Quality Flag of GOSAT/FTS Products Taking into Account Estimation Reliability

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Abstract—Quality and cloud flags of GOSAT/FTS: Fourier Transform Spectrometer onboard Greenhouse gasses Observation Satellite products taking into account cirrus clouds and thick aerosols are considered and proposed. Influence due to cirrus and thick aerosol on estimation of column CO_2 and CH_4 with GOSAT/FTS data is clarified. Relatively large estimation errors are observed in column CO_2 and CH_4 retrievals with FTS data in some atmospheric conditions. In order to find such cases, retrieval results and quality/cloud flags in the GOSAT/FTS data products are checked. Through the investigation, it is found that relatively large error is caused by convergence problem due to cirrus clouds and thick aerosols. In the proposed paper, some of the cases of which relatively large estimation error is occurred at the Saga TCCON (The Total Carbon Column Observing Network) site are investigated. Also, a comparative study is conducted between standard products provided by NASA/JPL and the Levenberg-Marquardt based least square method of column CO_2 and CH_4 retrieval. It is suggested that some improvements of estimation accuracy of column CO_2 and CH_4 retrieval with GOSAT/FTS data can be expected.

Keywords—Levenberg-Marquardt; FTS; GOSAT; aerosol; cirrus cloud

I. INTRODUCTION

GOSAT: Greenhouse gases Observing Satellite is a greenhouse gas observation technology satellite ("IBUKI" in Japanese) 1 jointly developed by the Ministry of the Environment, the National Institute for Environmental Studies (NIES), and the Japan Aerospace Exploration Agency (JAXA). Observe the concentration distribution of greenhouse gases such as carbon dioxide and methane gas, which are considered to be the cause of global warming, from outer space. On January 23, 2009, it was launched from the Tanegashima Space Center at H-IIA Launch Vehicle No. 15. Starting acquiring observation data from February 2009, in May 2009 uncalibrated value analysis results on a global scale have been published.

GOSAT carries TANSO - FTS (TANSO: Thermal And Near Infrared Sensor for Carbon Observation, FTS: Fourier Transform Spectrometer)[2] is a main IBUKI sensor measuring carbon dioxide and methane gas. We observe spectra of solar light (near infrared rays) reflected by the earth surface and spectra of the light radiated from the earth's atmosphere and the ground surface (far infrared rays) by Fourier spectroscopy[3].

Since carbon dioxide and methane present in the atmosphere have the property of absorbing light of a specific wavelength, the amount of carbon dioxide and methane that existed in the path of light, depending on the degree of absorption of light transmitted through the atmosphere, It can be calculated. Absorption band of carbon dioxide around 1.6 μm and around 2.0 μm is important as a wavelength band containing much information near the ground surface. On the other hand, the absorption band around 14 μm is mainly used to obtain altitude information higher than 2 km. The accumulated amount of carbon dioxide gas is measured by short wavelength infrared band 1 to 3 (SWIR: Short Wave Infrared Band 1 - 3), and the vertical concentration distribution of carbon dioxide is measured by thermal infrared band 4 (TIR: Thermal Infrared Band 4). For conditions without error factors such as clouds and aerosols, we aim to measure errors within 1%.

GOSAT also carries TANSO-CAI (CAI: Cloud and Aerosol Imager)[4] is an image sensor used for determination of the presence or absence of clouds and measurement of aerosol (atmospheric particulate matter), which is an error factor when measuring carbon dioxide at TANSO-FTS. It is a secondary sensor of IBUKI. It is used for correction of measured data obtained by TANSO-FTS.

CAI observes the state of the atmosphere and the surface of the earth as an image in the daytime. The presence or absence of clouds in a wide range including the field of view of FTS is judged from the observation data, and in the case of aerosol or thin clouds, the characteristics of the cloud and the amount of aerosol are calculated. These information are used to correct the influence of clouds and aerosols contained in the spectrum obtained from FTS.

Development of transportable Lidar[5] for validation of GOSAT satellite data products is well reported [1]. Also, advanced validation of the GOSAT observed CO_2 and CH_4 at TCCON (The Total Carbon Column Observing Network)[6] and prioritized observation sites is reported [2]. Meanwhile, Observations of XCO_2 and XCH_4 (total column CO_2 and CH_4

CO_2 and CH_4) with ground-based high-resolution FTS at Saga, Japan and comparisons with GOSAT products is discussed [3]. On the other hand, evaluation of cirrus cloud detection accuracy of GOSAT/CAI and Landsat-8 OLI[7] with laser radar: lidar and confirmation with CALIPSO/CALIOP [8] data is conducted [4] together with a comparative study on cloud parameter estimation among GOSAT/CAI, MODIS [9], CALIPSO/CALIOP and Landsat-8/OLI with laser radar as truth data [5].

