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Satellite observation of atmospheric methane: intercomparison between AIRS and GOSAT TANSO-FTS retrievals

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Abstract

Space-borne observations of atmospheric methane (CH_4) have been made using the Atmospheric Infrared Sounder (AIRS) on the EOS/Aqua satellite since August 2002 and the Thermal and Near-infrared Sensor for Carbon Observation Fourier Transform Spectrometer (TANSO-FTS) on the Greenhouse Gases Observing Satellite (GOSAT) since April 2009. This study compared the GOSAT TANSO-FTS thermal infrared (TIR) version 1.0 CH_4 product with the collocated AIRS version 6 CH_4 product using data from 1 August 2010 to 30 June 2012, including the CH_4 mixing ratios and the total column amounts. The results show that at 300–600 hPa, where both AIRS and GOSAT-TIR CH_4 have peak sensitivities, they agree very well, but GOSAT-TIR retrievals tend to be higher than AIRS in layer 200–300 hPa. At 300 hPa the CH_4 mixing ratio from GOSAT-TIR is, on average, 10.3 ± 31.8 ppbv higher than that from AIRS, and at 600 hPa GOSAT-TIR retrieved CH_4 is −16.2 ± 25.7 ppbv lower than AIRS CH_4. Comparison of the total column amount of CH_4 shows that GOSAT-TIR agrees with AIRS to within 1 % in the mid-latitude regions of Southern Hemisphere and in tropics. In the mid to high latitudes in the Northern Hemisphere, GOSAT-TIR is ∼ 1–2 % lower than AIRS, and in the high-latitude regions of Southern Hemisphere the difference of GOSAT from AIRS varies from −3 % in October to +2 % in July. The difference between AIRS and GOSAT TANSO-FTS retrievals is mainly due to the difference in retrieval algorithms and instruments itself, and the larger difference in the high latitude regions is associated with the low information content and small degree of freedoms of the retrieval. The degree of freedom of GOSAT-TIR retrievals is lower than that of AIRS also indicates that the constraint in GOSAT-TIR retrieval may be too strong. From the good correlation between AIRS and GOSAT-TIR retrievals and the seasonal variation they observed we are confident that the thermal infrared measurements from AIRS and GOSAT-TIR can provide valuable information to capture the spatial and temporal variation of CH_4, especially in the mid-upper troposphere, in most time and regions.

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1 Introduction

As the third most important long life greenhouse gases after carbon dioxide (CO_2) and water vapor, atmospheric methane (CH_4) has a life time of about 12 years, and is more effective in absorbing long-wave radiation as its radiative forcing is about 26 times more than that of CO_2 on a 100 year time horizon, and accounts for 32 % of the total anthropogenic well-mixed greenhouse gas radiative forcing (IPCC, 2013). Mainly attributed to the impact of human activities, the concentration of CH_4 in the atmosphere has increased from the pre-industrial levels of about 700 parts per billion (ppb) to recent level of about 1800–1900 ppb.

Ground-based networks, such as NOAA/ESRL/GMD (National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division), provide measurements of CH_4 in the lower troposphere with a high accuracy and long record, but in limited stations. Aircraft measurements from NOAA/ESRL/GMD (Tans, 2009) as well as some research campaigns provide sparse, intermittent measurements of CH_4 vertical profiles. Due to the limited observations in time and space domain, the quantification of CH_4 emission from different sources and in different regions still remains largely uncertain. In recent years, space-borne measurements from satellites have become available, such as the measurements using the thermal infrared (TIR) sensors, which include the Atmospheric InfraRed Sounder (AIRS) on NASA/Aqua (Aumann et al., 2003; Xiong et al., 2008, 2010a, b), Tropospheric Emission Spectrometer (TES) on NASA/Aura (Payne et al., 2009; Wecht et al., 2012; Worden et al., 2012), and the Infrared Atmospheric Sounding Interferometer (IASI) on METOP-A and -B (Xiong et al., 2013; Crevoisiter et al., 2009, 2013; Razavi et al., 2009); measurements using the Near-Infrared (NIR) sensors, which include the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) instrument onboard ENVISAT for 2003–2009 (Frankenberg et al., 2008, 2011), and the Thermal And Near infrared Sensor for carbon Observation (TANSO) onboard the Greenhouse gases Observation SATellite (GOSAT) from 2009 to present (Yokota et al., 2009; Paker

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et al., 2011; Schepers et al., 2012; Saitoh et al., 2012). These space-borne measurements provide complementary data sources to surface observations for monitoring atmospheric CH_4 with a large spatial and temporal coverage (Kirschke et al., 2013).

Both AIRS, GOSAT TANSO-FTS TIR and other thermal infrared sensors, including TES and IASI, have been used to retrieve atmospheric CH_4, and these data have been used for analyzing the spatial and temporal variation of CH_4, so an inter-comparisons of these two different products from AIRS and GOSAT will provide useful information to users to better understand the characteristics of these two products. On the other hand, AIRS V6 CH_4 data were already validated by comparing aircraft data (Xiong et al., 2015), so this comparison of GOSAT data with the "validated" AIRS V6 data is also a kind of indirect validation to GOSAT product, which will give some insight information about the possible over-constraint in GOSAT retrieval algorithm as illustrated later in this paper. This comparison is also a cross-validation to AIRS product, even though their difference can be due to many factors, such as the instruments, radiative transfer models and retrieval algorithms. Section 2 provides a brief introduction of these two instruments, their retrieval algorithms and the data used in this study. Section 3 shows the comparison results, which include the comparison of the retrieved profiles, information contents and the averaging kernels from these two instruments. Both the retrieved CH_4 mixing ratios and the total column amounts in different seasons and different regions are compared. A summary and conclusion are given in Sect. 4.

