al. 2009), CO2 information contents are almost identical for each IMG retrieval, which means that each IMG retrieval is comparable with each other. For both cases, IMG retrievals show the same direction of concentration change from the assumed a priori value of 360 ppmv, indicating the effectiveness of measurements made using the IMG. Compared with the margin of the a posteriori error, neither case shows large systematic bias in retrieved CO2 concentrations. The differences between IMG retrievals and aircraft observations were within approximately 4 ppmv.

During its 10 months of the operation, the IMG was operated most frequently in April 1997 during the observation campaign. The measurement locations of the IMG during that month cover almost the entire Earth. However, because the signal-to-noise ratios of IMG data were lower at high latitudes, the global analyses were limited to regions extending from the equator to middle latitudes. Figure 10 shows the global distribution of retrieved CO2 volume mixing ratios for April 1997, in which individual IMG observations are shown. Because of the magnitude of random retrieval noise as estimated in Section 4, the global distribution of single-shot measurements of the IMG is quite noisy compared with regional variations of CO2 concentrations. In addition, latitudinal distributions of the zonal mean CO2 volume mixing ratio.
mixing ratio for April 1997 are presented in Fig. 11, which were calculated by averaging individual IMG retrievals available for this month. The zonal means of IMG retrievals showed the latitudinal gradient of CO\textsubscript{2} concentrations, which were high in the northern hemisphere and low in the southern hemisphere. At a pressure level of 500 hPa, the concentration contrast between northern and southern hemispheres was apparent, although the CO\textsubscript{2} concentrations at 300 hPa were more uniform than those at 500 hPa.

Fig. 8. Comparison of the IMG retrieval with aircraft flask measurements of March 12, 1997. Panel (a) presents observation locations of the IMG (open circles) and aircraft (solid circles). Panel (b) shows CO\textsubscript{2} volume mixing ratios of the IMG (open circles) and aircraft measurements (solid diamonds). The dotted line represents the a priori value for CO\textsubscript{2} retrieval. Data are matched up within altitude of 500 m. Error bars show total retrieval errors (a posteriori errors).
Differences of the CO\textsubscript{2} mixing ratio between northern and southern middle latitudes were approximately 2 and 0.6 ppmv at pressure levels of 500 and 300 hPa, respectively. The CO\textsubscript{2} variation in each latitudinal zone, shown as vertical bars, was larger than the differences between the hemispheres because of regional differences of CO\textsubscript{2} concentrations. In the Northern Hemisphere, the CO\textsubscript{2} concentrations at 300 and 500 hPa were comparable within the standard deviation of the zonal mean. However, in the Southern Hemisphere, CO\textsubscript{2} concentrations at 300 hPa were 2–3 ppmv larger than those at 500 hPa.

6. Discussion

The most important issue might be the reduction of error arising from inaccurate temperature estimation. To reduce the temperature error reported in most of the earlier studies, CO\textsubscript{2} information was extracted

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Fig. 9. As in Fig. 8, but for April 25, 1997.
from thermal infrared radiation data in combination with radiosonde data or microwave radiometer data at wavelengths that were insensitive to ground surface emissions. In the present study, the meteorological re-analysis data of ERA40, obtained over both land and ocean areas, was used to ensure an accurate temperature baseline. This is true based on the fact that temperature data of the meteorological re-analysis data are inferred from information obtained using microwave radiometer data over the oceans and radiosonde data over land. It is also true that temperature information of ERA40 data is not completely independent from thermal infrared spectrum data observed by the IMG because the ERA40 itself includes satellite-based measurement data (except for IMG data) of thermal infrared radiation through the re-analysis procedure. However, because much temperature information comes from radiosonde and microwave radiometer measurements, the contribution of such satellite data in the re-analysis procedure is smaller than the directly retrieved atmospheric parameters obtained solely from the thermal infrared radiance spectrum data. Therefore, it is reasonable to regard temperature data of meteorological re-analysis data as almost independent from IMG radiance data and to employ ERA40 data in the CO2 retrieval using IMG data.

Two key procedures have been used to retrieve CO2 appropriately from IMG thermal infrared spectra: channel selection and an error conversion method to address several error sources. The former method confirmed that bias errors that correspond to water vapor, ozone, and surface skin temperature are removable in CO2 retrieval. It is best to use all channels to obtain the maximum content of CO2 information, especially for reducing random error in retrieved CO2 concentration. However, it would not be best when the baseline of retrieval has uncertain accuracy. Therefore, channel selection is necessary for accurate retrieval, especially from high spectral resolution spectrum data. According to the latter method, the random error attributable to the temperature of ERA40 and other error factors is regarded properly as a component of the measurement error. This method is especially useful for error factors that are not completely removable using channel selection. However, it should be noted that bias error associated with temperature of ERA40 might remain in the retrieved CO2 concentration. In addition, an important error source that has not been addressed explicitly in this study is cloud contamination. Although the influence of clouds can be regarded as a component of temperature error by the error conversion method, the entire discussion above relies on the assumption that no clouds obstruct the IMG field of view. Instruments observing thermal infrared radiation are expected to be operated with an instrument that is specially designed for detecting clouds sensitively such as GOSAT, thereby avoiding cloud-contamination problems.

