CH_4 variability over India derived from the GOSAT/TANSO-FTS TIR observations and simulated by MIROC4-ACTM model

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Objective

- This study attempts to analyze the vertical distributions of CH_4 over the Asian monsoon region.
- We used CH_4 mixing ratios observed from GOSAT/TANSO-FTS TIR (hereafter referred as “GOSAT-TIR”) and simulated by the Model for Interdisciplinary Research on Climate (MIROC, version 4.0) (Watanabe et al., 2008) based atmospheric chemistry transport models (ACTM) (Patra et al., 2018) referred to as "MIROC4-ACTM".
- We aim to understand relative contributions of surface emissions and transport in the formation of CH_4 seasonal cycles over different parts of India and the surrounding oceans.

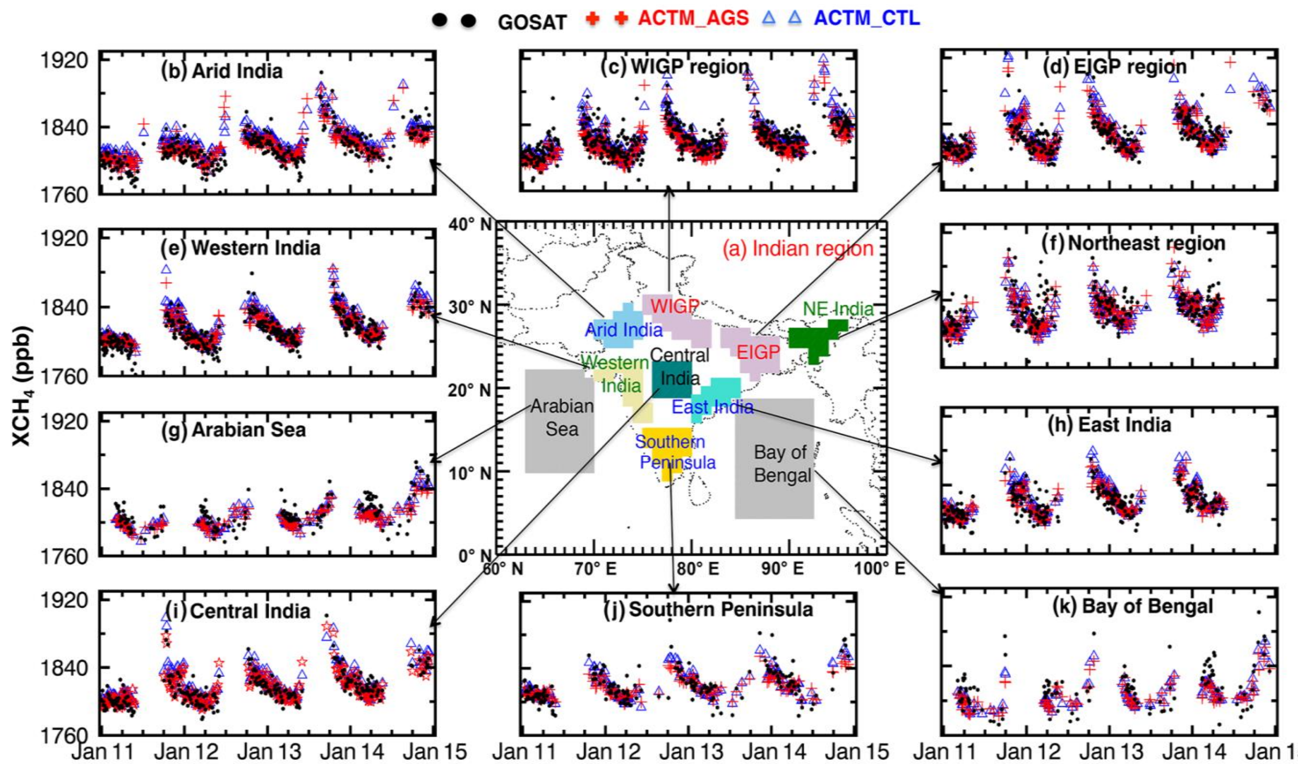
Motivation

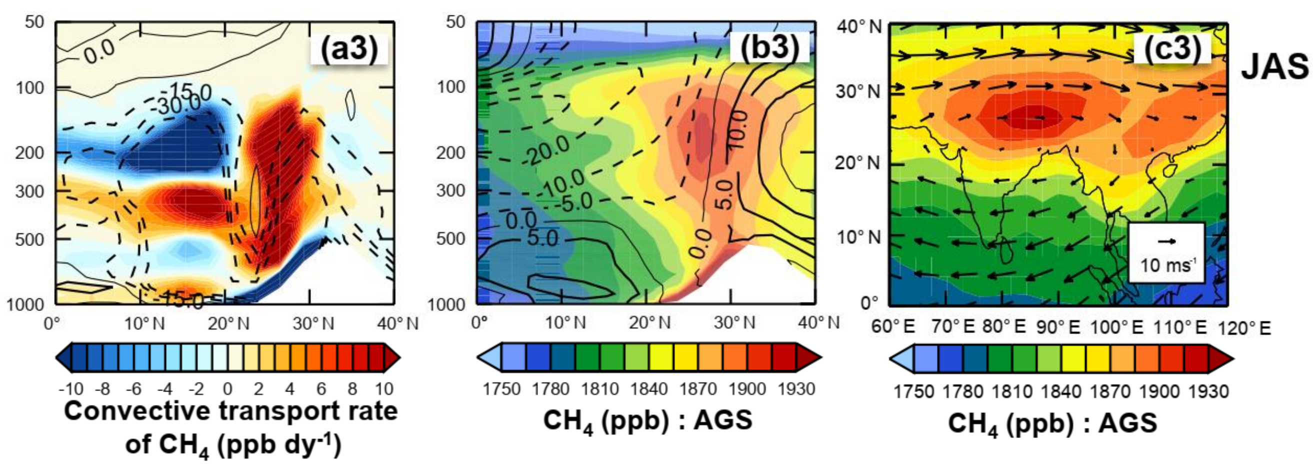
This work follows the setup described by (Chandra et al., ACP, 2017), which analyze XCH_4 from:

