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The 2007–2011 evolution of tropical methane in the mid-troposphere as seen from space by MetOp-A/IASI

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Abstract

Since July 2007, monthly averages of mid-tropospheric methane are retrieved in the Tropics over land and sea, by day and night, from IASI onboard MetOp-A, yielding a complete view of the geographical distribution, seasonality and long-term tendency of methane in the mid-troposphere. Retrieved methane displays a clear seasonal cycle of ~25 ppbv in the Northern Tropics, with a maximum in November and a minimum in April–May, a more complex cycle of ~15 ppbv in the Southern Tropics, and a south-to-north latitudinal variation of ~30 ppbv, in good agreement with regular aircraft measurements of the CONTRAIL program. Comparisons with CARIBIC aircraft measurements made at ~11 km yield an averaged difference between collocated IASI estimates and CARIBIC measurements of 7.2 ppbv with a standard deviation of 13.1 ppbv, and show that IASI captures well the evolution of mid-tropospheric methane. In particular, in 2007 and 2008, IASI shows an increase of mid-tropospheric methane in the tropical region of 9.5 ± 2.8 and 6.3 ± 1.7 ppbv yr^{-1} respectively, in excellent agreement with the rate of increase measured at the surface after almost a decade of near-zero growth. IASI also indicates a slowing down of this increase in the following years to ~2 ppbv yr^{-1}, with the highest increase in 2010. Assuming that the recent evolution of methane is mostly due to an increase in surface emissions, IASI might indicate a decrease in tropical wetland emissions for the period 2009–2011, in agreement with decreasing tropical precipitation over this period, together with an increase in biomass burning emissions in 2010 in the Southern Tropics.

1 Introduction

Methane (CH_4) is the third most important greenhouse gas in the atmosphere, after water vapor and carbon dioxide (CO_2), and is responsible for about 20 % of the total radiative forcing by long-lived greenhouse gases (Hofmann et al., 2006). On a per molecule basis, its global warming potential is even greater than for CO_2 (IPCC, 2007).

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Moreover, methane plays a significant role in tropospheric chemistry through its removal of OH that increases its radiative forcing by indirectly increasing the radiative forcing of ozone and stratospheric water vapor. There is therefore a considerable interest in monitoring the evolution of atmospheric methane to better characterize its atmospheric budget and infer how it might evolve in the future.

The average concentration of atmospheric methane stems from the sum of all its sources and sinks and mostly reflects the balance between emission from the surface and destruction by OH in the troposphere. Methane is emitted at the surface by several natural and anthropogenic sources (Matthews and Fung, 1987). The largest source of methane comes from natural wetlands (Ringeval et al., 2010), mostly in the tropical region, but also at mid-to-high northern latitudes. Major anthropogenic sources include coal mining, natural gas losses, solid waste burning and also emissions from ruminant animals, rice paddies and biomass burning. All together, global emissions of methane range from 500 to 600 Tg $CH_4\,yr^{-1}$ (IPCC, 2007). But the partition of the global emissions between these various sources, as well as the impact of human activities on these sources, remain poorly known. Most of the emitted CH_4 is destroyed in the atmosphere by the chemical reaction with tropospheric OH that accounts for 450–520 Tg $CH_4\,yr^{-1}$ and happens predominantly in the Tropics (Fung et al., 1991).

Over the last decades, the atmospheric methane burden has undergone a series of significant changes. Its global average has more than doubled since the beginning of the industrial era (Cunnold et al., 2002) with a persistent increase since the 1970s (Dlugokencky et al., 1994), but the rate of increase in CH_4 has been steadily decreasing since the late 1980s (Steele et al., 1992), reaching a near-zero increase from 1999 to 2006 (Dlugokencky et al., 2003; Worthy et al., 2009). Several hypotheses have been proposed to explain the atmospheric methane budget and its interannual and long-term variations: changes in various sources (for instance wetland emissions, Mikaloff-Fletcher et al., 2004; Bousquet et al., 2006, anthropogenic emissions, Dlugokencky et al., 1994, wild fires, Langenfelds et al., 2002), and changes in OH photochemistry (Dentener et al., 2003). From the end of 2006 or beginning of 2007, a renewed growth

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of atmospheric CH_4 has been observed by surface networks until the most recent measurements (Rigby et al., 2008; Dlugokencky et al., 2009; Terao et al., 2011), potentially stemming from a combination of a slight change in OH, and increased emissions in Northern high and low latitude regions (Bousquet et al., 2011). This increase has also been observed in 2007–2009 on total columns of methane retrieved, mostly over land, from near infrared observations by the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) instrument on board the European Space Agency's environmental research satellite (ENVISAT) (Frankenberg et al., 2011).