Advanced validation of the GOSAT observed CO_2 and CH_4 at priotized observation sites is reported [6]. On the other hand, Web based data acquisition and management system for GOSAT validation Lidar data analysis is developed [7]. Meanwhile, observation of aerosol parameters at Saga using GOSAT product validation Lidar is discussed [8]. Meantime, improvement of web-based data acquisition and management system for GOSAT validation Lidar data analysis (2013) is also discussed [9] together with observation of aerosol properties at Saga using GOSAT product validation LiDAR [10].

Impact of aerosol and cirrus clouds on the GOSAT observed CO_2 and CH_4 inferred from ground based lidar, sky-radiometer [10] and FTS data at prioritized observation sites,(2013) is clarified [11]. Comparison of lower tropospheric ozone column observed by DIAL: Differential Absorption Lidar [11] and GOSAT TANSO-FTS TIR is made [12]. Furthermore, impact of aerosols and cirrus on the GOSAT onboard CO_2 and CH_4 inferred from ground based Lidar, sky-radiometer and FTS data at prioritized observation sites is discussed [13]. Then, on the validation results of five year GOSAT SWIR XCO_2 and XCH_4 (total column CO_2 and CH_4) data is well reported [14].

Lidar observations at priotized sites for GOSAT validation is reported [15] together with lidar observation at TCCON site to investigate the influence of particles for GOSAT data [16]. On the other hand, influence due to cirrus and thick aerosol on estimation of column CO_2 and CH_4 with GOSAT/FTS data is discussed [17].

From the methodological point of view, estimation of XCO_2 and XCH_4 can be done with FTS data based on least square method. FTS data, however, is affected by clouds and thick aerosols. In order to avoid the cloud influence, clouds are detected with CAI imagery data then the FTS data which suffered from the clouds are identified with cloud flag. It, however, does not work properly. Thin cirrus type of clouds cannot be detected with CAI instrument. Other than this, quality flag can be used for analysis of the FTS data in concern. FTS data seems to also be suffered from thick aerosols. Such these FTS data are not reliable enough for analysis. Therefore, it is desirable to reconsider the method for reliability flag rather than the present quality flag.

Past FTS data are checked from the point of view of reliability. By using TCCON site of calibration site data, it is possible to check the estimation accuracy (discrepancy between the true and the estimated XCO_2 and XCH_4). Through careful check of the reliability, it is found that there is relation between reliability and clouds and thick aerosol. This paper intends to discuss this matter and suggest some reliability flag to the FTS data in concern.

Due to the fact that GOSAT/FTS does not cover the wavelength of water vapor absorption, it is hard to estimate influence of water vapor and clouds on estimation of XCO_2 and XCH_4. Therefore, it is required to use other sensor data than the GOSAT/FTS data for estimation of water vapor, aerosol, and clouds influences..

The following section describes current status of the GOSAT/FTS derived XCO_2 and XCH_4 followed by the relation between discrepancy between the true and the estimated XCO_2 and XCH_4 as well as clouds and thick aerosols measured with sky-radiometer. Then, some methods which allows to detect clouds and thick aerosols by using other data sources derived from the other mission instruments such as MODIS. After that, conclusion is described together with some discussions and with future research works.

II. RESEARCH BACKGROUND

A. Present Status of GOSAT Project

GOSAT satellite is operated in good health condition. In order to calibrate GOSAT TANSO-FTS, TCCON sites are also operated. One of the TCCON sites is situated at Saga University in Saga, Japan. Saga ground based-FTS operation started from July 2011. GOSAT targets at Saga are acquired every 3 days. In conjunction of GOSAT operation at Saga, OCO-2: Orbiting Carbone Observatory-2[12] can target 2 days in 16-day revisit cycle of GOSAT satellite. Fig. 1 shows outlook of the Saga TCCON site.

Fig. 1. Outlook of the Saga TCCON site.

[7] https://en.wikipedia.org/wiki/Landsat_8
[8] https://www-calipso.larc.nasa.gov/
[9] https://modis.gsfc.nasa.gov/
[10] http://www.kippzonen.com/ProductGroup/31/Sky-radiometers
[11] https://www.esrl.noaa.gov/csd/groups/csd3/instruments/lidar/dial.html
[12] https://oco.jpl.nasa.gov/

From the roof of the FTS container situated at Saga University, Saga Japan, solar irradiance comes in the ground based FTS instrument. The FTS measures solar irradiance which is absorbed by atmospheric molecules, aerosol, water vapor. Based on Fourier spectrum analysis, XCO_2 and XCH_4 can be estimated. On the other hand, sky-radiometer and sky-view camera are situated at the top roof of the building at Saga University nearby FTS container. From the sky-radiometer, aerosol refractive index and size distribution can be estimated while existing visible clouds can be observed with sky-view camera.

