B-2 A study on retrieval methods of greenhouse gas contents from satellite spectral data and its application to the sink/source analysis（Abstract of the Final Report）

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1. Introduction

The Greenhouse gases Observing SATellite (GOSAT)[1)] will monitor carbon dioxide (CO_2) and methane (CH_4) globally from space. GOSAT is scheduled to be launched in 2008.

One of the objectives of GOSAT is to observe Greenhouse Gases (GHGs) precisely, especially CO_2, in sub-continental spatial resolution and to identify its sources and sinks from the data obtained by GOSAT in conjunction with the ground-based data by using atmospheric transport forward/inverse models. It is relatively easy to detect the CO_2 column density in a clear sky condition within 1% error. However, many of the data will be obtained under cirrus and aerosol existing conditions. Therefore, the research on data retrieval in the cirrus/aerosols contaminating conditions has started from 2004 for efficient use of GOSAT data in future.

During 2004 - 2006, several remarkable results have been obtained from this research. Spectroscopic data were obtained with a quasi-satellite sensor (Fourier transform spectrometer, FTS) on board aircrafts (Cessna aircraft and an airship) for the first field experiments in Japan. Also, field experiments with the quasi-satellite sensor from top of the mountain, we have confirmed the data retrieval algorithms to work well. We developed a stepwise estimation method to overcome cirrus effects on CO_2 column density retrieval.

We have also researched on inverse modeling for global carbon sink/source estimation by adopting satellite data to the model. To cope with global climate change due to human activities, it is indispensable to quantify the global budget of anthropogenic CO_2. There are two basic approaches for that purpose: a bottom-up approach, in which local process knowledge is scaled up, and a top-down approach, in which the larger-scale constraint from atmospheric concentration measurements is applied in combination with transport models. However, to derive quantitative conclusions from relatively short-term measurements, the top-down approach is much more promising than the bottom-up approach. In this project, we study the top-down approach in terms of various facets to infer surface CO_2 fluxes using satellite CO_2 column concentration data. With respect to the improvement of the atmospheric transport model, we increased its spatial resolution of 2.5˚ (latitude) × 2.5˚ (longitude) to 0.125˚ × 0.125˚, and prepared the database of fossil fuel CO_2 with resolutions of 0.5˚, 0.25˚ and 0.125˚ on the basis of the existing 2.5˚ database and the 2.5' of world population distribution. We have proceeded these research works during three-year research period, and made some additional achievements.

2. Research Objectives

This study aimed to develop an algorithm to obtain the CO_2 column density by nadir-looking measurement of ground-reflected solar light under cirrus/aerosols existing conditions (see Figure 1), and to estimate the retrieval error. The spectral bands to be used are mainly in the Short Wavelength Infrared (SWIR) regions. In this research, more efficient satellite data will be utilized to estimate GHGs' sink/source distribution globally. A combination method to utilize the SWIR data and the Thermal Infrared (TIR) data from space will be studied. For the practical purpose, ground-based and airborne measurements will also be performed in this research to obtain actual spectral data under the various atmospheric conditions and to ensure and improve the retrieval methods. The purpose of this study is to develop a new technique for estimating spatial and temporal distributions of CO_2 source/sink fluxes on the Earth's surface, using a three-dimensional global atmospheric transport model and CO_2 concentration data from GOSAT satellite as well as from ground-based sites and aircraft. Scientific issues encountered in developing such a technique are also examined.

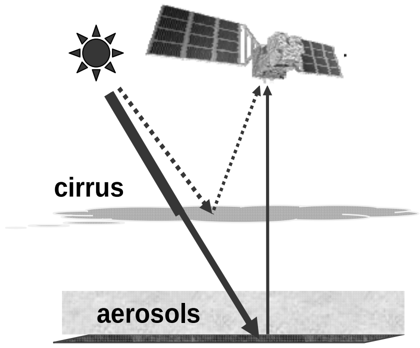

Figure 1 Nadir-lookig satellite measurement for detection of column density of greenhouse gases (CO_2, CH_4) with a short-wavelength infrared sensor under cirrus/ aerosol existing conditions.

3. Research methods

Three sub-themes have been studied.

(1) The research concerning the cirrus and aerosol effects on remotely sensed greenhouse-gas data is performed. In this study, spectroscopic data are obtained with a quasi-satellite sensor (Fourier transform spectrometer, FTS)[2] on board aircrafts and at the top of the mountain. Simultaneously, the high-resolution spectroscopic data obtained by a ground-based FTS and the in-situ measurement data on board the aircraft are also obtained to validate and improve gas retrieval algorithms. The precise observational data of carbon dioxide and methane with a gas cell in a laboratory are prepared and analyzed.