2 CH_4 retrievals from AIRS and GOSAT-TIR

2.1 AIRS instrument and the retrieval algorithm description

AIRS on the EOS/Aqua satellite was launched in polar orbit (13:30 LST, ascending node) in May 2002. It has 2378 channels covering 649–1136, 1217–1613 and 2169–2674 cm^{-1} at high spectral resolution ($\lambda/\Delta\lambda = 1200$) (Aumann et al., 2003), and the noise in the equivalent change in temperature (NeΔT) at a reference temperature of

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250 K ranges from 0.14 K in the 4.2 µm in the lower tropospheric sounding wavelengths to 0.35 K in the 15 µm in the upper tropospheric sounding region. The spatial resolution of AIRS is 13.5 km at nadir, and in a 24 h period, AIRS nominally observes the complete globe twice per day. In order to retrieve CH_4 in both clear and partially cloudy scenes, 9 AIRS fields-of-views (FOVs) within the footprint of the Advanced Microwave Sounding Unit (AMSU) are used to derive a single cloud-cleared radiance spectrum in a field-of-regard (FOR). The cloud-cleared FOR radiance spectrum is then used to retrieve profiles with a spatial resolution of approximately 45 km. The atmospheric temperature profiles, water vapor profiles, surface temperatures and surface emissivity are required as inputs to compute the radiances in the CH_4 absorption band. The differences between the computed radiances and the AIRS measured radiances for clear pixels or the derived cloud-cleared FOR radiances for partially cloudy pixels are used to derive CH_4 profiles. Fifty to sixty CH_4 absorption channels near 7.66 µm band are selected for the retrievals. The AIRS retrieval algorithm is a sequential retrieval method with multiple steps, in which the temperature and water vapor profiles were retrieved using its own sensitive channels in previous steps, thus the quality of the CH_4 retrievals depends on the whole AIRS science team's efforts in improving the temperature and moisture profiles as well as surface temperature and emissivity products. More detail of CH_4 retrievals in its most recent version, i.e. version 6 (V6), can be found in Xiong et al. (2015).

2.2 GOSAT TANSO-FTS TIR and the retrieval algorithm description

GOSAT was launched on 23 January 2009 with the primary goal of global observations of column amounts and profiles of CO_2 and CH_4 (Yokota et al., 2009). TANSO-FTS on board the GOSAT has TIR bands covering 5.5–14.3 µm with a resolution of 0.2 cm^{-1} (Kuze et al., 2009). In the TIR retrieval algorithm version 1.0, all the channels in 7.3–8.8 µm, which include both the CH_4 and N_2O absorption bands, are used for CH_4 retrieval. The retrieval algorithm is a non-linear maximum a posteriori (MAP) method with linear mapping (Rodgers, 2000). The a priori CH_4 profiles used in the re-

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trieval are taken from the National Institute for Environmental Studies (NIES) transport model (Maksyutov et al., 2008; Saeki et al., 2012). Profiles of temperature and water vapor required for the retrieval are taken from the Japan Meteorological Agency Grid Point Values (JMA-GPV) dataset. Values of surface emissivities are estimated by a linear regression analysis using the Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) Spectral Library (Baldridge et al., 2009), the information of land cover, sea ice, wind speed, and the vegetation index derived from the TANSO-Cloud and Aerosol Imager (CAI). Surface temperatures are estimated from the TANSO-FTS TIR spectra in the window region. The signal-to-noise ratios (SNR) of TANSO-FTS at around 7–8 μm band are estimated to be 70–100, and the measurement covariance matrix used in the retrieval is set based on the SNR values. The footprint of GOSAT-TANSO is 10.5 km in diameter, and the number of scan points of GOSAT in cross-track direction is 5 before July 2010, and 3 thereafter.

2.3 Data used

This study is made using the standard products of both sensors. GOSAT TANSO-FTS TIR Level 2 CH_4 profile products in version 01.01 for a two-year period from August 2010 to June 2012 are used, and the data during this period has been released to all registered users selected under the GOSAT Research Announcement (RA). AIRS V6 CH_4 data are used in this study and they are downloaded from Goddard Earth Sciences Data and Information Services Center (DISC) (http://disc.gsfc.nasa.gov/AIRS/index.shtml/). Only the data from the ascending mode of AIRS, with quality flag equal to 0 or 1, are used for comparison with GOSAT-TIR. Note that the number of retrieval profiles from AIRS is much denser than GOSAT-TIR, as shown in Fig. 1. In this case, the number of profiles from GOSAT-TIR is 1479, while the number of the AIRS profiles from ascending node with QC = 0 and 1 is 164 355. The AIRS retrievals within 1° from each GOSAT-TIR measurement and in the same day were averaged to match-up with each GOSAT-TIR measurement. The errors resulted from the time difference of about 4 h between AIRS and GOSAT-TIR observations were not accounted for in this

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study considering CH_4 is a long residence and well-mixed gas. For simplification, in the comparison of the total column CH_4, the AIRS gridded products from NASA DISC in $1^\circ \times 1^\circ$ were used directly, and the GOSAT-TIR data was interpolated to the same geographical grid as AIRS.

Comparisons between GOSAT-TIR and AIRS CH_4 products include: (1) CH_4 profile comparison, (2) Comparison of CH_4 mixing ratios with and without using the averaging kernels, and (3) Comparison of the column averaged CH_4 and the total column abundance in different latitude zones and different time. The CH_4 total column abundance from AIRS ascending mode whose unit is molecules cm^{-2} was used. Since the unit of GOSAT-TIR CH_4 profile was parts per billion (ppb), we converted it to the total column density using the surface pressure included in the GOSAT-TIR product. As GOSAT TANSO-FTS TIR CH_4 profile consists of 22 layers, and AIRS-V6 CH_4 profile contains 100 layers in the supporting product and 10 layers in the standard product, interpolation of AIRS CH_4 profile from 100 layers to 22 layers was made using the pressure data included in both CH_4 products.