Fig. 2 shows an example of GOSAT observation pattern around Japanese vicinity. Along with the GOSAT satellite track, grid observation can be done while target areas can also be observed in GOSAT operation. Fig. 2 also shows the location of Saga TCCON site. From the 2011 to up to now, not only XCO_2 and XCH_4 but also XCO, XN_2O can be estimated.
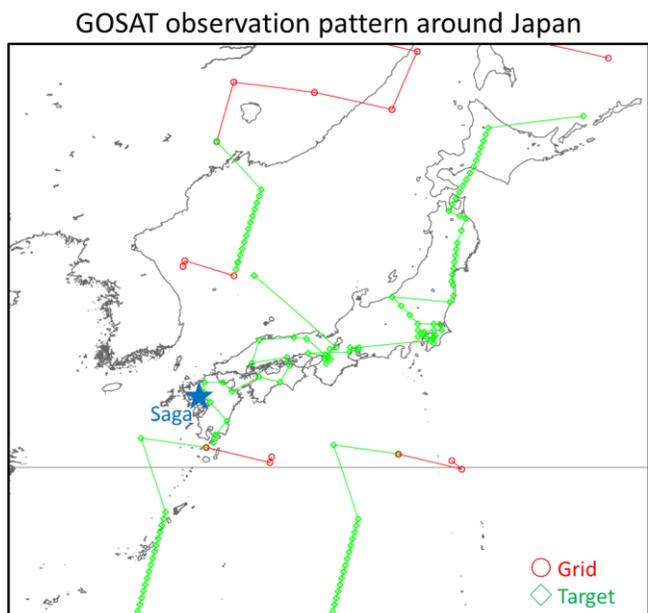

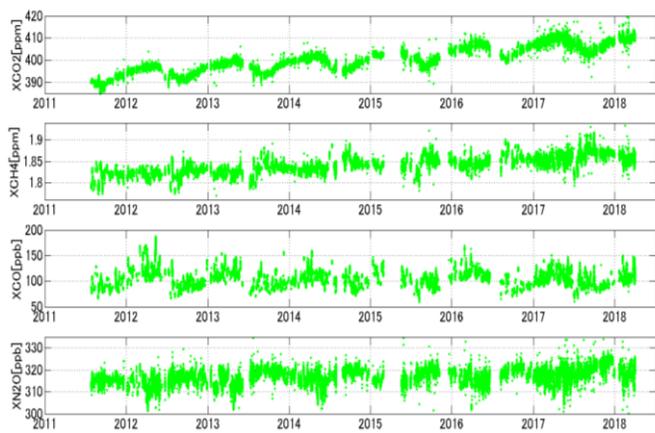Fig. 2.   Example of GOSAT observation pattern around Japanese vicinity.

Fig. 3.   Trends of the XCO_2 (upper), XCH_4 (second), XCO (third), XN_2O (bottom)

Fig. 3 shows the trends of the XCO_2 (in unit of ppm), XCH_4 (in unit of ppm), XCO (in unit of ppb), XN_2O (in unit of ppb) which are estimated with GOSAT FTS data. On the other hand, Fig. 4 shows XCO_2 and XCH_4 estimated from the ■NIES GOSAT V02.72 observation and from the ground based FTS observation at ●Saga-TCCON site. Overall trends of XCO_2 and XCH_4 estimated with GOSAT-FTS data and the ground based FTS show almost same.
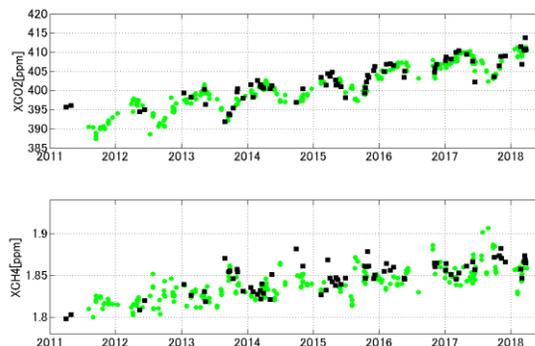

Fig. 4. XCO_2 and XCH_4 estimated from the ■NIES GOSAT V02.72 observation and from the ground based FTS observation at ●Saga-TCCON site

There are five major datasets, ACOS/GOSAT, AIRS/AQUA, OCO-2/OCO-2, TES/AURA, TCCON (ground based FTS)[13].

Correlation plots of NIES GOSAT v02 XCO_2 and XCH_4 and ground based FTS data derived XCO_2 and XCH_4 are shown in Fig. 5. The ground based FTS within ±30min. of GOSAT overpass time are averages. Solid and dashed lines denote linear fit with an intercept of 0 and 1-to-1 line respectively.
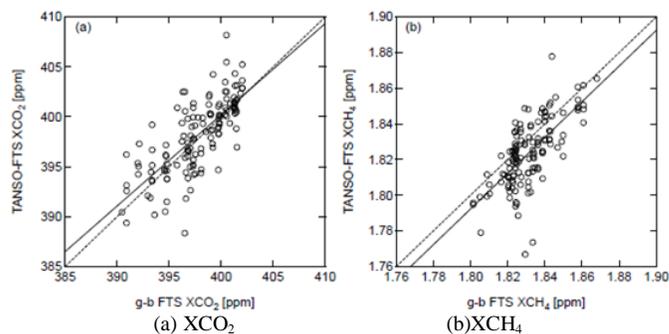

(a) XCO_2 (b)XCH_4

Fig. 5.   Correlation plots of NIES GOSAT v02 XCO_2 and XCH_4

Average differences as (TANSO-FTS minus ground-based FTS) are as follows,

XCO_2 : 0.40 +/- 2.51 ppm

XCH_4 : -7.6 +/- 13.7 ppb

As shown in Fig. 4 and 5, there are some significant discrepancy between GOSAT/FTS derived and the ground based FTS derived XCO_2 and XCH_4. In particular, relatively

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[13] https://co2.jpl.nasa.gov/#mission=ACOS

large difference between both is observed at the specific days. Therefore, careful check at the specific dates of estimated XCO_2 and XCH_4 has to be done.