(2) Algorithms and precision analyses of CO_2 column density detection from space under cirrus/aerosols conditions are investigated and developed. These studies were done by using numerical simulations with a radiative transfer code. The characteristics of the GOSAT FTS were used in this simulation. Statistical database on cirrus parameters from ICESat/GLAS data was newly created. This database will be used as an initial data for CO_2 and CH_4 retrievals from GOSAT data. Aerosol effects on the estimation error of column density have been investigated by numerical simulation. A noise model of the sensor characteristics has been developed and tested. As for the research on SWIR and TIR combination, two methods were investigated; 1) substituting upper CO_2 concentration obtained from TIR data from columnar concentration derived from SWIR data in order to deduce the concentration in the lower atmosphere, and 2) retrieving upper CO_2 profile from TIR data with columnar concentration data derived from SWIR data as an additional constraint in the retrieval process.

(3) To estimate global distributions of CO_2 source/sink fluxes using the top-down approach, an inversion method with a global atmospheric transport model and CO_2 concentration data covering the whole globe is required. In this project, we develop a high resolution

atmospheric transport model with a minimum horizontal resolution of 0.125° x 0.125° and a minimum calculation time step of 150 second by improving our NIES medium-resolution atmospheric transport model and examine its validity for depicting the atmospheric CO_2 concentration variations in detail. We also examine the influence of synoptic scale weather disturbances on the CO_2 column concentration and uncertainties of the estimated CO_2 budget which may arisen from concentration biases in satellite measurements and between satellite and surface measurements, using the NIES medium-resolution atmospheric transport model, as well as the difference between CO_2 fluxes derived from the CO_2 data from all sites and ocean-only sites using 16 atmospheric transport models. Furthermore, we develop not only an iterative optimization procedure to improve an ordinary inverse method for analyses of a large amount of CO_2 concentration data, but also a four-dimensional CO_2 data assimilation model based on our NIRE-CTM-96 global atmospheric transport model. In addition, we develop a system for displaying 3-dimensional CO_2 concentration distributions calculated using the NIES atmospheric transport model and the CO_2 fluxes estimated by the inversion analysis of surface CO_2 data, and investigate the possibility of obtaining preliminary CO_2 concentration data from major domestic and foreign institutes for analyses of the GOSAT satellite CO_2 data.

4. Results and Discussion

(1) Laboratory and field experiment research

A slant-path looking observation data of sunlight reflected by the ground surface, in SWIR region with the FTS at the top of the Mt. Tsukuba, was obtained twice in 2005 and 2006. The measured spectral data were analyzed to estimate CO_2 column density. The retrieved CO_2 column density, by assuming clear-sky measurement condition, agreed with the data obtained from the in-situ measurements in about 2 – 3 % difference. The in-situ data were obtained by direct air sampling at the ground, at the top of the mountain, and at several altitudes by using Cessna aircraft. At the field experiment in 2006, we additionally used sky-radiometers and sky-camera at the ground and at the top of the mountain to monitor the temporal variation of cloud and aerosols. An aerosol lidar was settled at the ground to monitor cloud and the height of the planetary boundary layer (PBL). The difference between the retrieved CO_2 column density by using in-situ aerosol information and the data obtained from the in-situ measurements improved about 0..2 -0.4 %. Based on these experiments, it was confirmed that the algorithm for the satellite data retrieval is practically usable.

The precise spectra of CH_4 around 1.67 μm were measured with an 8.75 cm gas-cell by a high-resolution FTIR, and collision broadening coefficients and pressure shift parameters were determined. By comparing with HITRAN 2004 database, it was supposed that line parameters in 1.67 μm spectral region were still insufficient.

Absorption line parameters such as pressure broadening and temperature dependency coefficient were precisely obtained from CO_2 and CH_4 measurements by using a laser cavity ring-down spectroscopy.

(2) Development of advanced retrieval algorithms for the data obtained under cirrus/aerosol existing conditions

We developed a stepwise estimation method to overcome cirrus effects on CO_2 column density retrieval. The outline of the methods is:

Step 1: Cirrus height (h), cirrus optical thickness (τ), and ground surface albedo spectra ($\alpha_{0.76}$) estimation from [0.76 μm band and H_2O saturated area of the 2.0 μm band (see Figure 2)],

Step 2: Simultaneous retrieval of CO_2 column density, cirrus optical thickness (τ'), and ground surface albedo spectra ($\alpha_{1.6}$) from 1.6 μm band.