Later in this paper the "differences" between GOSAT-TIR and AIRS CH_4 are calculated as:

$$\Delta X = X_G - X_A$$

or

$$(X_G - X_A)/X_A \times 100\% \quad (1)$$

where X_G denotes the CH_4 mixing ratios or column amounts from GOSAT-TIR, and X_A from AIRS.

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3 Results

3.1 Profile comparison

As one example, Fig. 2 shows a simple comparison of the GOSAT-TIR profiles and the match-up AIRS CH_4 profiles from a one-day global data on 4 September 2010. They are in a good agreement overall above 100 hPa and below 400 hPa, but at 200–300 hPa AIRS CH_4 spans a large range and tends to be smaller than GOSAT TIR on average.

The averaging kernels are defined to provide a simple characterization of the relationship between the retrieval and the true state. The retrieval sensitivity can be obtained from the sum of the columns of the averaging kernel matrix, which is also referred to as "the area of the averaging kernel" (Rodgers, 2000). To better demonstrate the differences in sensitivities between AIRS and GOSAT-TIR retrievals, Fig. 3 shows an example of the averaging kernels using data at (38° S, 180° W) on 4 September 2010. There are 10 retrieval layers for AIRS and 22 for GOSAT-TIR. The area of the averaging kernels, which is computed as the sum of all individual kernels, from AIRS is larger than that from GOSAT-TIR, as shown in Fig. 3. To demonstrate the sensitivity variations in latitudes, Fig. 4 shows a curtain plot of the area of averaging kernels using one day data on 4 September 2010. Overall, the patterns from AIRS are similar to GOSAT TIR, with their peak sensitivities located in the 300–600 hPa range in the high latitudes and 200–600 hPa in the tropics. The sensitivities below 800 hPa are small for both, which reflects the major limitation of TIR in measuring the change of CH_4 in the lower troposphere associated with surface emissions.

The information content, which is usually represented as the degree of freedom (DOF), is computed as the trace of the averaging kernel matrix (Rodgers and Connor, 2003). Figure 5 shows the variation of DOFs in different latitudes, and on average, the DOF of AIRS CH_4 is approximately 1.1 whereas the mean of DOFs of GOSAT-TIR CH_4 is approximately 0.61.

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3.2 Comparison of CH_4 with and without using the averaging kernels

In order to take into account the skill of the CH_4 retrievals, the averaging kernels are usually applied to the "truth" based on the following equation (Rodgers and Connor, 2003):

$$\hat{\boldsymbol{x}} = \mathbf{A}\boldsymbol{x} + (\mathbf{I} - \mathbf{A})\,\boldsymbol{x}_{\mathbf{a}} \quad (2)$$

where $\mathbf{I}$ is the identity matrix, $\mathbf{A}$ is the averaging kernel matrix, $\boldsymbol{x}_{\mathbf{a}}$ is the first guess profile for AIRS and the a priori profile for GOSAT-TIR (unit: part per billion volume, ppbv), $\boldsymbol{x}$ is the "true" profile, and the computed value of $\hat{\boldsymbol{x}}$ is referred to as the convolved data later in this paper, which is usually compared with the retrieved CH_4 mixing ratio in validation studies. Considering the AIRS retrieval layers are coarser than those of GOSAT-TIR and the first guess of AIRS is simple, we used the AIRS averaging kernels, $\mathbf{A}$, and AIRS first guess, $\boldsymbol{x}_{\mathbf{a}}$ in Eq. (2), to convert the GOSAT-TIR CH_4 profiles, $\boldsymbol{x}$, and the convolved (or smoothed) GOSAT-TIR profiles ($\hat{\boldsymbol{x}}$) is then compared with AIRS retrieved profiles. As the AIRS averaging kernel is a 10 by 10 matrix, the GOSAT-TIR CH_4 profile and AIRS first guess profile were interpolated into the 10 pressure layers of AIRS retrieval grid when using Eq. (2).

In order to investigate whether the differences between AIRS and GOSAT-TIR retrieved profiles are consistent with their error characteristics and vertical sensitivity, we calculate the error chi-square using Eq. (14) in Rodgers and Connor (2003). Figure 6a shows the RMS of difference (upper panel) and error chi-square (lower panel) of retrieved CH_4 profile from AIRS and GOSAT-TIR. Figure 6b shows the scatter plot of RMS difference vs. error chi-square. The RMS of difference is more than 1.1 times of the error chi-square, and the correlation coefficient R^2 is 0.51, which indicate good consistence.

To show the impact of using averaging kernels in the intercomparison, Fig. 7 shows the scatter plot of AIRS vs. GOSAT-TIR CH_4 mixing ratios in four retrieval layers of 272–343, 343–441, 441–575 and 575–777 hPa. The correlation coefficients between AIRS

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and the smoothed GOSAT-TIR values are 0.70, 0.70, 0.79 and 0.87 in these four layers respectively, while the correlation coefficients between AIRS and GOSAT-TIR without smoothing are 0.36, 0.45, 0.57 and 0.75 respectively.

A comparison of the column averaged mixing ratio, X_{CH_4}, in Fig. 8 also shows that the correlation coefficient between AIRS and GOSAT TANSO-FTS TIR retrievals increases from 0.88 to 0.91 after using the smoothed data, and the mean difference decreases from −21.32 to −2.78 ppb. The mean difference and standard deviation between AIRS and the smoothed GOSAT-TIR data are smaller than those without smoothing using the averaging kernels, demonstrating that applying the averaging kernels helps achieving better agreements in the intercomparison between two different measurements, as suggested by Rogers and Connor (2003). For simplicity in the next sections we will focus on the direct comparison of the total abundance between AIRS and GOSAT-TIR retrievals.