B. Check the GOSAT Products, Flags

Flag information is stored in the analyzed data. There is a high possibility that the estimation does not go well if the flag $\neq$ 0. For instance, Fig. 6 shows an example of a relation between sky-view camera images and Saga-TCCON flag. As shown in Fig. 6, flag=0 for the clear sky condition (a) while flag=33 for the partly cloudy condition (b).

(a)js20170401saee0a.0020   (b) js20170401saee0a.0062
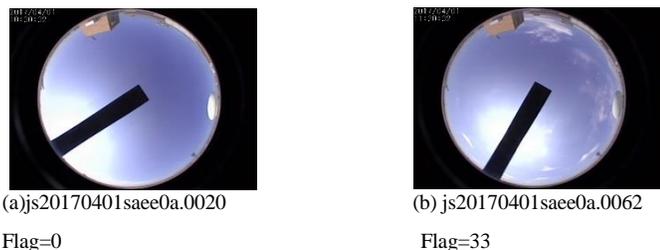
Flag=0   Flag=33

Fig. 6. Example of a relation between sky-view camera images and Saga-TCCON flag.

Fig. 7 shows a result from the comparison between the changes of solar irradiation data (red) and Saga-TCCON flag (blue).
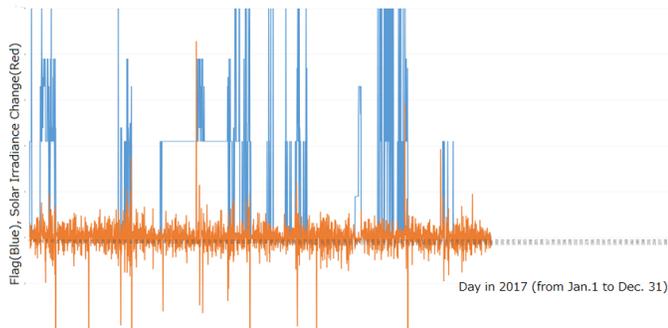

Fig. 7. Result from the comparison between the changes of solar irradiation data (red) and Saga-TCCON flag (blue).

Coincidentally, the flag is large when the solar irradiation changes a lot. When the weather condition is changed from clear sky to cloudy, solar irradiation is also changed a lot. Therefore, both are occurred coincidentally. Table 1 shows the relation between Saga-TCCON flag and Mean and Standard deviation of solar irradiation as well as correlation coefficient between Saga-TCCON flag and solar irradiation.

TABLE I. RELATION BETWEEN SAGA-TCCON FLAG AND MEAN AND STANDARD DEVIATION OF SOLAR IRRADIATION AS WELL AS CORRELATION COEFFICIENT BETWEEN SAGA-TCCON FLAG AND SOLAR IRRADIATION.

Saga-TCCON flag	Off	On
Mean of daily changes of solar irradiation	1.979	2.472
Standard deviation	3.340	4.218
Correlation	0.481	0.580

Saga-TCCON flag is on when the solar irradiation is relatively large. Therefore, there is a possibility to find estimated XCO_2 and XCH_4 with relatively poor accuracy by taking into account the changes in solar irradiation.

C. Comparison of Estimated XCO_2 and XCH_4 by the Proposed Least Square Method based on the Levenberg-Marquardt with the Conventional Method

Typical cases of estimation accuracy is relatively good (fine weather: clear sky condition) and of estimation error seems to be large comparatively (cloudy condition) are selected. Those are FTS data of April 4, 12, 13, 19, and 24 2018. Fig. 8 shows sky-view camera images (Top left: April 4, Top right: April 12, Middle left: April 13, Middle right: April 19 and Bottom: April 24). The left side image shows cloud condition in the morning while the right side image shows cloud condition in the afternoon. It is clear that it is clear in the morning on April 4, 13 and 24 while there are some clouds in the afternoon on April 4, 12, 24. In accordance with the Saga brunch of the JMA: Japan Meteorological Agency, CC: Cloud Coverage at 12:00 and 15:00 of each day is as follows,

April 4: 2, 7. April 12: 2, 3. April 13: 0, 7. April 19: 3, 7. April 24: 0, 8.