Although the current surface atmospheric measurement networks allow to monitor the average evolution of atmospheric methane, it is not sufficient to fully describe the global atmospheric methane burden and to resolve methane surface fluxes. This is particularly true in the Tropics: despite the fact that natural tropical sources are believed to be the largest methane sources (natural wetlands, rice paddies in Asia, biomass burning), their emissions are not well captured by the current surface stations networks because of its scarcity and because of intense convective mixing which dilutes the signal of surface fluxes in the air column, causing a smaller sensitivity of surface stations to CH_4 sources. Another major flaw in the current network is that measurements have mostly been made at the surface and therefore lack the information in the free troposphere despite the major role this part of the atmosphere plays in the atmospheric budget of methane through tropospheric chemistry. This is particularly true in the Tropics where more than half of the total destruction of CH_4 by OH occurs (Fung et al., 1991). Here, we present more than 4 yr of mid-tropospheric methane derived from the Infrared Atmospheric Sounding Interferometer (IASI) over the Tropics, spanning July 2007–December 2011, from which we infer characteristics of tropospheric methane and its most recent evolution.

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2 Method and data

2.1 IASI

IASI, developed by CNES in collaboration with EUMETSAT, is a Fourier Transform Spectrometer based on a Michelson Interferometer coupled to an integrated imaging system that measures infrared radiation emitted from the Earth. IASI provides 8461 spectral samples, aligned in three bands between 645.00 cm^{-1} and 2760.00 cm^{-1} (15.5 µm and 3.63 µm), with a spectral resolution of 0.50 cm^{-1} after apodisation and a spectral sampling interval of 0.25 cm^{-1}. IASI was launched on October 2006 onboard the European MetOp-A platform and declared operational in July 2007. Since then, it has been providing water vapour and temperature soundings for operational meteorology, while observing simultaneously the most important trace gases (Hilton et al., 2012).

2.2 Methane retrieval process

As described in details in Crevoisier et al. (2009a), use is made of 10 IASI channels located in the 7.7 µm spectral region that are mostly sensitive to CH_4 and, as all infrared channels, to atmospheric temperature. Observations made in the microwave by the AMSU instrument, flying with IASI onboard MetOp-A (both instruments are synchronized), are also sensitive to temperature, but are insensitive to CH_4. Thus, combining IASI and AMSU allows separating the two signals. The retrieval scheme, initially developed to retrieve CO_2 from thermal infrared sounders (Chédin et al., 2003; Crevoisier et al., 2009b), is based upon a non-linear regression inverse radiative transfer model using Multi-Layer Perceptrons. Given that, since the beginning of 2009, AMSU channel 7 has started to degrade and now exceeds specifications, precluding any further use, AMSU 8 has replaced AMSU 7 in the retrieval process described in Crevoisier et al. (2009a).

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In this work, potential radiative systematic biases existing between simulations used to train the networks and observations are computed for each channel by averaging, over the first three years of operation (July 2007–June 2010), the differences between simulations and collocated (in time and space) satellite observations. The simulations are performed using the 4A/OP-2009 forward model (Scott and Chédin, 1981; http://www.noveltis.net/4AOP/), which is based on the updated 2009 version of the GEISA spectroscopic database (available at http://ether.ipsl.jussieu.fr/) (Jacquinet-Husson et al., 2011), and radiosonde measurements from the Analyzed RadioSoundings Archive database (available at http://ara.lmd.polytechnique.fr/) (Scott et al., 2012) as inputs.

Because of the lesser variability of the atmospheric temperature profiles in the Tropics compared to higher latitudes, the decorrelation between temperature and methane signals in the observations is easier to do in the tropical belt, yielding a better precision there. We thus restrict our study to latitudes between 20° N to 20° S. The retrieved CH_4 integrated columns are weighted to the tropical mid-troposphere with peak sensitivity at about 230 hPa (~ 11 km), half the peak sensitivity at 100 and 500 hPa (~ 6 and 16 km), and no sensitivity to the surface. Retrievals are performed over land and sea, night and day at 9:30 a.m./p.m. LT.

2.3 Aircraft and in-situ data

Very few measurements of CH_4 are available in the mid-troposphere, rendering the validation of satellite retrievals as well as model simulations in the mid-troposphere quite delicate. In the following, we will use measurements made by commercial aircrafts in the framework of two programs that provide valuable information about CH_4 variations in the middle troposphere: CONTRAIL (Comprehensive Observation Network for Trace gases by AIrLiner) and CARIBIC (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container). The CONTRAIL project originates from regular in-situ measurements of CO_2 made by commercial airliners of the Japan Airlines (JAL) between Japan and Australia since the mid 1980s (Nakazawa et al.,

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1991; Matsueda et al., 2002; data available at: http://ds.data.jma.go.jp/gmd/wdcgg). In November 2005, the National Institute for Environmental Studies (NIES), the Meteorological Research Institute (MRI), Tohoku University, and Japan Airlines started a new phase of the JAL project called CONTRAIL, expanding the commercial aircraft measurement program to include regular JAL flights from Japan to Europe, North America, and Asia and providing measurements of CO_2, CH_4 and CO (Machida et al., 2007, 2008; Matsueda et al., 2008; Sawa et al., 2008). The acquired air samples are returned to NIES within a day from the sampling, and the mixing ratios of various trace gases including CH_4 are analyzed. The CH_4 mixing ratio of each air sample is determined against the NIES-94 CH_4 scale using a gas chromatograph (Agilent 5890, Agilent Technologies Inc.) equipped with a flame ionization detector (GC-FID) (Tohjima et al., 2002; Machida et al., 2008). According to the results of the 2002–2007 WMO Round-Robin inter-calibration (Zhou et al., 2009), NIES-94 scale is higher than NOAA/GMD scale by 3.5–4.6 ppbv in a range between 1750 and 1840 ppbv.

