Comparison of Atmospheric Methane Retrievals From AIRS and IASI

Xiaozhen Xiong, Yong Han, Quanhua Liu, and Fuzhong Weng

***Abstract*—Atmospheric methane (CH_4) is a standard product of the atmospheric infrared sounder (AIRS) aboard NASA's Aqua satellite, generated at the NASA Goddard Earth Sciences Data and Information Services Center (NASA/GES/DISC), and a product of the infrared atmospheric sounding interferometer (IASI) aboard METOP-A,-B, generated at National Oceanic and Atmospheric Administration's Comprehensive Large Array-data Stewardship System. In order to understand the capability of these two sensors in observing the spatial and temporal distribution of CH_4, this paper compares the CH_4 products from AIRS and IASI with aircraft measurements, as well as the corresponding time series in tropics and high northern latitude regions. It is found that the mean degree of freedom from AIRS is smaller than IASI by –0.049 $\pm$ 0.152, and in their peak sensitive altitude between 350 and 650 hPa their difference (AIRS – IASI) is about 2.8 $\pm$ 17.2 ppb. Both AIRS and IASI can capture the latitudinal gradient, but there is a large scattering in the high northern latitude regions. They agree well in observing the summer enhancement of CH_4 during the Monsoon season over South Asia, and the seasonal cycles over Siberia (except for a relatively larger difference in the cold season). These results highlight that AIRS and IASI can provide valuable information to capture the spatiotemporal variation of CH_4 in the mid-upper troposphere in most periods and regions, but it is needed to further improve the data quality to make a consistent product using both sensors.**

***Index Terms*—Gases, infrared sensors, remote sensing, satellites.**

I. Introduction

As the third most important long-living greenhouse gas, atmospheric methane (CH_4) plays an important role in atmospheric chemistry and absorbing long-wave radiation that warms the atmosphere. The concentration of CH_4 in the atmosphere has increased from the preindustrial levels of about 700 parts per billion (ppb) to the current of 1800–1900 ppb, which is believed to be mainly attributed to the impact of human activities. Accurate measurements of CH_4 in the boundary layer of the troposphere have been made from ground-based networks for over 25 years, such as the measurements from National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory/Global Monitoring Division networks and other sites under the umbrella of the World Meteorological Organization Global Atmosphere Watch programme [1]–[3]. However, due to the limited distribution of those stations over the globe and sampling of measurements, the quantification of different CH_4 emission sources in different regions still has large uncertainties [4]. Such uncertainty is also evident from the studies on the causes of the recent CH_4 rapid increase observed beginning in 2007 and the following years [3], [5], [6].

Recent improvements in sensor technology, particularly the increase of spectral resolution, make space-borne measurements of CH_4 from satellites more reliable. A review of the most instruments can be found in [7]. Measurements of Pollution in The Troposphere (MOPITT) is an instrument flying on NASA's Earth Observing System Terra spacecraft, measuring tropospheric carbon monoxide (CO) on the global scale, but there is no operational MOPITT product for methane, due to a variety of problems with the methane-channel radiances [8]. Of these concurrent measurements with operational products, one type is using hyperspectral thermal infrared (TIR) sensors, such as the atmospheric infrared sounder (AIRS) on NASA/Aqua [7], [9], the tropospheric emission spectrometer on NASA/Aura [10], the infrared atmospheric sounding interferometer (IASI) on METOP-A and METOP-B [11]–[13], and the thermal and near-infrared sensor for carbon observation onboard the Greenhouse gases Observation SATellite (GOSAT) from 2009 till present [14]. With their large spatial and temporal coverage, these satellite sensors provide complementary measurements with respect to surface and airborne observations of atmospheric CH_4.

Several previous studies have demonstrated the capability to use satellite observations from AIRS [15] and IASI [12] to capture the enhancement of CH_4 in the middle-upper troposphere over South Asia and during the Monsoon season, which has a good agreement with aircraft measurements [16]. Following [15], the reasons for this enhancement are mainly due to the dynamic transport associated with the strong upwelling convection over the Tibetan Plateau and the confinement by the strong Asian Monsoon anticyclone, while the impact of the enhanced emission from rice paddies is secondary.