It, however, is not always true. There are some visible cirrus clouds in the morning on April 12 clearly. Therefore, FTS data derived XCO_2 and XCH_4 on April 12 is compared to that of April 13.
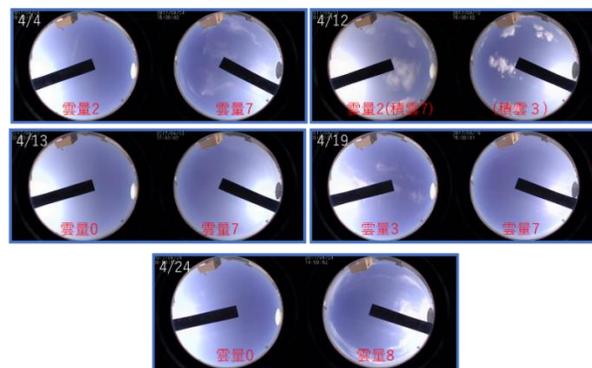

Fig. 8. Sky-view camera images (Top left: April 4, Top right: April 12, Middle left: April 13, Middle right: April 19 and Bottom: April 24)

As mentioned in the previous section, the conventional method for estimation of XCO_2 and XCH_4 is called GGG algorithm. Table 2 shows a comparison of mean and standard deviation of the estimated XCO_2 between GGG and the proposed least square method based on the Levenberg-Marquardt of nonlinear least square method. As shown in Table 2, relatively large discrepancy between the estimated XCO_2 is observed during 9 a.m. and 11:30 a.m. on April 12. Those estimated XCO_2 is shown in Fig. 9. In the figure, black dots denote XCO_2 of GGG while blue dots denote XCO_2 of the proposed least square method.

These discrepancy is caused by the difference between algorithms of the proposed least square and GGG. Therefore, there is a possibility to check the reliability of estimated XCO_2 by using the discrepancy between both.

TABLE II. COMPARISON OF MEAN AND STANDARD DEVIATION OF THE ESTIMATED XCO$_2$ BETWEEN GGG AND THE PROPOSED LEAST SQUARE METHOD

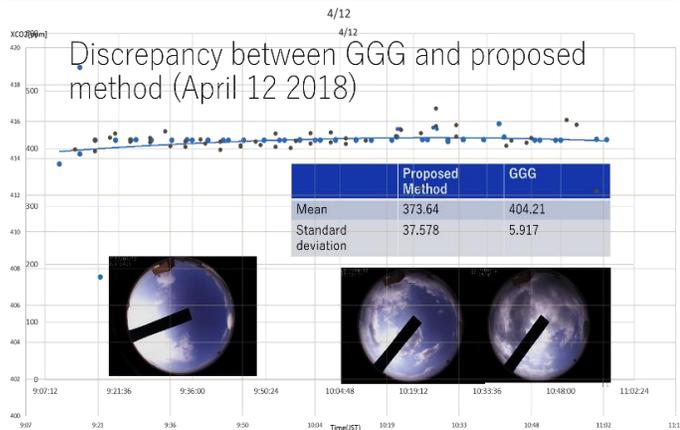|	April 4	April 12	April 13	April 19	April 24
Mean (Proposed)	415.98	373.64	415.23	413.6	413.33
St.Dev.(Proposed)	0.81	37.58	0.93	0.59	1.11
Mean (GGG)	409.45	404.21	410.69	408.66	410.47
St.Dev.(GGG)	0.52	5.92	1.16	1.18	1.05

Fig. 9. Estimated XCO$_2$ derived from GGG and from the proposed least square method (Black dots denote XCO$_2$ of GGG while Blue dots denote XCO$_2$ of the proposed least square method.

D. Possible Causes of Relatively Large XCO$_2$ Estimation Error

Cloud condition on April 12 2018 is shown in Fig. 10. Cloud Coverage ratio (CC) at 9:00 is 7 (Cumulus clouds), then CC at 12:00 is 2 (Cirrus clouds), and CC at 15:00 is 3 (Cumulus clouds), respectively. Also, hourly Solar Irradiance (SI) at 9:00 is 1.22, then SI at 12:00 is 1.96, and SI at 15:00 is 2.72. Averaged CC of the day is 6 and total solar irradiance a day is 20.88 MJ/m^2.