CARIBIC is a long-term atmospheric measurement program based on the use of a comprehensive scientific instrument package aboard a commercial passenger aircraft operated by Lufthansa (Brenninkmeijer et al., 2007). Its first operational phase was from 1999 through 2001. Since May 2005 the new, extended CARIBIC instrumentation package is employed once per month during regular passenger flights out of Germany to Asia, Africa, North and South America. Both, real-time measurements and air sample collection are performed. The air samples are analysed for a large number of trace gases in several laboratories, including GC-FID analysis of CH_4 (Schuck et al., 2009). CH_4 data are reported on the NOAA/GMD scale, with a precision of 2.2 ppbv.

While comparing IASI and aircraft observations, it must be kept in mind that CONTRAIL and CARIBIC CH_4 is representative of methane at the aircraft altitude ($\sim$ 11 km), whereas IASI gives access to a mid-tropospheric integrated content.

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3 General features of mid-tropospheric CH_4

3.1 Seasonal variations

Figure 1 displays the zonally averaged tropical distribution of methane in the mid-troposphere as retrieved from IASI from July 2007 to December 2011. Several features are summarized in this figure, which can be compared to the zonally averaged representation of the global distribution of methane in the marine boundary layer obtained from surface stations (e.g. Dlugokencky et al., 1994). Methane measured at the surface is generally characterized by low mixing ratios in local summer months, a combined effect of larger sources and stronger chemical losses, and large concentration in winter months, with a decreasing amplitude with latitudes from ∼ 40 ppbv in the Northern Hemisphere (NH) to ∼ 20 ppbv in the Southern Hemisphere (SH). IASI mid-tropospheric methane also displays strong seasonal variations in Fig. 1, with a more pronounced cycle in the Northern than in the Southern Tropics. However, compared to surface data, the amplitude of the cycle is lower and varies from ∼ 25 ppbv in the north to ∼ 15 ppbv in the south.

In the Northern Tropics, the maximum is reached in November and the minimum in March–April. In the Southern Tropics, the seasonal variation is more complex. This may be attributed to the weak seasonal cycle of methane in the SH that makes it sensitive to year-to-year fluctuations of upper-tropospheric winds at ∼ 200 hPa which modulates the inter-hemispheric transport during ENSO phases (Prinn et al., 1992), yielding enhanced exchanges in December–May during cold phases (as in 2007 and 2008), and a cancellation in the Southern Tropics of the summer minimum due to photochemical destruction of methane. Differences in phase and amplitude between surface measurements and IASI mid-tropospheric retrievals might be attributed to the time-lag of the emitted methane when going from the surface to the upper-troposphere, combined with the seasonality of destruction by OH which mostly happens in the free troposphere.

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Figure 2 shows the seasonal cycles in the Northern and Southern Tropics measured by CONTRAIL and retrieved from IASI. Use is made of CONTRAIL flights between Japan and Australia from December 2005 to March 2009. IASI CH_4 retrievals have been averaged over a 20° longitudinal band centered on the flight tracks to get enough data. To ease the comparison a bias of −9 ppbv (3 ppbv) has been added to CONTRAIL data in the Northern (Southern) Tropics. Part of this bias can be attributed to the use of NIES-94 scale to determine CONTRAIL CH_4 mixing ratio. IASI and CONTRAIL cycles agree quite well for the period July 2007–March 2009 when both data are available. This is particularly true in the Northern Hemisphere where the seasonal cycle is well defined. The amplitudes of CONTRAIL and IASI cycles are in good agreement with each other: about 25 ppbv in the Northern Tropics and 15 ppbv in the Southern Tropics. In the Southern Tropics, there seems to be an over-estimation of IASI CH_4 compared to CONTRAIL in August–October 2008. However, such high values of methane are not seen for the other years and seem to be specific of 2008. CONTRAIL data lie in the standard deviation of IASI data.

3.2 Latitudinal variations

A clear interhemispheric variation of mid-tropospheric methane is observed by IASI with a north to south decrease of about 30 ppbv between 20° N and 20° S. As stated in Crevoisier et al. (2009a), this is in excellent agreement with aircraft measurements performed over a few months in 1993 at 10–11 km, which corresponds to the peak of sensitivity of IASI in the channels selected to perform the retrievals, but lower by more than a factor of 2 when compared to the gradient estimated from surface measurements, highlighting the influence of the proximity of emissions to the measurements and vertical mixing. Methane is well-mixed in the Southern Tropics while a gradient persists with methane regularly increasing with latitude in the Northern Tropics.