3.3 Comparison of CH_4 total column abundance in different latitude zones

As the sensitivity of TIR measurements is impacted by the surface thermal contrast and the water vapor content in the atmosphere (Deeter et al., 2007; Xiong et al., 2010b), the sensitivity varies with latitudes and seasons. Below we compared the differences between AIRS and GOSAT TANSO-FTS TIR retrieved total column abundance in 6 latitude zones from south to north with an interval of 30°. As shown in Figs. 9 and 10, the correlations between AIRS and GOSAT-TIR are reasonably good, and the correlation coefficient for the least correlated case is 0.83 in zone 30–60° S. To show the change of their differences with time, Figs. 9 and 10 also shows the monthly means of the differences from July 2010 to July 2012. In the tropics their differences are less than 1 % in all seasons, but in the mid to high latitudes in the Northern Hemisphere, GOSAT-TIR is ∼ 1 ∼ 2 % lower than AIRS, with the largest bias occurring in the September. In the high attitudes in the Southern Hemisphere (60–90° S) the differences of GOSAT from AIRS show a large variation with time, i.e. from −3 % in October to +2 % in July. This large difference in the high attitudes in the Southern Hemisphere is related to the very

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low DOFs, particularly in GISAT-TIR retrievals (see Fig. 5), and the large uncertainties in the retrieval of atmospheric states when there are snow/ice coverage over the ocean during October to July.

To better show the difference between GOSAT-TIR and AIRS in different latitudes, we computed the mean difference in a two-year period from 1 August 2010 to 30 June 2012 and in each 15-degree zone. As shown in Fig. 11, the standard deviations in the Southern Hemisphere high latitudes are much larger than in the other latitudes, and the mean differences are smaller from 60° S to 10° N but increases in the north hemisphere to −1.5 % at 60° N.

4 Comparison of seasonal cycles from AIRS and GOSAT

Using the monthly-average total column density of CH_4 from AIRS and GOSAT products, we compared the seasonal cycles of CH_4 from 1 August 2010 to 30 June 2012. The left panels in Fig. 12 are the comparisons in the Northern Hemisphere and the right panels are the comparisons in the Southern Hemisphere. Again, GOSAT-TIR agrees with AIRS to within 1 % in the mid-latitude regions of Southern Hemisphere and in tropics, however the seasonal variation in the tropics from AIRS observations is larger than that from GOSAT. In the mid to high latitudes in the Northern Hemisphere, GOSAT-TIR is ∼ 1–2 % lower than AIRS, but the seasonal variations from them agree well. In the high-latitude regions in Southern Hemisphere, seasonal variation of the total column of CH_4 is large, which is due to a lot of data points with very low total column of CH_4 observed during October–January, however, AIRS and GOSAT agree well in capturing the variation even though their difference is relatively larger than in other regions (see Fig. 10).

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5 Summary and conclusions

A thorough comparison of AIRS V6 and GOSAT TANSO-FTS TIR V1.0 CH_4 products using two years data (1 August 2010 to 30 June 2012) has been made. In this comparison, AIRS measurements within a collocation window of 1° by 1° from each GOSAT-TIR measurement in the same day were used. Both the CH_4 mixing ratios and total column amounts have been compared. To understand the differences in the retrievals from these two different instruments, we also compared the differences in the averaging kernels and the DOFs, and examined the use of averaging kernels on the comparison results.

The peak sensitive layers of AIRS and GOSAT-TIR are at similar height, which is at 200–600 hPa in the tropics and 300–600 hPa in the high latitude regions. However, due to the lower SNR of GOSAT TANSO-FTS spectra at 7–8 μm CH_4 band, or over constraint in the GOSAT retrieval algorithm, the degree of freedom of GOSAT-TIR V1.0 retrievals is lower than AIRS.

The comparisons of the profiles showed that the AIRS CH_4 are similar to GOSAT-TIR CH_4, except AIRS values tend to be lower than GOSAT-TIR at 200–300 hPa. At 300 hPa, the CH_4 mixing ratios from GOSAT are 10.3 ± 31.8 ppbv higher than AIRS, and at 600 hPa, the GOSAT-TIR CH_4 is -16.2 ± 25.7 ppb lower than AIRS. Between 300–600 hPa, where they have peak sensitivities, AIRS and GOSAT-TIR agree very well. As expected, applying the averaging kernels to smooth the GOSAT-TIR retrievals makes a better agreement between GOSAT with AIRS products.

The comparison of the total column amounts of CH_4 shows that the correlation coefficients between AIRS and GOSAT TANSO-FTS TIR are more than 0.8 in all cases, and the GOSAT-TIR CH_4 agrees with AIRS to within 1 % in the mid-latitudes of the Southern Hemisphere and tropics, but in the mid to high latitudes of the Northern Hemisphere, GOSAT-TIR is ~ 1–2 % lower than AIRS depending on different seasons. In the high latitudes of the Southern Hemisphere the bias varies from −3 % in October to +2 % in July. This large difference in high latitude regions is associated with the low information

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content (or DOF), suggesting a larger uncertainty of retrievals in these regions and a much stricter quality control should be used. We also found AIRS and GOSAT-TIR have a good agreement in capturing the monthly variation of CH_4 density.

In this study, the time difference between AIRS and GOSAT-TIR measurements has not been taken into account. So, the differences, if they could have been measured in the same time, could be slightly smaller than what we presented here. These results demonstrate that the thermal infrared sensors such as AIRS and GOSAT TANSO-FTS TIR can provide valuable consistent information of CH_4 in the mid-upper troposphere. Further comparisons using more recent data as well as direct comparison with aircraft measurements are ongoing.