Other than these, solar direct and diffuse irradiance are measured with sky-radiometer, POM-1 of sun-photometer and aureole-meter which is manufactured by Prede Co. Ltd. in Japan. Using this data, aerosol refractive index, size distribution, single scattering albedo, atmospheric optical depth, etc. can be estimated.
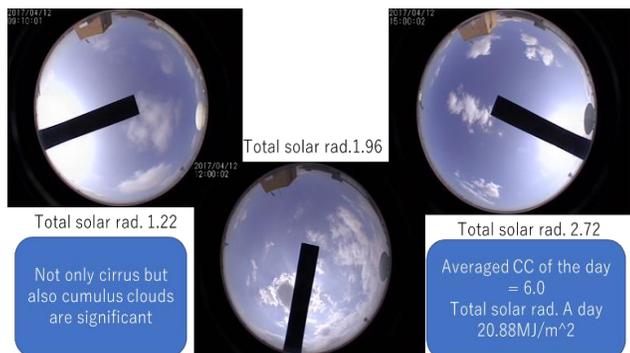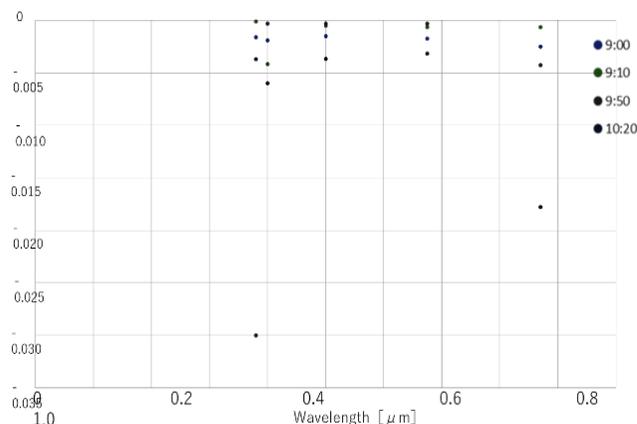

Fig. 10. Cloud condition on April 12 2018

TABLE III. SINGLE SCATTERING ALBEDO AND TOTAL ATMOSPHERIC OPTICAL DEPTH

(A)SINGLE SCATTERING ALBEDO

Wavelength[µm]	April 4	April 12	April 13	April 19	April 24
0.38	0.841	0.826	0.846	0.787	0.808
0.4	0.961	0.927	0.960	0.908	0.954
0.5	0.965	0.948	0.989	0.938	0.953
0.675	0.962	0.948	0.990	0.932	0.952
0.87	0.750	0.854	0.813	0.897	0.717

(b)Total Atmospheric Optical Depth

Wavelength[µm]	April4	April 12	April 13	April 19	April 24
0.38	0.303	0.681	0.503	0.257	0.263
0.4	0.271	0.622	0.456	0.238	0.226
0.5	0.201	0.501	0.344	0.201	0.165
0.675	0.123	0.369	0.217	0.159	0.102
0.87	0.099 5	0.312	0.171	0.145	0.0878

Single scattering albedo of each day is shown in Table 3 (a) while total atmospheric optical depth of each day is shown in Table 3 (b), respectively.

The single scattering albedo on April 12 is relatively small while the total atmospheric optical depth on April 12 is comparatively large. Therefore, absorption in the atmosphere is relatively large while comparatively thick atmosphere on April 12.

Imaginary part of aerosol refractive index estimated for 9:00 to 10:20 a.m. on April 12 is shown in Fig. 11 (a) while that of 9:50 to 15:00 on April 13 is shown in Fig. 11 (b), respectively. Not so significant difference is observed between both of imaginary part of aerosol refractive index estimated for April 12 and April 13. Also, relatively large changes are observed for imaginary part of aerosol refractive index during from 9:00 to 10:20 on April 12 while that for 9:50 to 15:00 on April 13 is very stable.
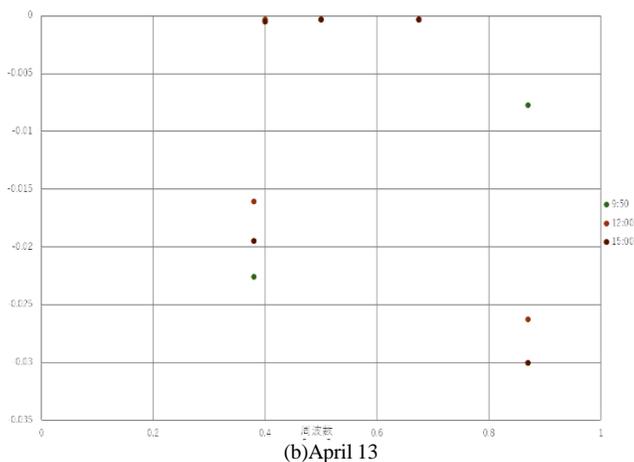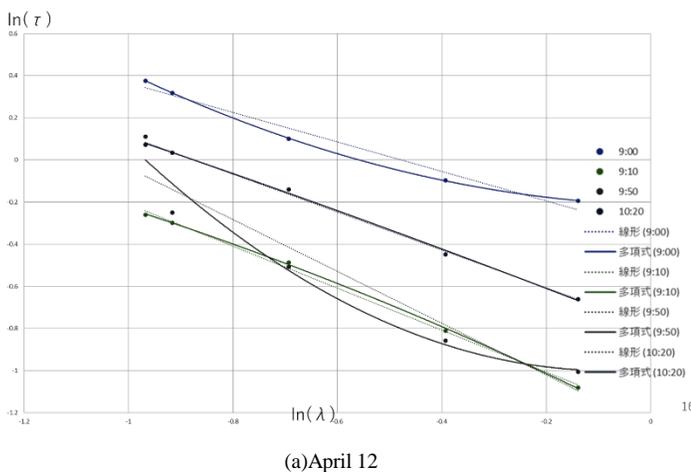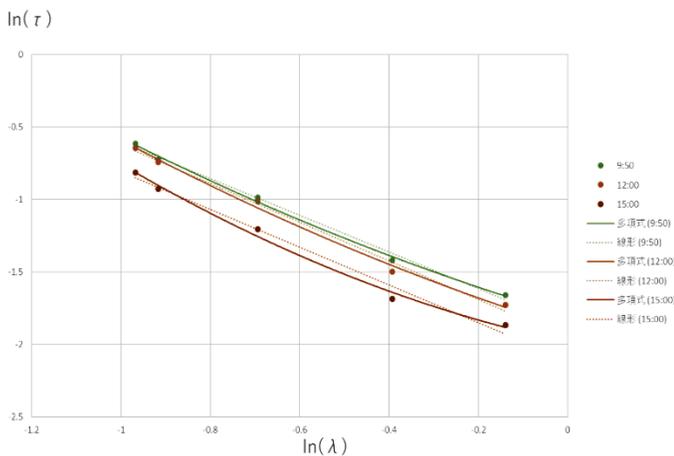