IASI mid-tropospheric CH_4 is now compared with CH_4 CARIBIC aircraft measurements made at ∼11 km over the African continent during 13 flights spanning the period March 2009–March 2011. Figure 3 shows the daily retrieved IASI CH_4 (two to

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three orbits per day in the region of interest) together with the measured CARIBIC CH_4 (two flights per month, except for November 2010 for which a single flight is available) for 6 consecutive months between November 2010 and March 2011. Difference in the spatial coverage and lack of retrievals because of cloudiness render the comparison between both datasets difficult. Nonetheless, the general features of methane appear to be consistent between IASI and CARIBIC: lower methane in the South than in the North with high values of methane localized in a region between 5° S and 10° N, where large wetland emissions (e.g. Bergamaschi et al., 2007) that are upvected in the mid-troposphere can be found. The general agreement between both datasets is better seen with the monthly averaged CH_4 retrieved from IASI that is also plotted in Fig. 3. In particular, the location of high values of wetland-emitted methane is shown to vary in latitude around the equator: in December, CH_4 is higher between 10° N and the equator, whereas in February–March, higher concentrations are found between the equator and 10° S. This variation is in good agreement with CARIBIC features, even if higher values are measured by the aircrafts than retrieved by IASI. This may be due to the fact that the aircrafts measure methane at one altitude whereas IASI retrievals integrate methane over 6–16 km.

The latitudinal variations of CARIBIC and monthly IASI methane are plotted in Fig. 4, together with the associated standard deviation of IASI retrievals. For this figure, monthly 1° × 1° IASI fields have been collocated with CARIBIC tracks. Once more, both IASI and CARIBIC display similar variations and the aircraft data stay within the monthly variability retrieved from IASI with the two exception of very high values measured locally on 12th December 2010 and 18th January 2011. These two days illustrate the high variability of mid-tropospheric methane that is particularly seen on the two CARIBIC flights performed on 18th and 19th January 2011 (Fig. 4c): between 10° S and 5° S, a more than 60 ppbv difference is observed in methane between the two flights. This difference is consistent with the spatial variability of IASI CH_4 in January displayed in Fig. 3 (third line): lower values of methane are well seen for this month (bluish colours) east of 28° E between 10° S and the equator, whereas high values of

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methane (yellowish colours) are located west of this longitude and are mostly missed by IASI due to persistent cloudiness. Such a structure is in agreement with wind patterns, which display a positive (negative) gyre east and west of this longitude creating two regions of respectively high and low concentrations of methane. The lack of retrievals explains the discrepancy between IASI and CARIBIC in Fig. 4c for the 18th of January (full lines), whereas the agreement is quite good for the 19th of January (dashed lines).

More quantitatively, the consistency between IASI and CARIBIC methane can be evaluated by averaging daily IASI CH_4 in a $4^\circ \times 4^\circ$ box (to get enough co-locations) centered on the measurements performed during the 13 CARIBIC flights. This comparison yields a bias between IASI and CARIBIC of 7.2 ppbv with a standard deviation of 13.1 ppbv. The mean standard deviation of IASI retrievals in the $4^\circ \times 4^\circ$ boxes is 18 ppbv. Given the difference in the products, and the large co-location criteria, these values confirm the good agreement between IASI and CARIBIC methane.

4 Discussion

A striking feature displayed in Fig. 1 and 2 is the increase of mid-tropospheric methane from 2007 to 2011, in agreement with the renewed growth of methane measured at the surface since the end of 2006 (Rigby et al., 2008; Dlugokencky et al., 2009, thereafter referred to as R08 and D09 respectively). To investigate this increase in the mid-tropospheric methane burden, we use the sum of a quadratic polynomial and a series of four harmonics to respectively represent the averaged long-term trend and the averaged seasonal cycle of methane. The differences between the fitting curve and the data (the residuals) are smoothed by applying a low-pass filter to account for interannual variations in the trend. The result is added to the quadratic polynomial to obtain a deseasonalized trend function (Duglokencky et al., 1994).

Figure 5a shows the fitted methane cycle estimated from IASI data over the IASI-period (July 2007 to December 2011) for the entire tropical region. Also shown are the

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deseasonalized trend function and its associated standard deviation. The growth rate of methane given by the derivative of the deseasonalized trend function is plotted in Fig. 5b. An increase of methane in the mid-troposphere in the tropical region is clearly seen in this figure, with the highest increase rate in 2007–2008. Unfortunately, the beginning of the increase (end of 2006–beginning of 2007) is missed by IASI, which was declared operational in July 2007. In the following years, the rate of increase of methane appears to be decreasing, with an average increase of $\sim 2\,\mathrm{ppbv\,yr^{-1}}$ in 2009 and 2011.