The Arctic has experienced the fastest warming compared to other regions over the globe. The thawing of subarctic peat land permafrost was observed to accelerate over the last 50 years in the discontinuous permafrost zone of northern Canada (53–58°N) [17]. The carbon-rich arctic soils and lakes are underlain with either continuous or discontinuous permafrost, thereby constituting a large reservoir of carbon. Shakhova *et al.* [18] reported convincing evidence of CH_4 outgassing from the Arctic continental shelf of northeastern Siberia (Laptev and East Siberia Sea), and they estimated the

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annual outgassing to the atmosphere to be ~8 Tg C. An increase in permafrost degradation and the shoreline erosion of existing lakes, along with the formation of new permafrost-thawing lakes, is expected due to continued climate warming, and these changes could increase CH_4 emissions and become a positive feedback to increase global warming. Since it is difficult to observe the temporal and spatial variation of CH_4 in the pan Arctic regions by ground-based instruments, it is worthy to explore the capacity of satellite measurements. Xiong *et al*. [19] demonstrated that, in agreement with aircraft measurements and model simulations, an abnormal seasonal cycle in the mid-upper troposphere is captured from AIRS observations, and this seasonal cycle reflects the strong surface emission of CH_4 and its transport to the upper troposphere in the summer. However, the reasons for the observed peaks of CH_4 from AIRS in the period from late winter to early spring are not clear, and it might be associated with some unknown emission sources (e.g., the use of energy or gas leakage) during this period, and/or the larger retrieval uncertainties in the polar winter season [19].

To better understand the capability of TIR measurements in observing the spatial and temporal variation of CH_4 in the mid to upper troposphere, in this study we compare both AIRS and IASI with aircraft measurement data and analyze the time series of AIRS and IASI observations in the tropics and high latitude regions. Section II gives a brief introduction to AIRS and IASI instruments and algorithms, the data used and the comparison method. Section III shows the comparison results. A summary and discussion are given in Section IV.

II. Data and Method

AIRS was launched in polar orbit (13:30 LST, ascending node) on the EOS/Aqua satellite in May 2002. It has 2378 channels covering 649–1136, 1217–1613, and 2169–2674 cm^{-1} at high spectral resolution ($\lambda/\Delta\lambda = 1200$). 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. IASI is a cross-track scanning Michelson interferometer that measures 8461 channels at 0.25 cm^{-1} spacing in three bands between 645 to 2760 cm^{-1} in a 2×2 array of circular footprints with a nadir spatial resolution of roughly 50 km $\times$ 50 km (with a corresponding single footprint spatial resolution at nadir of roughly 12 km). IASI on the Metop-A platform of the European Organization for the Exploitation of Meteorological Satellites was launched into a 817 km altitude polar orbit on 19 October 2006, and Metop-B was launched on Sept. 17, 2012. The satellites cross the equator at approximately 9:30 A.M. and 9:30 P.M. local time. Like AIRS, IASI has a wide swath with a scan angle of $\pm 48.3°$. Its nominal scan line covers 30 scan positions toward the Earth with four instantaneous IFOV.

The Advanced Microwave Sounding Unit (AMSU) is flying on both platforms with AIRS and IASI. In order to retrieve CH_4 in both clear and partial cloudy scenes, nine AIRS fields of view (FOVs) within the footprint of 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 for retrieving profiles with a spatial resolution of about 45 km for AIRS. Different from AIRS, four IASI FOVs within the footprint of AMSU are used. The retrieval algorithm for both AIRS and IASI is a sequential retrieval with multiple steps, in which the temperature and water vapor profiles, surface temperature and surface emissivity are retrieved first using channel subsets optimized for the component being retrieved. For simplicity, these products before the CH_4 retrieval are referred to the "upstream products." The CH_4 retrieval is performed on the basis of successful retrievals of the water vapor profile, the temperature profile, and surface characteristics, and can work under clear and partially cloudy conditions.