Applying the retrieval procedures described as a result of this study to IMG spectrum data, CO2 concentrations were retrieved and compared to those obtained from in situ aircraft measurements. The results revealed no significant systematic biases between retrieval and in situ measurements, compared with the magnitude of a posteriori random errors. The
channel selection method for CO₂ retrieval is probably crucially important to remove systematic biases caused by temperature and other error factors. Those results are based closely on the high resolution of IMG spectrum data, which sustain the effectiveness of the channel selection method. However, in Section 4, the CO₂ retrieval noises attributable to temperature and other error factors were described as approximately 2.5 % and 2.0 % at pressure levels of 500 and 300 hPa, respectively. Because of the magnitude of those errors, it is not easy to identify the regional characteristics of the CO₂ distribution using single-shot measurements of the IMG. It might be effective to integrate the retrieved CO₂ data over time and space to provide more accurate CO₂ concentration data.

The latitudinal gradient of the CO₂ concentration between the northern and southern hemispheres is known to be most prominent at the ground surface level in April. Although variances of CO₂ zonal means are large because of regional CO₂ distributions as well as the retrieval noise of each IMG measurement, the CO₂ distributions obtained in this study showed a latitudinal gradient that was consistent with those from ground measurements. The latitudinal gradient of the retrieved CO₂ concentration at a pressure level of 500 hPa is larger than that of 300 hPa, which is consistent with the current knowledge of the atmospheric CO₂ distribution (e.g., Niwa et al. 2011). They support the validity of the CO₂ retrieval in this study and the effectiveness of thermal infrared radiation measurements by the IMG for upper tropospheric CO₂ observations. On the other hand, comparing CO₂ concentrations between 300 and 500 hPa, CO₂ concentrations at 300 hPa are 2–3 ppmv larger than those at 500 hPa in the southern hemisphere, although CO₂ concentrations in the northern hemisphere are comparable within the standard deviation of zonal mean. This may

Fig. 11. Latitudinal distribution of zonal mean CO₂ volume mixing ratios calculated from all retrievals in April 1997. Vertical bars show the variation in each latitudinal zone (a) at pressures of 300 hPa and (b) 500 hPa. Positive and negative values of latitude respectively denote northern and southern latitudes.
correspond to the diffusion of high \( \text{CO}_2 \) concentration from the northern Hemisphere to the southern Hemisphere through the tropopause.

7. Concluding remarks

An optimal \( \text{CO}_2 \) retrieval method for thermal infrared radiation data has been presented along with its error characterization. Error factors comprise temperature, water vapor, ozone, surface skin temperature, and instrumental characteristics. Selecting effective channels for \( \text{CO}_2 \) retrieval has demonstrated that the \( \text{CO}_2 \) signal and temperature errors are separable to some degree. It has also shown that the respective errors attributable to water vapor, ozone, and surface skin temperature are avoidable. We presented an error conversion method by which those errors are regarded as components of the measurement error and are incorporated properly into the retrieval procedure to assess the influences of those error factors on \( \text{CO}_2 \) retrieval. Although temperature is the main error factor related to retrieval of \( \text{CO}_2 \) from thermal infrared radiation data, meteorological re-analysis data are useful for the accurate estimation of temperature to retrieve \( \text{CO}_2 \).

The retrieval method was applied to cloud-free IMG spectrum data in the 15 mm band using meteorological re-analysis data of ERA40. Results show that the main error factors in the \( \text{CO}_2 \) retrieval from IMG data are the temperature estimation error and the error attributable to the uncertainty of the ILS function of IMG. Using the methods described herein, \( \text{CO}_2 \) retrieval noise quantities attributable to the error factors were estimated as 2.5 % and 2.0 % at pressures of 500 and 300 hPa, respectively, most of which is attributable to temperature estimation error.

Comparison to in situ aircraft measurements demonstrated that \( \text{CO}_2 \) concentrations retrieved from IMG data concurred well. Differences between the IMG retrievals and aircraft measurements are within the magnitude of a posteriori random errors, with no notable systematic biases. The \( \text{CO}_2 \) retrieval method has also been applied to an entire cloud-free IMG dataset obtained for April 1997. A zonal distribution of \( \text{CO}_2 \) concentrations was produced for equatorial to middle-latitudinal areas over both land and ocean. It is noteworthy that the contrast of \( \text{CO}_2 \) concentrations between the northern and southern hemispheres at a pressure level of 500 hPa was clear.