Figure 6 shows the latitudinal and temporal variations of the growth rate of methane obtained from IASI and from the GLOBALVIEW-CH_4 (2009) surface stations located in the tropical band for the period 2007–2010. It should be kept in mind that IASI provides a homogeneous coverage of the tropical band, whereas surface measurements are only available at ~ 20 stations in this band. Nonetheless, growth rates measured at the surface and in the mid-troposphere are similar, with a good match both in terms of temporal and geographical locations of positive and negative growth rates. According to Fig. 6, methane has been increasing in both the Northern and Southern Tropics, but there are differences in the intensity of the growth rate. Annual increases of methane are given in Table 1 together with their standard deviations. They are determined for each year by taking the difference between January in one year and January in the next year on the deseasonalized trend curve in Fig. 5a. Since only half of 2007 is available from IASI, the annual increase for this year is based on the extrapolation of the fit to the other half of the year. The resulting standard deviation for 2007 is thus higher than for the years fully constrained by IASI data. The values inferred from IASI retrievals for 2007 ($9.5 \pm 2.8\,\mathrm{ppbv\,yr^{-1}}$) and 2008 ($6.9 \pm 1.2\,\mathrm{ppbv\,yr^{-1}}$) are in good agreement with the growth rates reported by D09 and R08.

As seen in Fig. 6., according to IASI, the increase in the Southern Tropics was larger than in the Northern Tropics for 2007 (10.7 ± 2.5 vs. $8.2 \pm 1.8\,\mathrm{ppbv\,yr^{-1}}$) and 2008 ($7.9 \pm 1.2$ vs. $6.0 \pm 1.2\,\mathrm{ppbv\,yr^{-1}}$). D09 did report a larger increase of atmospheric methane in the SH than in the Northern Hemisphere (NH) for 2007, as seen in Fig. 6,

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with a zonally averaged SH trend of 9.2 ± 0.3 ppbv yr^{-1} compared to a zonally averaged NH trend of 7.3 ± 1.3 ppbv yr^{-1}. This may again be due to the enhanced transport from the NH to the SH in La Niña years (Prinn et al., 1992). According to R08, stations located in the Southern Tropics experienced a higher increase than stations located at higher Southern latitudes, which might explain the highest increase we find in the [EQ:20S] band compared to the SH increase reported by D09. For 2008, these authors found the largest increase at low northern latitudes with a value of 8.1 ± 1.6 ppbv yr^{-1}, for a slowing global increase of 4.4 ± 0.6 ppbv yr^{-1}, whereas IASI estimates seem to indicate a larger increase in the Southern Tropics. This disagreement on the exact location of the highest increase of methane in 2008 might be due to the different spatial coverage of both datasets, with 1 to 2 surface stations located in each 5° latitude band when IASI coverage is more homogeneous. According to IASI observations, the increase of methane seems to continue in the Tropics but at a slower rate with an average of 1.0 ± 0.5 ppbv yr^{-1} in 2009, 4.2 ± 0.5 ppbv yr^{-1} in 2010 and 2.2 ± 0.7 ppbv yr^{-1} in 2011.

Methane variability can be attributed to variations in the surface emissions or in the strength of OH sink. D09 have suggested a slight change in OH, but a significant contribution of emissions at high latitudes in 2007, and an increase of methane emission from tropical wetlands due to enhanced La Niña precipitation in 2007 and 2008. Such a hypothesis has been confirmed by Bousquet et al. (2011) by using both atmospheric inversions and a process-based model of methane emissions by natural wetland ecosystems. As seen in Fig. 5, IASI data suggests a slowing down of the increase in 2009–2011. This result thus indicates either an increase of the destruction of methane by OH or a decrease in methane surface emissions in the Tropics (predominantly wetlands and biomass burning). The analysis of ECMWF precipitation fields reveals that precipitation has continuously decreased in wetland tropical regions over these three years, the total rain fall in 2010 reaching a similar value to that of 2007. In particular, a severe drought happened in Amazonia in 2010 due to a particularly high value of the Atlantic Multidecadal Oscillation (Lewis et al., 2011). Moreover, our

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analysis of MODIS burned area (Roy et al., 2008) shows: (i) no significant change in fires, and thus in biomass burning CH_4 emissions, in the tropical region over 2007–2009; (ii) a sharp increase of fire in 2010 (Thonat et al., 2012), which might explain part of the increase of methane seen in the second half of 2010 by IASI since the fire season extends from July to October in most of the southern regions. These results seem to confirm that tropical wetland emissions driven by higher than average, although decreasing after 2008, precipitation are one of the main drivers of the 2007–2008 strong increase and of the less pronounced increase of methane suggested by IASI observations in the following years.