In this study, the AIRS data used are from AIRS level-2 version 6 supporting products AIRX2SUP.v006, downloaded at NASA Goddard Earth Sciences Data and Information Services Center (NASA/GES/DISC) (http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings/by-data-product-V6), and the IASI data are from IASI on Metop-A products, downloaded from NOAA's Comprehensive Large Array-data Stewardship System (http://www.nsof.class.noaa.gov/saa/products/search?datatype_family = IASI). The CH_4 retrieval algorithms for AIRS and IASI are almost the same, including the use of the first-guess profile of CH_4. One major difference is related to the upstream retrieval products of temperature and moisture profiles. As in the AIRS-V6 algorithm, the first-guess temperature and water vapor profiles are derived from the neural network [20], while in the IASI algorithm, the regression method is used as in AIRS-V5. The improvements in the first-guess temperature and water vapor profiles in AIRS-V6 greatly help to improve AIRS-V6 temperature and water products [21]. This in turn helps to improve the CH_4 retrieval in AIRS-V6. It was found that the errors of AIRS-V6 CH_4 in layers 343–441 and 441–575 hPa are –0.76 $\pm$ 1.56% and –0.05 $\pm$ 1.16%, respectively [9], while the errors of IASI CH_4 in layers 374–477 and 596–753 hPa are –1.74 $\pm$ 1.20%, and –0.69 $\pm$ 1.07%, respectively [13]. The retrieval errors increase in the high northern latitude regions and/or under cloudy conditions. More details about the CH_4 retrieval algorithms and the validation results for the CH_4 products from AIRS-V6 and NOAA IASI can be found in [9] and [13], respectively.

Since the aircraft measurements from different campaigns were used for AIRS [9] and IASI CH_4 validations [13], a simple comparison of the results from these two papers cannot tell the difference of the products between these two instruments accurately. In this study, we focus on the direct comparison of AIRS and IASI CH_4 products against the same matched up aircraft measurements of the CH_4 vertical profiles by the HIAPER Pole-to-Pole Observations (HIPPO) program over the Pacific Ocean [22]. One advantage of HIPPO measurements is their coverage in a wide latitudinal range. The National Science Foundation's Gulfstream V (GV) was used during all five HIPPO missions. The GV transected the Pacific Ocean from 85°N to 67°S, performing in-progress vertical profiles every 220 km or 20 min [22], [23]. CH_4 was measured with a quantum cascade laser spectrometer at 1 Hz frequency with accuracy of 1.0 ppb and precision of 0.5 ppb. In this study, HIPPO data were downloaded from http://hippo.ornl.gov/dataaccess. Fig. 1 shows their spatial locations on the globe. The aircraft measurements of HIPPO-1 were taken from January 8 to January 30, 2009, HIPPO-2 from