Considering results obtained from the comparison of retrieved individual \( \text{CO}_2 \) concentrations with aircraft measurements, and a comparison of zonal distribution features with our current knowledge of atmospheric \( \text{CO}_2 \), it can be concluded that satellite-based measurements of atmospheric \( \text{CO}_2 \) using the retrieval method presented herein are effective. However, because of the magnitude of retrieval noise, it is not easy to identify the regional characteristics of \( \text{CO}_2 \) distributions using single-shot measurements of IMG. In conclusion, IMG data certainly include \( \text{CO}_2 \) information. The data can be retrieved, but further refinement is necessary to decrease the retrieval noise related to temperature estimation and uncertainty of the IMG ILS function. Those results suggest that thermal infrared observation by the IMG might be an effective measure for evaluating upper tropospheric \( \text{CO}_2 \) concentrations in the 1990s.

Appendix A: Characterization of the retrieval error

Elucidation of error characteristics is necessary to assess and interpret the retrieval results obtained using an optimal estimation approach. Assuming the forward model to be moderately nonlinear, linear approximation is adequate for error analyses (Rodgers 2000). In this case, the retrieved state can be written as

\[
\hat{x} = Ax + (I - A)x_a + Ge + GK_b (b - \hat{b}),
\]

where \( x \) and \( b \) signify the true state and forward model parameters, respectively, \( K_b \) is the Jacobian matrix with respect to \( b \), \( I \) is a unit matrix, and \( A \) is the averaging kernel matrix defined as

\[
A = \frac{\partial \hat{x}}{\partial x} = GK.
\]

The averaging kernel matrix is an important measure of the information obtained from measurements (or the true state) to the retrieved state. The row of the matrix (averaging kernel functions) can be interpreted as the vertical sensitivity function of the retrieval for each vertical level. The peak represents the vertical level of maximum sensitivity. The vertical dispersion of the averaging kernel functions can be interpreted as the vertical resolution of the retrieval.

The error in the retrieved state is defined as the difference between the retrieved and true states. By transforming Eq. (A1) into the form of

\[
\hat{x} - x = (A - I)(x - x_a) + Ge + GK_b (b - \hat{b}),
\]

one can recognize that the retrieved state has a retrieval error of three types: smoothing error \((S)\), retrieval noise \((M)\), and forward model parameter error \((F)\), respectively, on the right-hand side of Eq.
(A3). The smoothing error can be interpreted as the difference between the fine structure of the true state and the structure of the retrieved state smoothed by the averaging kernel functions. The error covariance of those errors can be evaluated as

$$S_S = (A - I)S_a (A - I)^T,$$

(A4)

$$S_M = GS_aG^T,$$

(A5)

and

$$S_F = GK_bS_bK_b^T G^T,$$

(A6)

where $S_b$ is the covariance matrix, which represents uncertainty in the estimation of the forward model parameter $\hat{b}$. In the absence of the forward model parameter error, the total retrieval error (a posteriori error) covariance is defined by the sum of Eqs. (A4) and (A5) as

$$\hat{S} = (S_a^{-1} + K^T S_c^{-1} K)^{-1}.$$

(A7)

Appendix B:

Information contents of measurements

Selective use of the channels for retrieval has been introduced based on the concept of information contents for respective channels (Lerner et al. 2002; Rabier et al. 2002; Rodgers 1996). The information content of a measurement is defined as the difference in the entropy of the system found before and after measurements. If the state of the system is represented by the Gaussian probability density function, then the information content of the measurement is expressed as the logarithm to base two of the ratio of prior error to posterior error covariances in the form of

$$I = \frac{1}{2} \log_2 |S_a \hat{S}^{-1}|,$$

(B1)

where the posterior error covariance matrix is defined as presented in Eq. (A7). To formulate the information content of each channel, the scaled Jacobian matrix is introduced using the measurement error covariance matrix as

$$H = S_a^{-1} K.$$

(B2)

Then the information content of the $j$th channel can be expressed as

$$I_j = \frac{1}{2} \log_2 \left( 1 + h_j^T S_a h_j \right),$$

(B3)

where $h_j$ is the column vector with components of the $j$th row of $H$ corresponding to the $j$th channel. The information content in Eq. (B3) shows the figures of merit for each channel to be used in the retrieval of the state.

Acknowledgments

The CO₂ measurement data obtained using commercial aircraft (Japan Airlines) were provided from the website of the World Data Centre for Greenhouse Gases (WDCGG). The IMG Level-1C (L1C) data were provided by the Earth Remote Sensing Data Analysis Center (ERSDAC). This study was partially supported by a program of the Ministry of Education, Culture, Sports, Science and Technology—Japan (MEXT), “Green Network of Excellence—Environmental Information,” (GRENE-ei), and Research and Development for Applying Advanced Computational Science and Technology program of Japan Science and Technology Agency (ACT-JST).

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