5 Conclusions

Observations made in the infrared by IASI have been used to derive the distribution of methane in the mid-troposphere (6–16 km), in the Tropics from July 2007 to December 2011. A strong seasonal cycle of 25 ppbv is observed in the Northern Tropics, with a maximum (minimum) in November (March–April). The cycle observed in the Southern Tropics is more complex, with an amplitude of ∼ 15 ppbv. Comparisons performed with aircraft measurements from the CONTRAIL and CARIBIC programs show that methane fields derived from IASI observations agree well with the features of in-situ measurements of mid-tropospheric methane in terms of seasonality, amplitude and latitudinal variations. The latitudinal and temporal variations of the methane growth rate measured by IASI are also in good agreement with those measured at the surface.

According to IASI observations, methane has increased by 19.1 ± 3.0 ppbv over the period 2007–2011, with a decreasing annual growth rate from 9.5 ± 2.8 ppbv yr^{-1} in 2007, in agreement with surface increase rate, to 2.2 ± 0.7 ppbv yr^{-1} in 2011. A higher rate of increase is found in the Southern Tropics than in the Northern Tropics during 2007 and 2008, possibly due to enhanced interhemispheric exchange characteristic of such La Niña years (Prinn et al., 1992).

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Assuming that the recent increase of atmospheric methane in the Tropics is mostly due to an increase in wetland emission, IASI retrievals would indicate a decrease of methane emission from wetlands for 2009–2011. Such a hypothesis is supported by the continued decrease in precipitation over these years in wetland tropical regions indicated by ECMWF precipitation fields, and small changes in tropical biomass burning emission for 2008–2009 indicated by MODIS burned area. Higher values of methane observed in 2010 in the Southern Tropics might be attributed to intense biomass burnings that took place in the Southern Tropics.

Only continuous measurements of methane from a variety of instruments (at the surface, airborne and spaceborne) will help to better understand atmospheric methane budget and its evolution. The results presented here show that IASI can provide a powerful constraint on the monitoring and understanding of atmospheric methane burden. With the launch of two other successive IASI-like instruments scheduled for 2012 and 2017, more than 20 yr of observations of mid-tropospheric methane will be available for climate studies.

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Table 1. Annual increase (ppbv yr^{-1}) in mid-tropospheric methane inferred from IASI for three tropical latitude zones. Values reported for the Northern and Southern Hemisphere (NH and SH) by Dlugokencky et al. (2009) are also given. For 2007, only half of the year is available from IASI.

	IASI			Dlugokencky et al. (2009)	
Year	20° N : 20° S	20° N : EQ	EQ : 20° S	NH	SH
2007	9.5 ± 2.8	8.2 ± 1.8	10.7 ± 2.5	7.3 ± 1.3	9.2 ± 0.3
2008	6.9 ± 1.3	6.0 ± 1.2	7.9 ± 1.2	8.1 ± 1.6*	
2009	1.0 ± 0.8	−0.3 ± 0.5	2.3 ± 0.7		
2010	4.2 ± 0.9	3.6 ± 0.5	4.8 ± 0.8		
2011	2.2 ± 0.7	2.5 ± 0.7	1.8 ± 0.7		

*This value is attributed to low northern latitudes.

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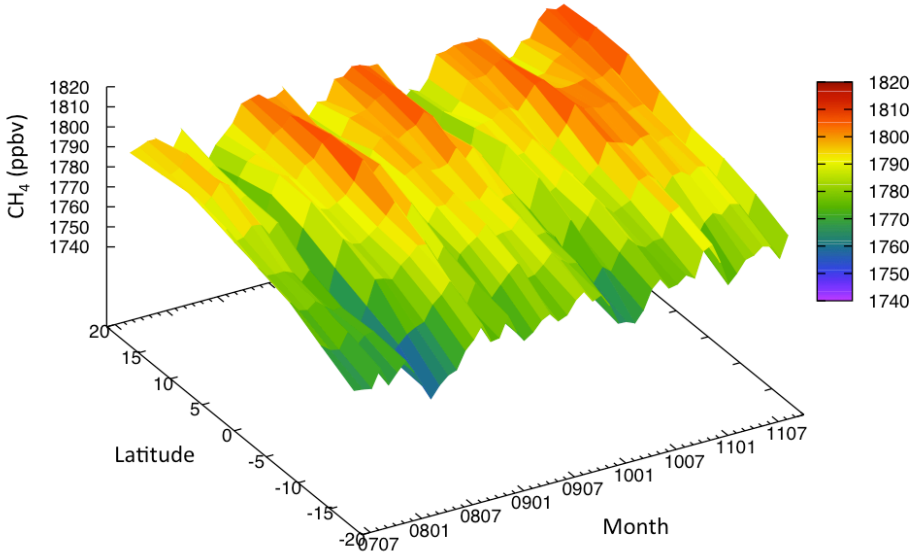

Fig. 1. Zonally averaged tropical distribution of methane in the mid-troposphere as retrieved from IASI from July 2007 to December 2011.