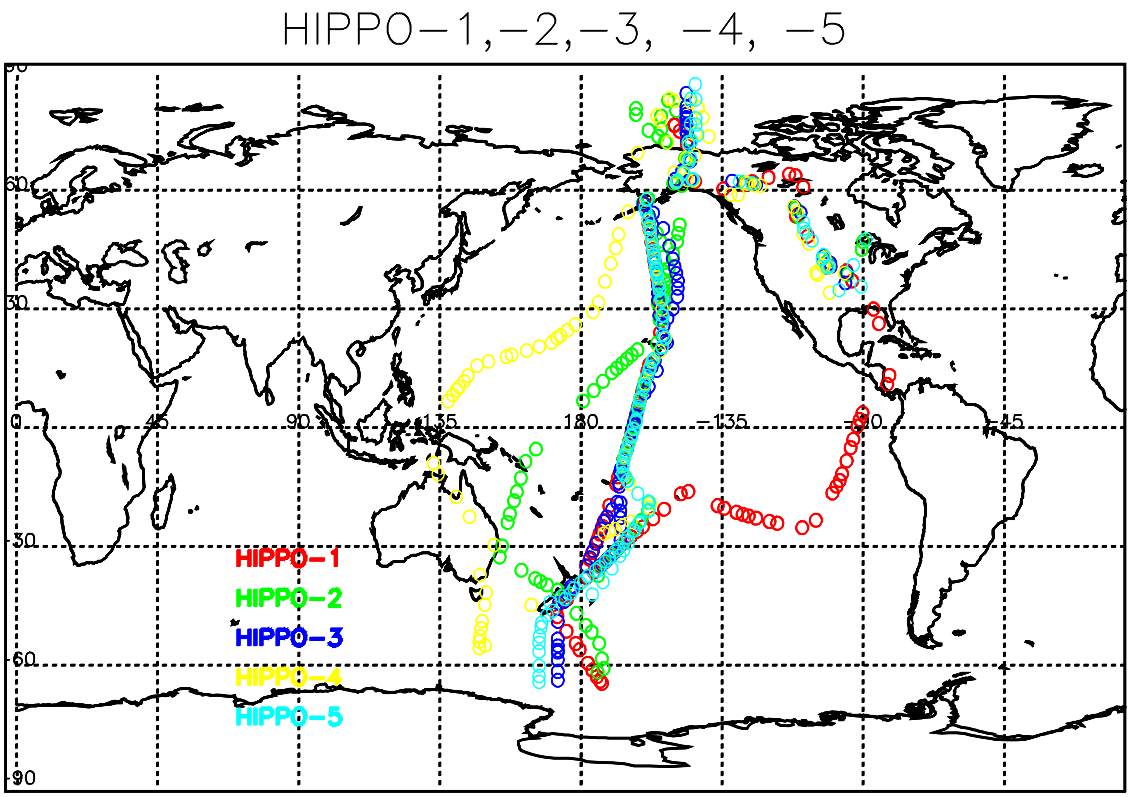

Fig. 1. Locations of aircraft measurement profiles selected for validation from HIPPO-1 (red), HIPPO-2 (green), HIPPO-3 (blue), HIPPO-4 (yellow), and HIPPO-5 (cyan).

October 31 to November 22, 2009, HIPPO-3 from March 24 to April 16, 2010, HIPPO-4 from June 14 to July 11, 2011, and HIPPO-5 from August 9 to September 8, 2011. We used the AIRS or IASI retrievals within 250 km from HIPPO measurements on the same day. The averages of these match-up AIRS and IASI data were compared by each other. Another potential error source is the temporal gap of a few hours between AIRS, IASI and aircraft measurements, which has been taken into account in this study.

Due to the limit of information content in infrared sounding, the vertical resolution of satellite measurements is much coarser than aircraft measurements. Rodgers and Connor [24] use the averaging kernel to smooth high-resolution profile measurements to the vertical resolution of remotely sensed measurements through the following equation:

$$\hat{x} = Ax + (I - A)\, x_a \tag{1}$$

where $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{A}$ is the averaging kernel matrix, $\boldsymbol{x}_{\mathrm{a}}$ is the first guess profile (unit: part per billion, ppb), and $\boldsymbol{x}$ is the *in situ* aircraft measurement profile (unit: ppb). The CH_4 first guess profile ("*a priori*") is a function of latitude and pressure and was generated through a nonlinear polynomial fitting [7]. The averaging kernels, $\boldsymbol{A}$, are defined to provide a simple characterization of the relationship between the retrieval and the true state, and are computed as the retrieval operator or gain matrix, multiplied by the derivatives matrix. More detail of the computation of averaging kernels can be found in [25]. The degree of freedom (DOF) is computed as the trace of the averaging kernel matrix.

In this paper, the computed value of $\hat{x}$ will be compared with the retrieved CH_4 mixing ratio. As the aircraft profiles do not span the entire vertical range defined by the averaging kernels, an extension of the aircraft profiles, which is usually made using the output from a chemistry model or climatology, is required. In this paper, we used the monthly averaged CH_4 data from 2007 from an atmospheric general circulation model-based chemistry transport model [26] to extrapolate from the ceiling of the aircraft profiles, which are mostly above 300 hPa, to the top of atmosphere, and extrapolate from the lowest height of aircraft profile, which are mostly below 950 hPa, to the bottom of the atmosphere. If the top of the profile from aircraft measurements is lower than 400 hPa, it will not be used.

III. Results

Fig. 2 shows the comparison of AIRS and IASI corresponding to 463 HIPPO aircraft measurements. The mean DOF for these profiles from AIRS is slightly smaller than that from IASI, and their difference is –0.049 $\pm$ 0.152. On average, the biases of IASI retrievals are larger (negative) than the retrievals from AIRS in most of layers, and the differences (AIRS-IASI) are 10.2 $\pm$ 23.8 ppb below 650 hPa and 27.4 $\pm$ 26.9 ppb above 350 hPa, respectively. At around 600 hPa, AIRS CH_4 is smaller than IASI, but the mean difference between 350 and 650 hPa is relatively small as 2.8 $\pm$ 17.2 ppb.