(a)April 12

Fig. 11. Estimated imaginary part of aerosol refractive index

On the other hand, real part of aerosol refractive index which is estimated for 9:00 to 10:20 on April 12 and 9:50 to 15:00 on April 13 is shown in Fig. 12 (a) and (b), respectively.
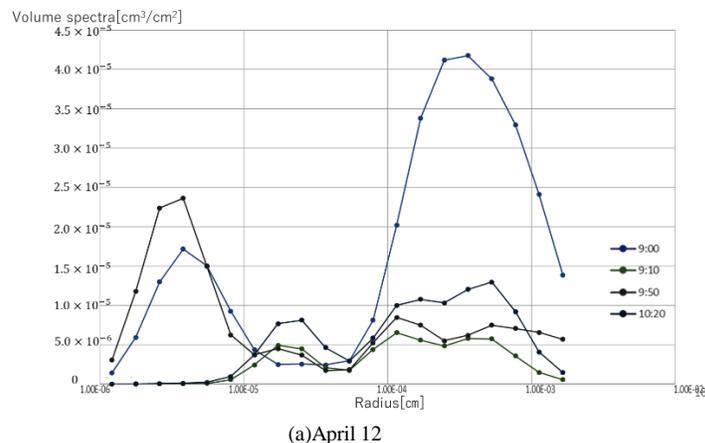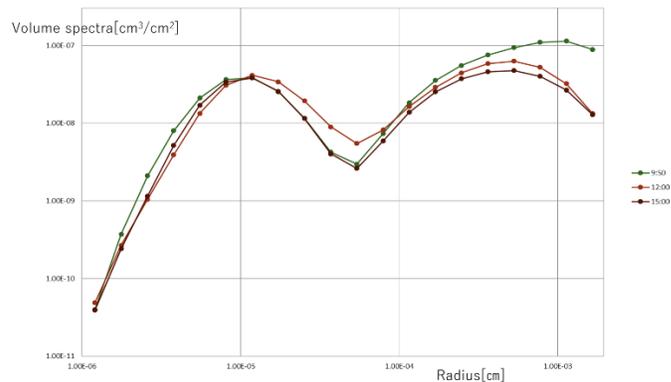

(a)April 12

(b)April 13

Fig. 12. Real part of aerosol refractive index which is estimated for April 12 and April 13

Also, relatively large changes are observed for real part of aerosol refractive index during from 9:00 to 10:20 on April 12 while that for 9:50 to 15:00 on April 13 is very stable. Meanwhile, aerosol size distribution which is estimated for 9:00 to 10:20 on April 12 and 9:50 to 15:00 on April 13 is shown in Fig. 13 (a) and (b), respectively. Also, relatively large changes are observed for aerosol size distribution during from 9:00 to 10:20 on April 12 while that for 9:50 to 15:00 on April 13 is very stable. More importantly, aerosol size distribution on April 13 is bi-modal and stable during from 9:50 to 15:00 while that on April 12 is changed dramatically during from 9:10 to 9:50. It is thought type of aerosol particles are changed during the period.

(a)April 12

(b)April 13

Fig. 13. Aerosol size distribution which is estimated for April 12 and April 13

E. *Another Possible Method for Identification of Relatively Poor Estimation Accuracy of XCO_2*

Another possible method for identification of relatively poor estimation accuracy of XCO_2 is investigated. The most reliable method is comparison between ground based FTS data derived XCO_2 and XCH_4 and GOSAT/TANSO-FTS, obviously. It does work for the data location at TCCON sites. As mentioned in the previous section, most significant causes for poor accuracy of XCO_2 and XCH_4 estimations are clouds. Therefore, the method which uses sky-view camera data might be useful. It, however, can be used for the FTS data nearby TCCON sites. Also, TANSO-CAI is applicable to find clouds. It, however, does not work for cirrus cloud detection.