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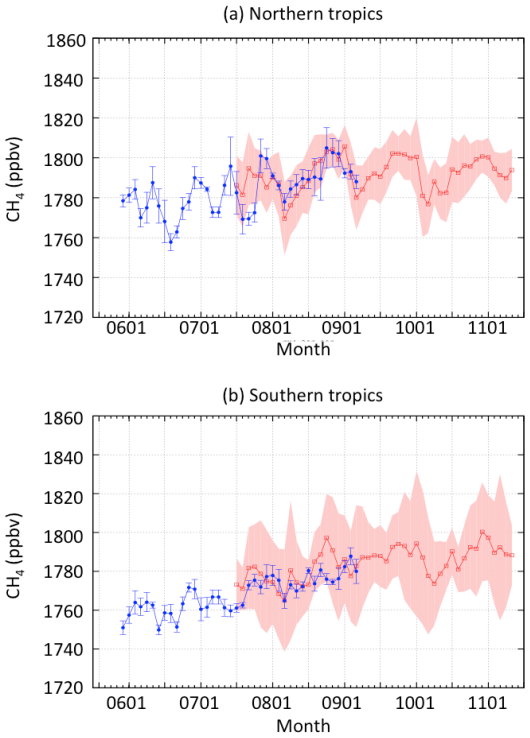

Fig. 2. Monthly evolution of mid-tropospheric methane measured by CONTRAIL (December 2006 to March 2009) at an altitude of ∼11 km (blue) and retrieved from IASI observations (since July 2007) for the 6–16 km range (red) in the Northern **(a)** and Southern **(b)** Tropics between Japan and Australia. Standard deviation are shown as bars for CONTRAIL and as an envelope for IASI. A bias of −9 ppbv (3 ppbv) has been added to the CONTRAIL data in the Northern (Southern) Hemisphere.

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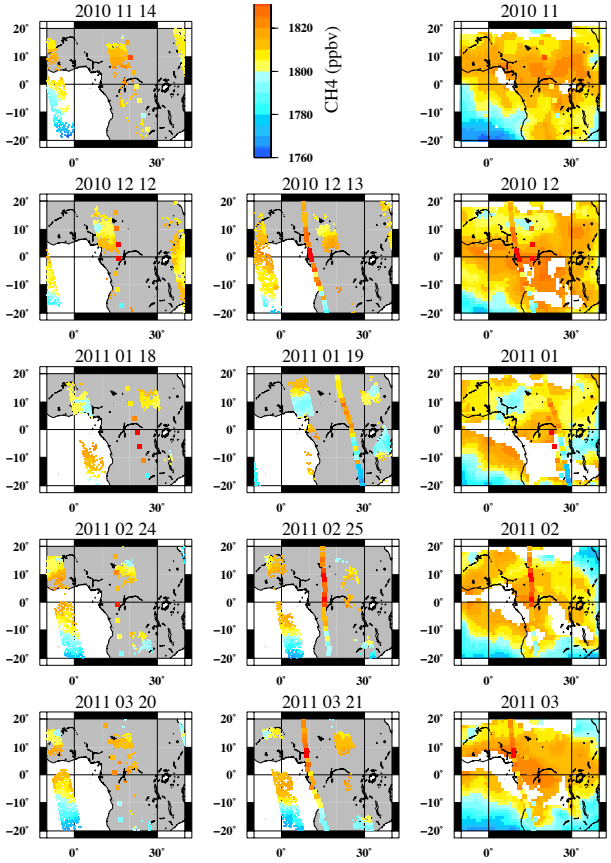

Fig. 3. Maps of daily IASI methane (first and second column) for the 9 days when CARIBIC measurements were performed between November 2010 and March 2011 and maps of monthly IASI methane (third column) for the same months. CARIBIC methane is shown as square on each map.

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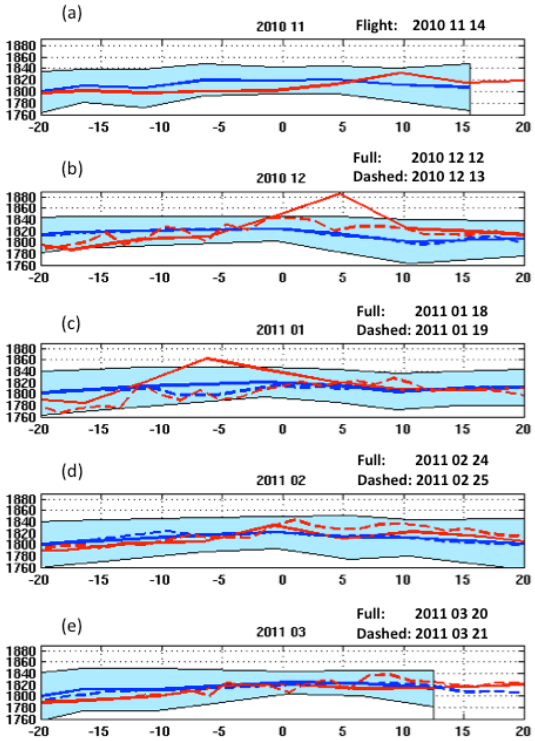

Fig. 4. Latitudinal variations of CH_4 as measured by CARIBIC (red) and as retrieved by IASI (blue) between November 2010 and March 2011. $1^\circ \times 1^\circ$ monthly IASI CH_4 have been collocated with CARIBIC measurements. The blue envelope gives the IASI monthly standard deviation along the aircraft tracks. With the exception of November 2010 (one flight only), the full line corresponds to the first flight of the month, and the dashed line to the return flight on the following day.