To better see the differences between AIRS and IASI retrievals against aircraft measurements, Fig. 3 shows the latitudinal variation of CH_4 at 500 hPa for different seasons. A

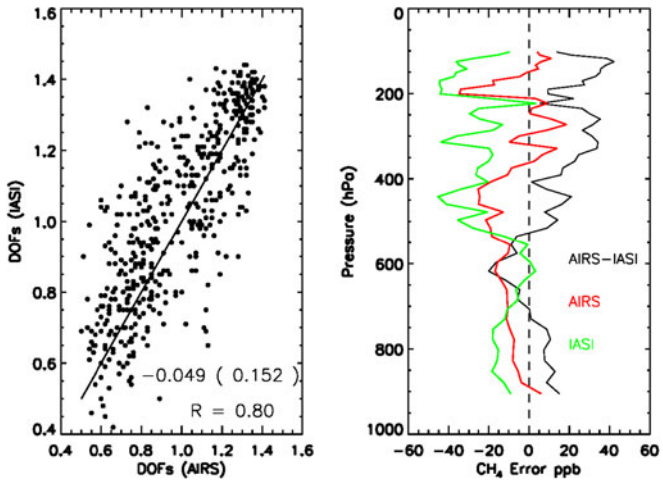

Fig. 2. DOFs of AIRS retrievals versus IASI retrievals for 463 cases corresponding to HIPPO campaign (left panel). The correlation coefficient between AIRS and IASI DOFs is $R = 0.80$. Right panel is the mean biases of AIRS and IASI profiles with respect to aircraft measurements, and the difference between AIRS and IASI.

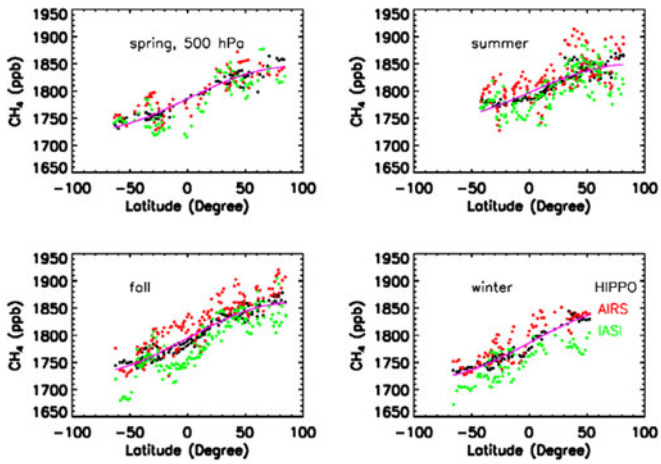

Fig. 3. Comparison among AIRS, IASI, and HIPPO aircraft measurements of CH_4 at 500 hPa for different latitude bands and seasons. The line (magenta) shows the linear fit of a sine function of latitude to aircraft observations.

linear fit to HIPPO measurements as a sine function of latitude, sin(lat), is added in Fig. 3. Overall, the seasonal gradient is well caught by both AIRS and IASI, and the mean mixing ratio of AIRS CH_4, averaged using the data in all latitudes and seasons in Fig. 3, is larger than the mean of aircraft measurements by 12.64 ± 21.47 ppb, and the mean of IASI CH_4 is smaller than aircraft measurements by –16.06 ± 23.07 ppb. The scatter is larger in the high northern latitude regions above 55°N, where, on average, IASI CH_4 is lower than AIRS CH_4 by 29.04 ± 25.82 ppb. Analysis of the correlation between AIRS and aircraft measurements shows the correlation coefficient is 0.86 for the regions below 55°N, and 0.68 for the high latitude regions above 55°N, and the correlation coefficients between IASI and aircraft measurements are 0.85 and 0.27, respectively. For the regions below and above 55°N, the correlation coefficients between AIRS and IASI are 0.81 and 0.41, respectively. The smaller correlation coefficients in high northern latitude

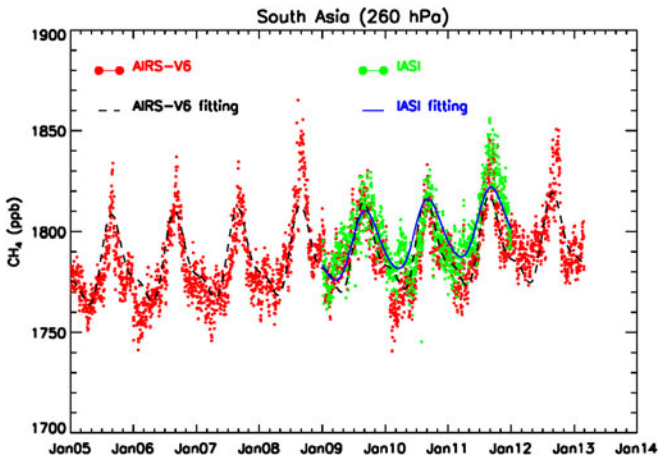

Fig. 4. Comparison of the seasonal cycles of CH_4 at 260 hPa from AIRS and IASI over South Asia. Each point shows the area average over South Asia using the ascending data on each day. The fittings to AIRS and IASI CH4 were made using sinusoidal functions of time (see Eq. (2)).