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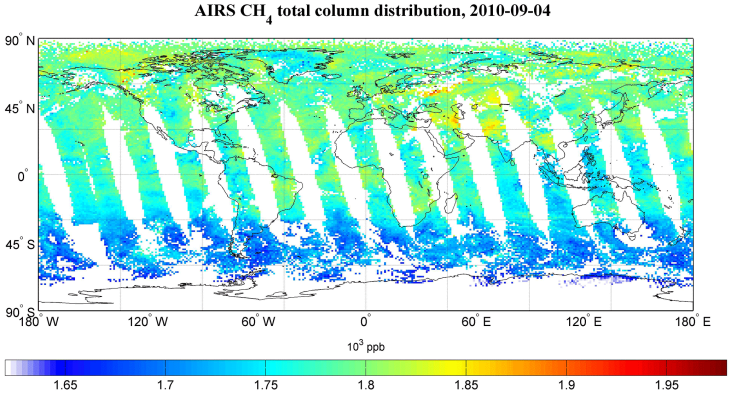
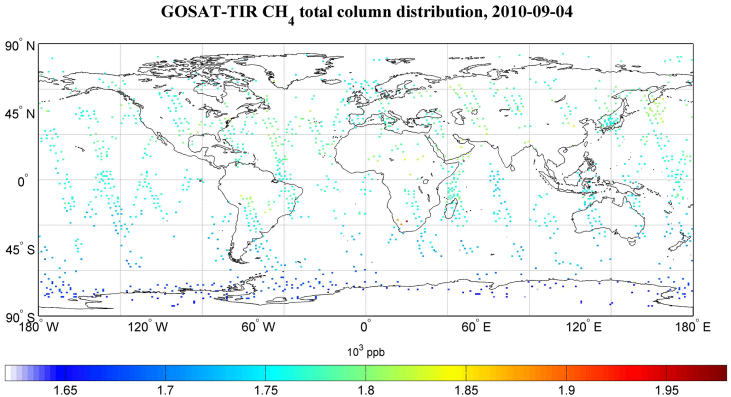


(a)



(b)

Figure 1. Much larger coverage of AIRS retrievals **(a)** as compared to GOSAT TANSO-FTS **(b)** as shown from the global CH_4 total column density on 4 September 2010. AIRS data from ascending mode with QC = 0, 1 are plotted.

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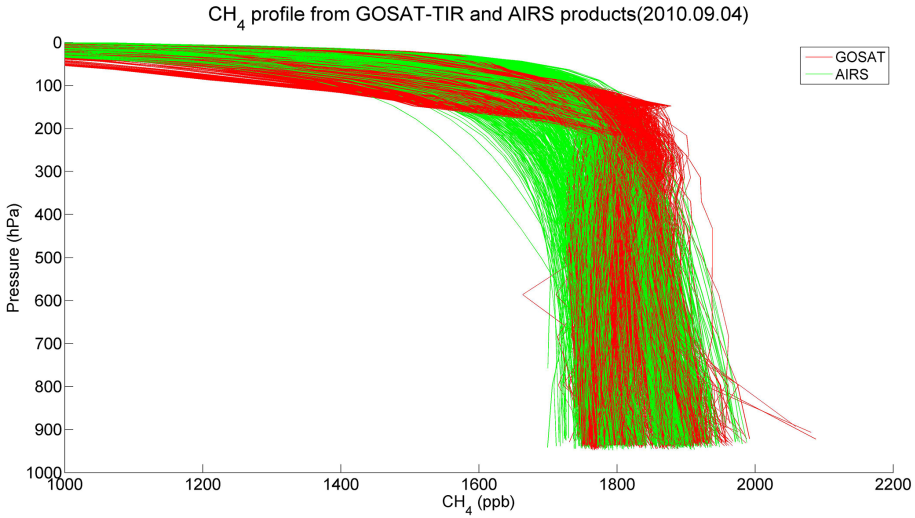

Figure 2. Comparison of the match-up AIRS CH_4 profiles vs. the GOSAT-TIR profiles using one day global data on 4 September 2010. N = 1182.

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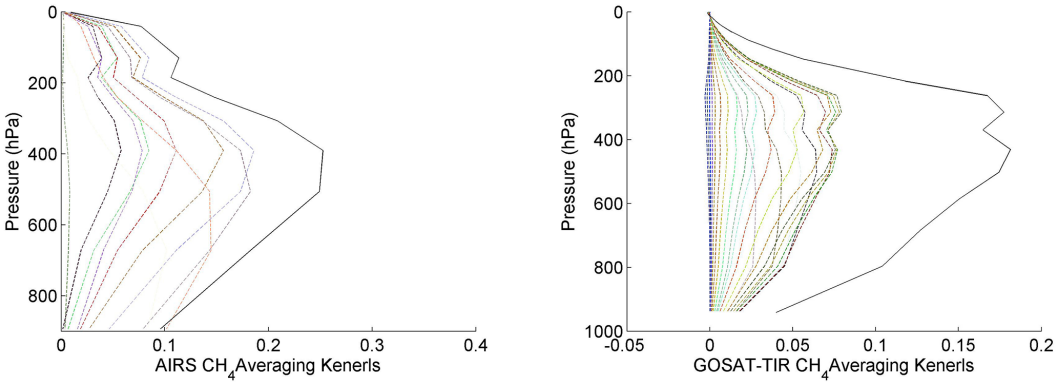

Figure 3. The averaging kernels of AIRS and GOSAT TANSO-FTS TIR V1.0 CH_4 retrievals on 4 September 2010. There are 10 dash lines for AIRS retrievals and 22 dash lines for GOSAT retrievals, corresponding to the retrieval layers used in each of them. The black solid line is the area of kernels divided by 4.