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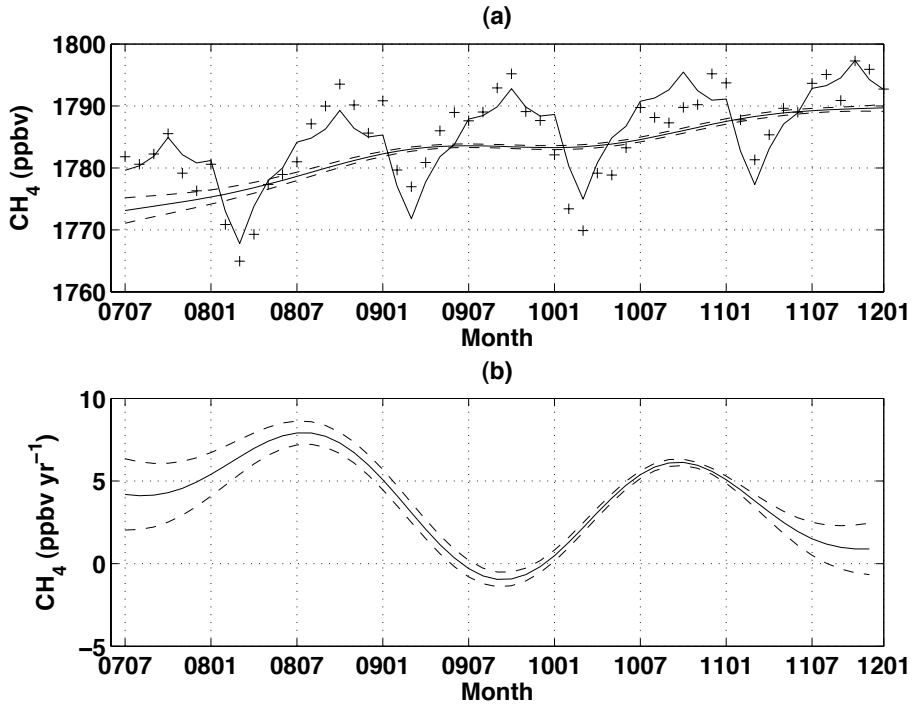

Fig. 5. (a) Monthly mean of IASI CH_4 in the whole tropical region (crosses), fitted with a polynomial trend and 4 harmonics for the period July 2007 to December 2011. Also shown is the deseasonalized trend with ±1 standard deviation as dashed lines. **(b)** Instantaneous growth rate for globally averaged atmospheric CH_4 (solid line) and ±1 standard deviation (dashed lines). The growth rate is the time-derivative of the deseasonalized trend in **(a)**.

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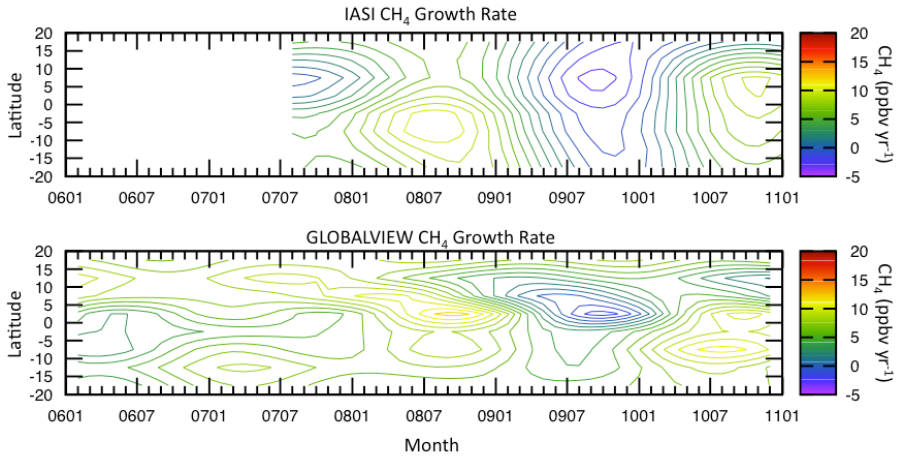

Fig. 6. Growth rate of CH_4 as retrieved from IASI (top) and as derived from the GLOBALVIEW-CH4 surface stations (bottom) from January 2006 to December 2010.

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