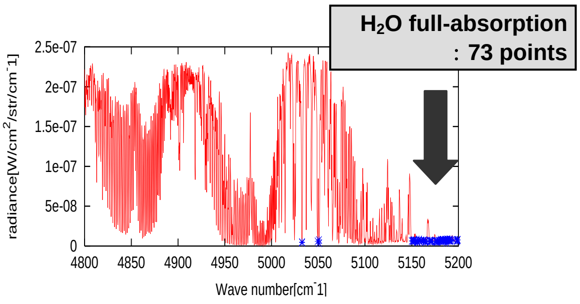

Figure 2 Absorption saturation area of water vapor in 2.0 μm band for cirrus reflected signal estimation

This method was tested by simulation; and the performance has been verified. In case of cirrus clouds with an optical thickness τ of 0.2 exist at the altitude of 10 - 11 km, CO_2 column density was retrieved within 0.2 % error by the stepwise estimation. Therefore, it was confirmed that this stepwise method will be useful for the cirrus contaminated measurement condition.

As for the development of combination strategy of SWIR and TIR data, a method of CO_2 retrieval from TIR data by constraining with columnar data from SWIR was developed. Generally, accuracy of columnar CO_2 concentration derived from SWIR is relatively higher than that of vertical profiles retrieved from TIR data because the latter can be easily disturbed by temperature estimation error. One of the possible ways for more reliable retrieval is to use SWIR data as an additional constraint in the retrieval process.

In the maximum a posteriori (MAP) method, CO_2 concentration profile to be retrieved is expressed as a vector $\hat{x}$ as follows;

$$\hat{x} = x_a + \left(\mathbf{K}^T \mathbf{S}_\varepsilon^{-1} \mathbf{K} + \mathbf{S}_a^{-1}\right)^{-1} \mathbf{K}^T \mathbf{S}_\varepsilon^{-1} \left(y - \mathbf{K} x_a\right) \quad (1)$$

where x_a is initial guess profile, and S_a and S_ε are initial guess error and observational error, respectively. $\boldsymbol{y}$ is an observed radiance and $\boldsymbol{K}$ represents radiative transfer matrix. Since the columnar concentration derived from SWIR data is a scalar, we need a policy to constrain a vector based on the scalar value. In this study we assume that degree of constraint is in inverse proportion to the statistical variation of concentration at each vertical level, and the variations are calculated from global CO_2 data simulated by the CO_2 transport model. The schematic of the concept is shown in Figure 3.

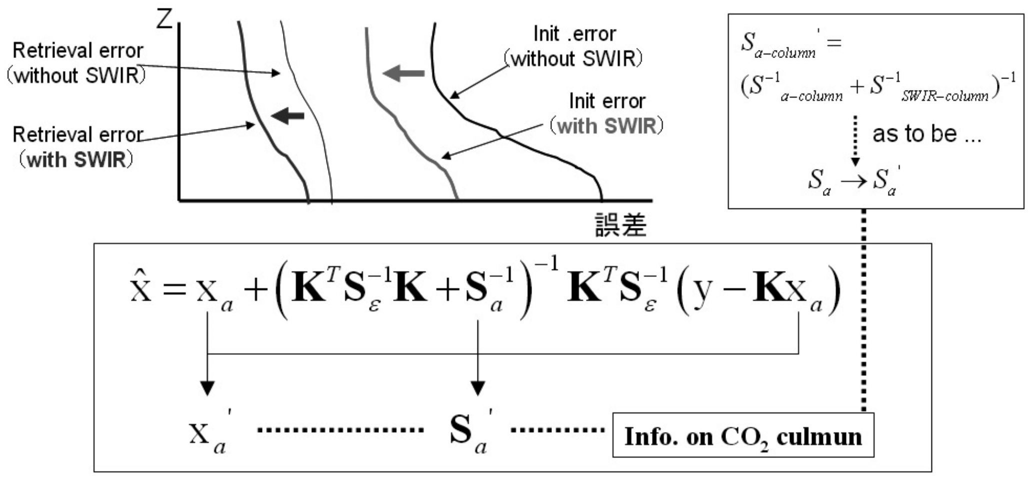

Figure 3. Schematic of the concept for constraining retrieval of CO_2 profile based on the columnar concentration derived from SWIR data and the statistical variation data simulated by a CO_2 transport model.