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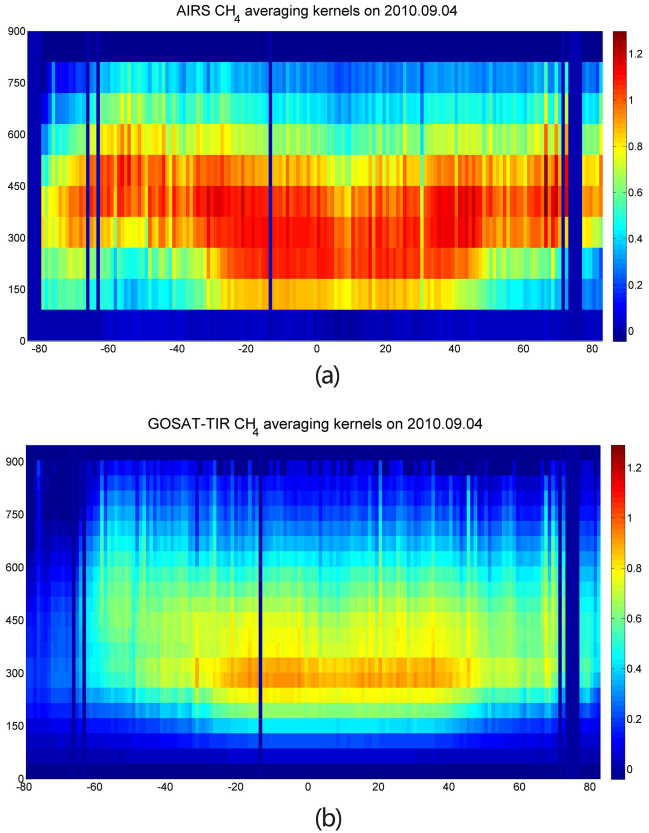

Figure 4. The area of the averaging kernels of CH_4 retrievals from **(a)** AIRS and **(b)** GOSAT TANSO-FTS V1.0 TIR observations in different latitudes on 4 September 2010.

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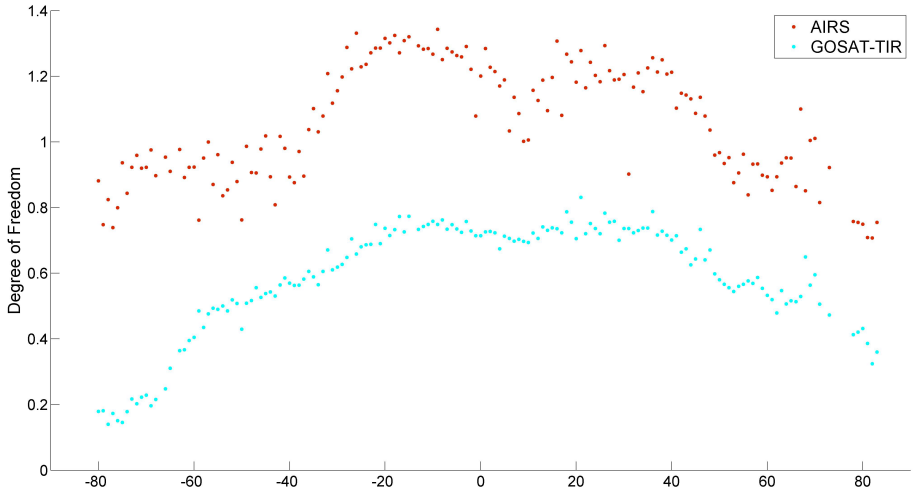

Figure 5. Latitudinal variation of DOF for AIRS and GOSAT TANSO-FTS V1.0 CH_4 retrievals on 4 September 2010.

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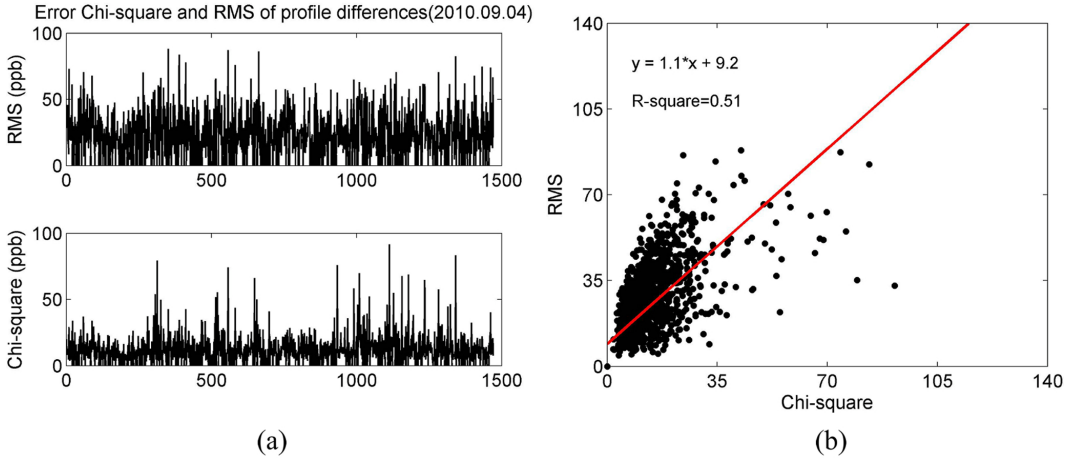

Figure 6. Comparison of the RMS difference and error chi-square of retrieved CH_4 profiles from AIRS and GOSAT-TIR. **(a)** The upper panel shows the RMS of CH_4 profile difference and the lower panel is the error chi-square, **(b)** the scatter plot of RMS difference and error chi-square.