(a) Cloud reflectance
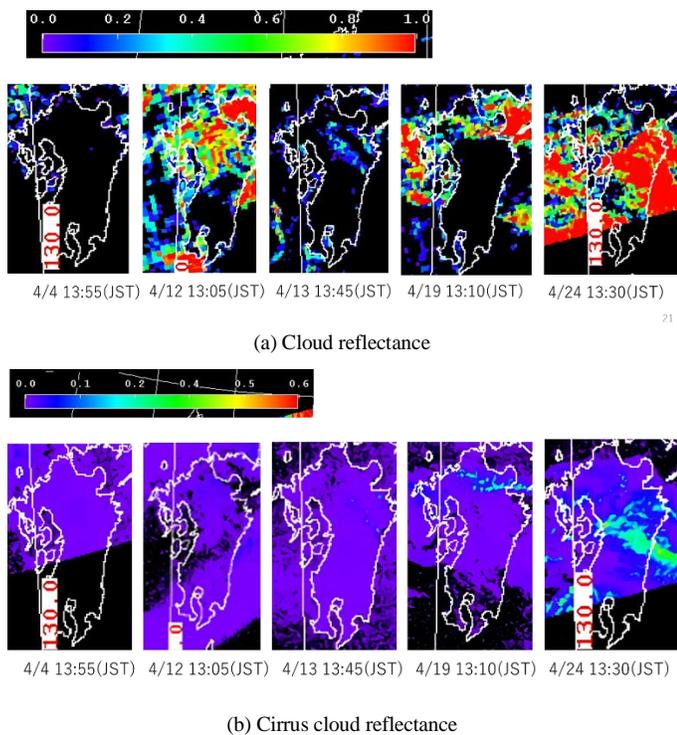

(b) Cirrus cloud reflectance

Fig. 14. MODIS data derived cloud and cirrus cloud reflectance

Therefore, the following method utilizing MODIS data derived cloud reflectance as well as cirrus cloud reflectance is proposed. Fig. 14 (a) shows cloud reflectance on April 4, 12, 13, 19, and 24 2018 while Fig. 14 (b) shows cirrus cloud reflectance on the same days, respectively. These reflectance are derived from AQUA/MODIS data. Therefore, it measures in the afternoon because local mean time of the AQUA satellite orbit is afternoon. It, however, shows great possibility of cirrus cloud detection.

III. CONCLUSION

Quality and cloud flags of GOSAT/TANSO-FTS: Fourier Transform Spectrometer onboard Greenhouse gasses Observation Satellite products taking into account cirrus clouds and thick aerosols are considered and proposed. Influence due to cirrus and thick aerosol on estimation of column CO_2 and CH_4 with GOSAT/TANSO-FTS data is clarified. Relatively large estimation errors are observed in column CO_2 and CH_4 retrievals with FTS data in some atmospheric conditions.

In order to find such cases, retrieval results and quality/cloud flags in the GOSAT/TANSO-FTS data products are checked. Through the investigation, it is found that relatively large error is caused by convergence problem due to cirrus clouds and thick aerosols. In the paper, some of the cases of which relatively large estimation error is occurred at the Saga TCCON (The Total Carbon Column Observing Network) site are investigated. Also, a comparative study is conducted between standard products provided by NASA/JPL and the Levenberg-Marquardt based least square method of column CO_2 and CH_4 retrieval. It is suggested that some improvements of estimation accuracy of column CO_2 and CH_4 retrieval with GOSAT/TANSO-FTS data can be expected.

The purpose of this research is to develop a method for identifying poor accuracy of XCO_2 and XCH_4 estimation with GOSAT/TANSO-FTS data. The conventional method is to use the flag which reflect cloud detection with GOSAT/TANSO-CAI imagery data and quality of FTS data. It, however, GOSAT/TANSO-CAI does not work for cirrus clouds. Therefore, alternative methods are attempted and proposed here. One of those is to use MODIS data derived cloud reflectance and cirrus cloud reflectance. For the FTS data is acquired around TCCON sites, sky-view camera images are useful. Also, solar irradiance is useful for the FTS data is acquired around meteorological stations which allow measurement data of solar direct irradiance.

There are some reasons for relatively large discrepancy between GGG and the proposed XCO_2 estimation methods as well as between ground based measurement data and GOSAT based XCO_2 measurement data. Therefore, it is possible to create quality flag through comparisons of the estimated XCO_2 and XCH_4 derived from the different methods, GGG and Levenberg-Marquardt.

Cirrus cloud (cloud type, MODIS derived cloud reflectance including cirrus cloud reflectance) while, thick aerosol (Refractive index, size distribution, single scattering albedo, optical depth, Angstrom exponent, etc.). Therefore, there is a possibility to identify a poor accuracy of XCO_2 and XCH_4 estimation by using MODIS data derived cloud reflectance as well as cirrus cloud reflection. Cloud flag can be created with MODIS derived cloud and cirrus cloud reflectance as well as sky-radiometer data derived refractive index and size distribution together with sky view camera data

Further study is required for establishment of XCO_2 and XCH_4 retrieval method with a variety of remote sensing satellite imagery data.

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