regions above 55°N may indicate that there is a larger uncertainty of the retrievals in high northern latitude regions for AIRS and IASI. IASI seems not to be able to capture the real variation of CH_4 in this region since the correlation coefficient is as low as 0.27. Among different seasons, the correlations between AIRS, IASI and aircraft measurements are the best in the fall and the worst in the summer. The disagreement among them in the summer in the high northern latitude regions can be partly due to the large surface emissions, which lead to a larger spatial and temporal variation of CH_4 in the atmosphere. Under this situation, the time difference between satellite observations and aircraft measurements is an important factor that needs to be considered. The stratosphere to troposphere transport also has some impact [27] and is another potential error source if the air masses observed by AIRS and IASI are different.

Note that the samples shown in Fig. 3 lie mostly over the ocean. The following analysis of time series and seasonal cycles will focus on the CH_4 over land. Since the peak sensitive layer near the tropics is at a higher altitude range than in the high latitude regions [9], we used the data of South Asia and Siberia in two different altitude layers. As illustrated by Xiong *et al.* [15] and Crevoisier *et al.* [12], the CH_4 enhancement over South Asia is evident in the upper troposphere during Monsoon season. Thus, the time series of CH_4 at 260 hPa over South Asia (20–35°N, 80–110°E) from AIRS and IASI are compared against each other (see Fig. 4). The area average of the retrieved CH_4 from the ascending node is used. AIRS and IASI agree well in capturing the enhancement of CH_4 from June to September, with the maximum occurring at late August to early September [15], [16]. With declining Monsoon and dissipation of the respective anticyclone in September, the plume over South Asia disappears quickly. To model the seasonal cycles, we tried to use sinusoidal functions of time to fit the time series of CH_4 as follows:

$$Y = a0 + a1 * \mathrm{t} + \mathrm{a2} * \sin(2\pi t) + a3 * \cos(2\pi t) + a4 * \sin(4\pi t) \quad (2)$$

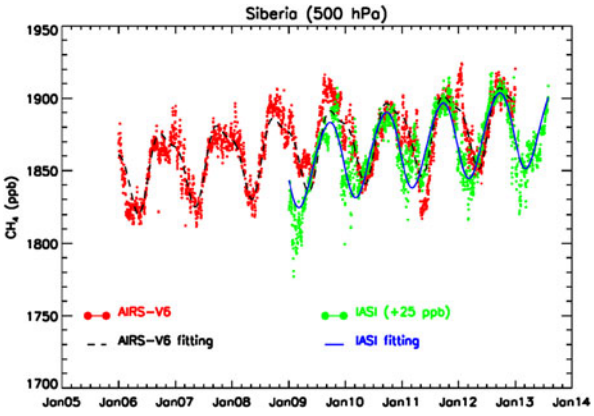

Fig. 5. Same as Fig. 4 but using data at 500 hPa over Siberia. 25 ppb is added to IASI data.

where Y is the CH_4 concentrations, a0, a1, a2, a3, and a4 are constants, and t is the decimal year. From the difference between AIRS measurements and the fitting, a rapid increase of CH_4 is evident in 2008 and 2011. The annual increase rates of CH_4 are 12.8 ppb from 2007 to 2008 and 11.2 ppb from 2010 to 2011, respectively. Similarly, an annual increase rate of 14.7 ppb from 2010 to 2011 is found from the IASI measurements. The major difference in the seasonal cycles between AIRS and IASI occurs in the spring where the IASI CH_4 is higher than AIRS CH_4. The reason for this difference in the spring is not quite clear, but it demonstrates a larger uncertainty in the cold season, which might be associated with the lower sensitivity of the retrievals when the thermal contrast is low and the surfaces (e.g., mountains) are covered by snow and ice. More investigation needs to be done by checking individual profiles and their quality flags. However, compared to AIRS V6, the quality flags of IASI retrievals are insufficient.