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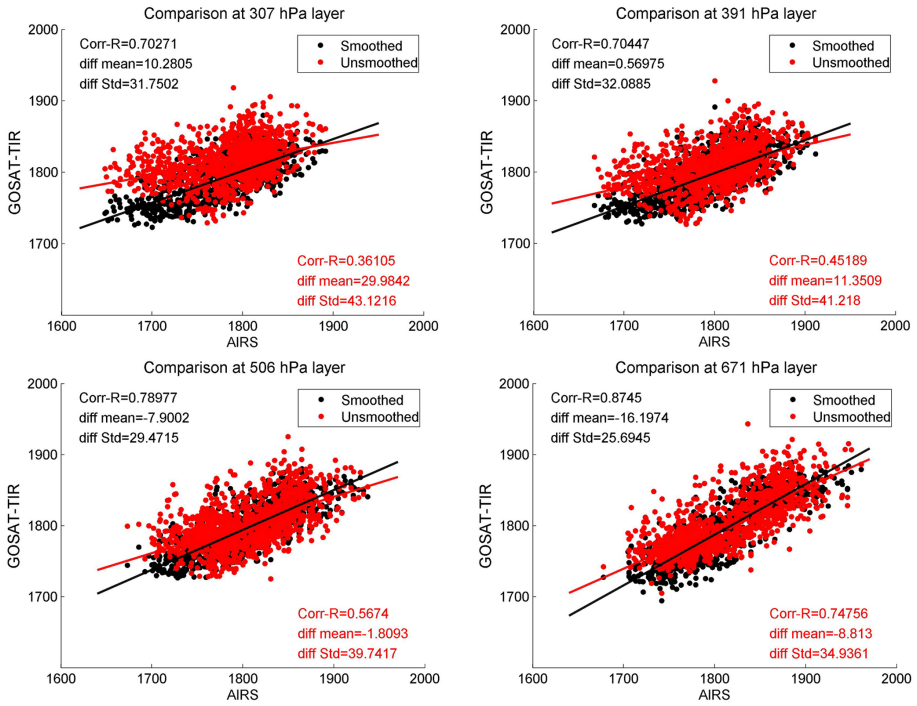

Figure 7. Comparisons of AIRS and GOSAT TANSO-FTS TIR smoothed CH_4 at four retrievals levels of 272–343, 343–441, 441–575 and 575–777 hPa (the mean effective pressures are 307, 391, 506 and 671 hPa respectively).

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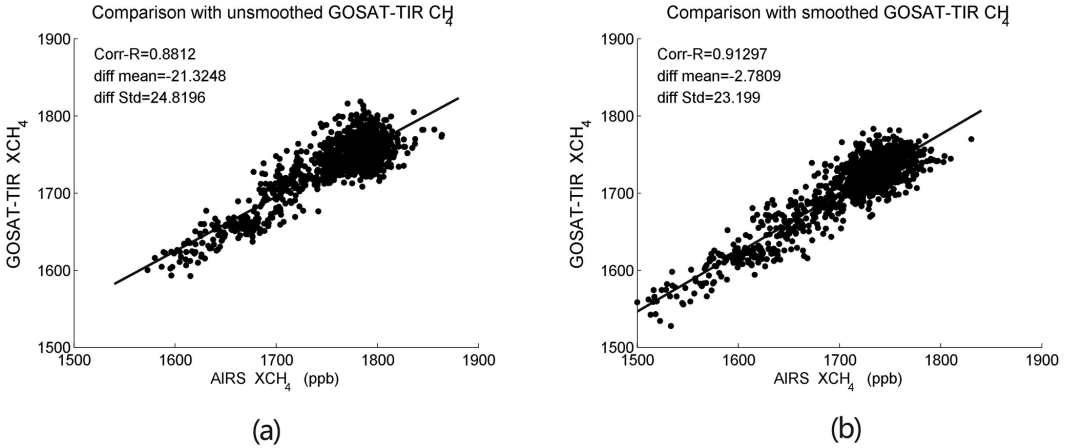

Figure 8. Comparison of X_{CH_4} between AIRS and **(a)** unsmoothed GOSAT TANSO-FTS TIR X_{CH_4} and **(b)** smoothed GOSAT-TIR X_{CH_4} using AIRS averaging kernel. Global data on 4 September 2010 are used.

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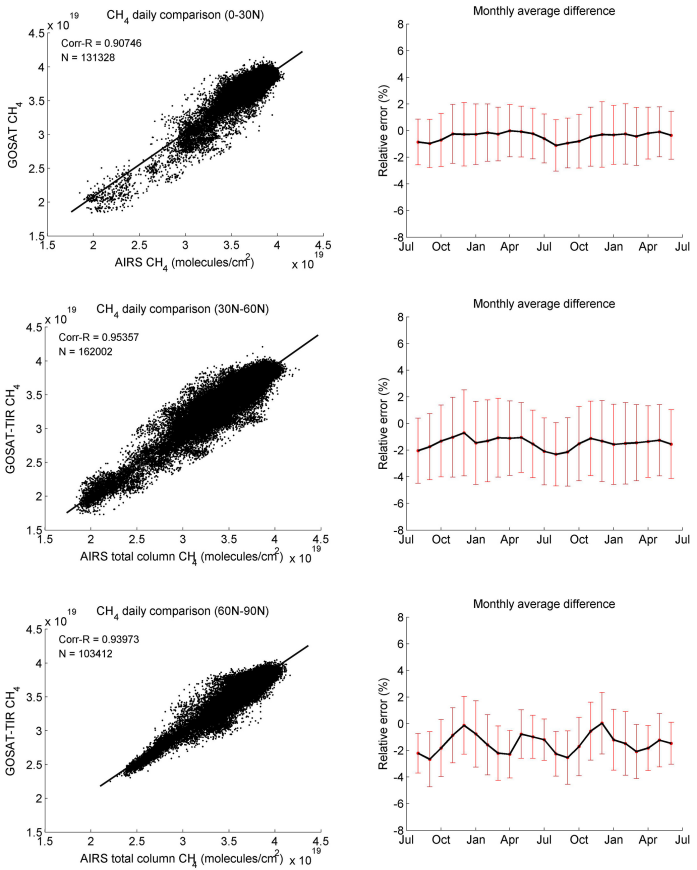

Figure 9. Scatter plot of AIRS vs. GOSAT TANSO-FTS TIR CH_4 total column density over 3 latitude zones in the Northern Hemisphere using data from 1 August 2010 to 30 June 2012 (left panels). Right panels show the variation of the mean difference r in each month, and the bars are the standard deviation.