(3) Data assimilation method to calculate carbon flux and application to global carbon sink/source analysis

From simulations of the atmospheric CO_2 concentration using the high-resolution atmospheric transport model developed in this study, we found that the concentration variability by synoptic scale disturbances is captured well by the model in a similar way regardless of the resolution, and the simulated time series match the observed result better at higher resolutions. In the presence of diurnally varying surface CO_2 flux signal, the city CO_2 plumes of anthropogenic origins are only visible at sufficiently high resolutions and above surface level where the diurnal CO_2 cycle amplitude is lower. At many sites located within 300 km of metropolitan areas, the increase of spatial resolution produces significant impact on the annual average CO_2 concentration by simulating a better contrast between polluted-urban and clean-countryside areas. It was also demonstrated that anomaly in the column average CO_2 concentration has a fairly good correlation with that in the surface atmospheric pressure, especially over Siberia and North America in summer. Such a correlation is due to upward air motion associated with the low-pressure system, which leads to lower column CO_2 concentrations over these regions by lifting CO_2-depleted summertime PBL air. It is important to consider this bias when the column CO_2 concentration data from space-borne observations are analyzed together with surface observation data, because most satellite observations are not available under cloudy conditions, typically covering by the low-pressure system.

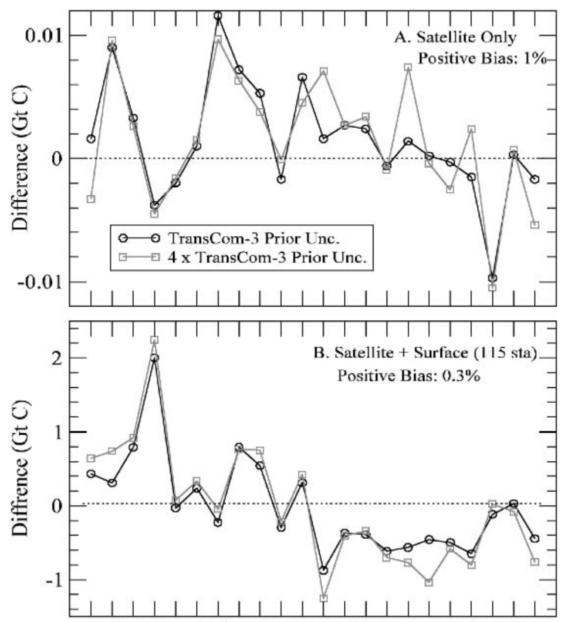

Figure 4 Differences in the estimated CO_2 fluxes (flux after introducing a positive bias in the satellite data - flux without any bias) shown as a function of 22 regions of an inverse model; (a) use of satellite data only and 1% positive bias, and (b) 0.3% positive bias in satellite data and 115 surface station data. Precision of the satellite data is set to zero ppm.

We also developed an iterative optimization procedure to improve an ordinary inverse method, so that the procedure is applicable to inverse model analyses with large number of unknown fluxes and available CO_2 observations.

The examination of the CO_2 budget analysis using the satellite CO_2 concentration data showed that if we use only the satellite data, a uniform bias of 1% added to the data yields no significant influence on the CO_2 budget, while only slight differences between the satellite and surface data would greatly affect the budget, as seen in Figure 4. It was also found to need to inspect changes in the CO_2 budget which are arisen from time difference between the satellite observation and the model analysis, as well as from the interference effect by clouds and aerosols. Furthermore, we examined the differences in CO_2 fluxes estimated using ocean-only and all-site (i.e. over ocean and land) observations of CO_2 in a time-independent inverse modeling framework, based on widely used 16 atmospheric transport models. The fluxes estimated using the ocean-only network were more robust compared with those obtained using all-sites network. This makes the global, hemispheric and regional flux determinations less dependent on the selection of transport model and observation network, if ocean-only CO_2 observations are used.

For data assimilation of the CO_2 concentration, we prepared a flexible and rapid adjoint code based on our atmospheric transport model of NIRE-CTM-96. Using this code, we examined the adjoint sensitivity over a relatively long time, targeting over the Sahara Desert where GOSAT satellite must make an observation, and confirmed its good performance as an adjoint code. By estimating surface CO_2 fluxes using the adjoint code and continuous CO_2 concentration records at 6 locations of Pt. Barrow, Minamitorishima, Mauna Loa, Samoa, Cape Grim and South Pole, we found that the flux for each region depends on the combination of model error and initial guess error. The data assimilation procedure was applied to a location where the annual mean CO_2 concentration varies from 365 ppm to 380 ppm, and an error of 2 ppm was confirmed to be attained by 20-30 time-repetition calculation.

We also developed a display system for the atmospheric CO_2 concentration calculated using the transport model, which can be used by users on the web server (http://cgermetex.nies.go.jp/gosat/co2nies/).

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