Since the peak sensitive layer for both instruments is at about 500 hPa in the high northern hemisphere, Fig. 5 shows the time series of CH_4 at 500 hPa over Siberia (50–70°N, 75–170°E) from AIRS and IASI retrievals. In agreement with Fig. 3, the IASI CH_4 is systematically lower than AIRS CH_4. Therefore, in this figure, a bias of 25 ppb is added to IASI retrievals. Overall their seasonal cycles look similar, with the maxima occurring in August and September. However, the minimum of AIRS CH_4 is in May, and the minimum of IASI is in winter. There are more spikes of large CH_4 observed in December and January by AIRS [19] than IASI. The relatively larger difference between IASI and AIRS in the period from winter to early spring is likely associated with the larger uncertainties of both retrievals. As we know, the thermal contrasts and the DOFs of retrievals are small when the surfaces are covered by snow/ice in the cold season in the Arctic [9]. The impact of cloud contamination on the retrieval of IASI is likely larger than for AIRS since AIRS uses nine FOVs and IASI uses four FOVs corresponding to one AMSU footprint for cloud-clearing algorithm to eliminate the impact of cloud in each FOR. Due to the limited aircraft measurements that can be used for validation in the Arctic, particularly in the cold season, more work needs to be done for validation and improvements to the algorithms and quality control.

IV. Summary and Discussion

The hyperspectral infrared sounder AIRS has provided over 13 years of CH_4 measurements since August 31, 2002. IASI has provided similar measurements since 2008. Measurements can be continued using the cross-track infrared sounder on the Suomi National Polar-orbiting Partnership Satellite, whose full spectrum data are available since December 4, 2014, and JPSS series. With these hyperspectral infrared thermal sensors, a long-term data record of at least two decades will be available to monitor the global distribution of CH_4 in the mid-upper troposphere. This study compared the atmospheric CH_4 from AIRS and IASI using the data matched with aircraft measurements. We also discussed the time series between AIRS and IASI measurements in the tropics and high latitude regions.

Comparison between AIRS and IASI retrievals of CH_4 against the coincident aircraft measurements shows that the mean DOF from AIRS is slightly smaller than IASI by 0.049 ± 0.152. In their peak sensitive altitude between 350 and 650 hPa, the difference of the retrieved CH_4 between AIRS and IASI, on average, is rather small, but the mean AIRS CH_4 is larger than IASI by 10.2 ± 23.8 ppb below 650 hPa and 27.4 ± 26.9 ppb above 350 hPa. Both AIRS and IASI can capture the latitudinal gradient, but comparison to HIPPO aircraft measurements shows the agreement between them is worse at high northern latitude regions. Comparison of the CH_4 time series observed by AIRS and IASI shows that they agree well over South Asia, particularly in the observed summer enhancement during the Monsoon season. Over Siberia their seasonal cycles are also similar but there are larger differences in the cold season.

The differences between AIRS, IASI and aircraft measurements can be attributed to the time difference between these measurements, and to differences in the retrievals, such as the input temperature and water vapor profiles and the radiative transfer models used. The retrieval accuracy is also impacted from the instrument itself, which includes the uncertainty in the observed radiances associated with the noise and calibration, as well as the error in cloud-clearing which used nine FOVs for AIRS and four FOVs for IASI within one AMSU footprint to remove the impact of clouds. Quality control should be improved, particularly for IASI products.

From the correlation between AIRS and IASI retrievals and the seasonal variations of CH_4 they observed, we are confident that the TIR measurements from AIRS and IASI can provide valuable information to capture the spatial and temporal variation of CH_4 in most periods and regions.

The disagreement between AIRS, IASI and aircraft measurements suggest that more work in validation and further improvements in the retrieval algorithms need to be done, particularly in the high northern hemisphere where the surface emissions are large and more sensitive to global warming. Improvements in the spectroscopy of CH_4 peak absorption channels near 1306 μm and the quality control are mandatory [9]. Some improvements in the algorithm by using an adjustable constraint parameter are desirable [13] since the information contents of retrievals have a large spatial and temporal variation.

Finally, we need to emphasize that IASI CH_4 data used in this paper are from NOAA. There are a few groups in Europe that have developed IASI CH_4 products using different algorithms and different forward radiative transfer models for example [11], [12]. Comparison of the IASI CH_4 products from NOAA with other products might help researchers to better understand the characteristics and difference of these products.

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