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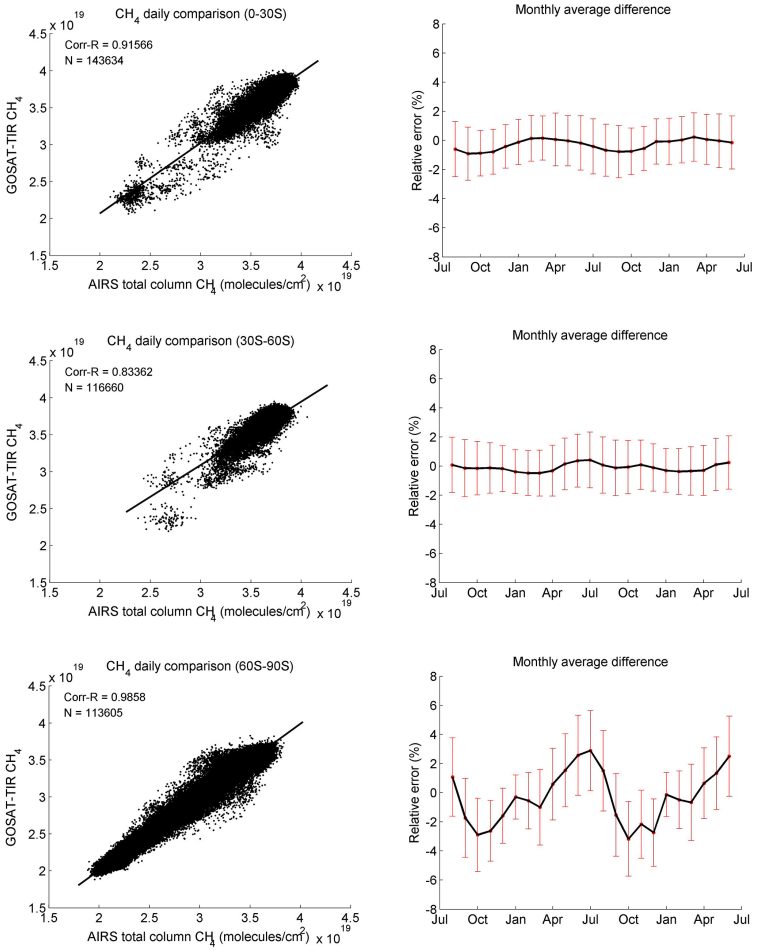

Figure 10. Same as Fig. 8 but for 3 latitude zones in the Southern Hemisphere.

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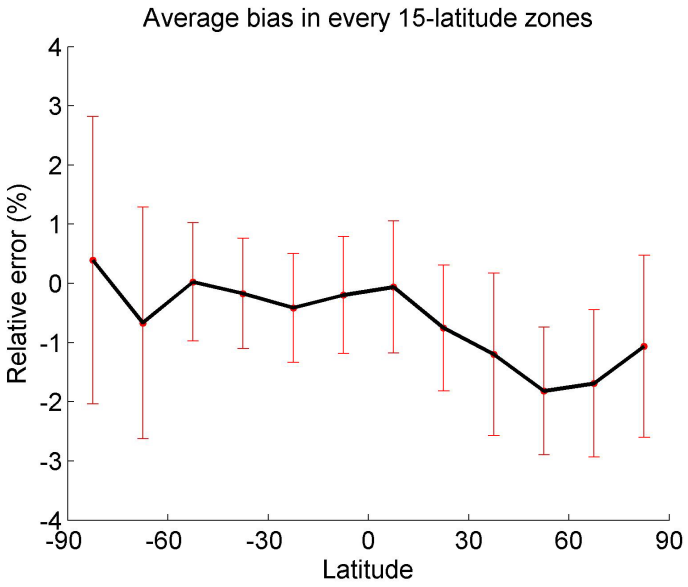

Figure 11. Errors of GOSAT-TIR total column CH_4 relative to AIRS total column CH_4 in different latitude using data from 1 August 2010 to 30 June 2012.

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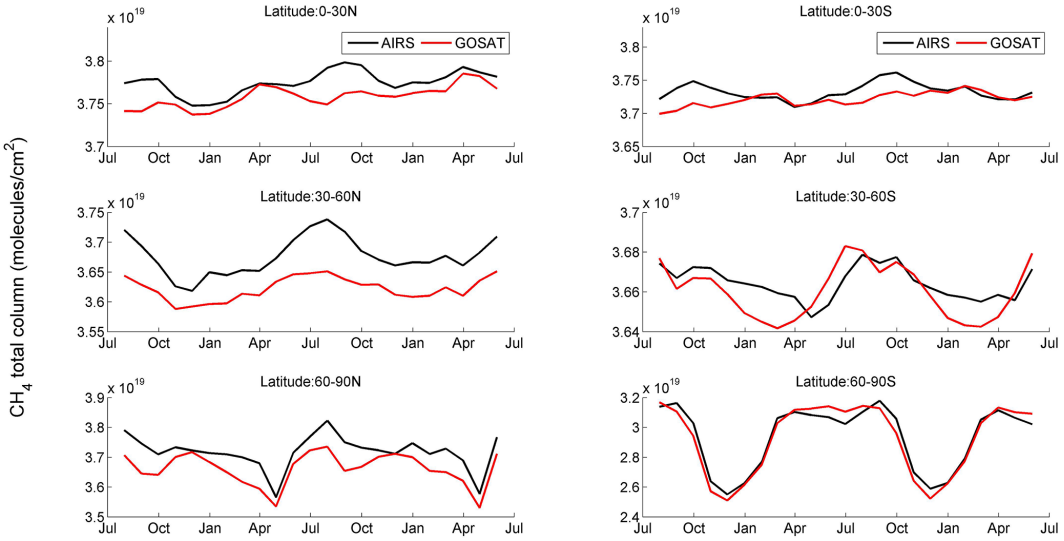

Figure 12. Trends of CH_4 monthly-average total column amounts in different latitudes using AIRS and GOSAT-TIR products from 1 August 2010 to 30 June 2012. The left panels are the comparison in the Northern Hemisphere and the right panels are the comparison in the Southern Hemisphere.

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