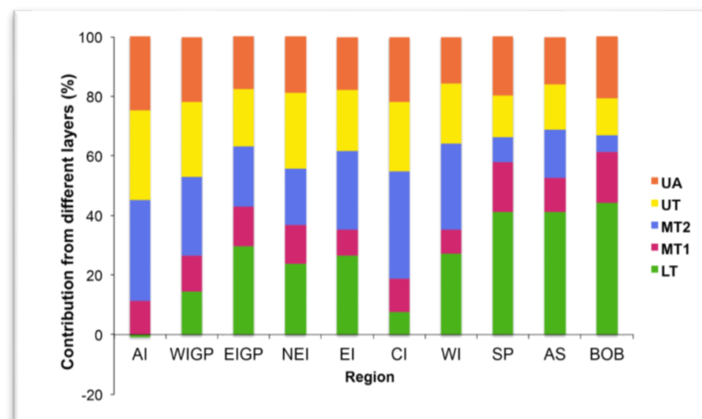
- GOSAT SWIR
- AGCM57b-ACTM model

In this work we consider CH_4 profile from:

- GOSAT TIR
- MIROC4.0-ACTM model







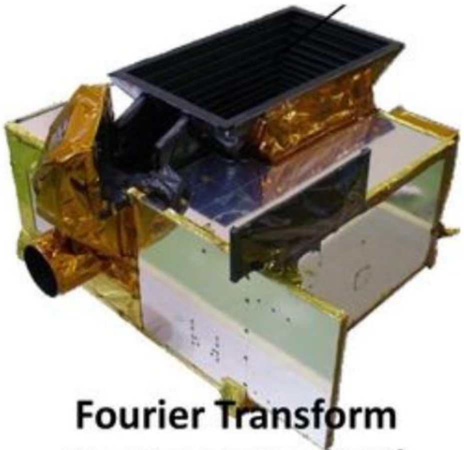
Chandra, ACP, 2017

GOSAT (Greenhouse gases Observing SATellite "IBUKI")

GOSAT on orbit since 2009

666km altitude
3 days revisit

Thermal And Near infrared Sensor for carbon Observation (TANSO)



Fourier Transform Spectrometer (FTS)

Cloud and Aerosol Imager (CAI)

Fourier Transform Spectrometer (FTS)	
Mission	GHGs measurements
Band	SWIR-0.76μm, 1.6μm, 2.0μm bands with P/S polarization (O_2-A, CO_2, CH_4, H_2O band)
	TIR-5.5~14.3μm (CO_2, CH_4, O_3 band)
SPC Res.	0.2cm^{-1}
Swath	750km(3 points every 260km)
IFOV	10.5km

Cloud and Aerosol Imager (CAI)	
Mission	Cloud detection and aerosol correction within FTS IFOV
Band	Nadir view 0.38, 0.67, 0.87, 1.60μm band
Swath	750-1000km
Footprint	0.5 and 1.5km

by Kei Shiomi, JAXA

GOSAT-TIR CH_4 product

This study uses the GOSAT-TIR V1 CH_4 product, which is released for the period from April 23, 2009, through May 24, 2014. The number of vertical grid layers of the GOSAT-TIR V1 CH4 product is 22 from the surface to 0.1 hPa.

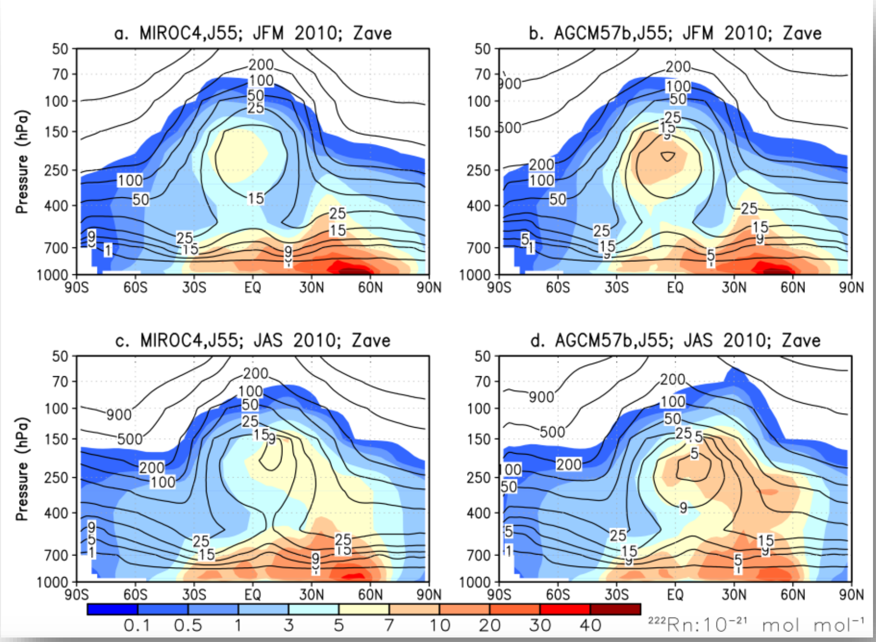
GOSAT-TIR CH_4 precision:

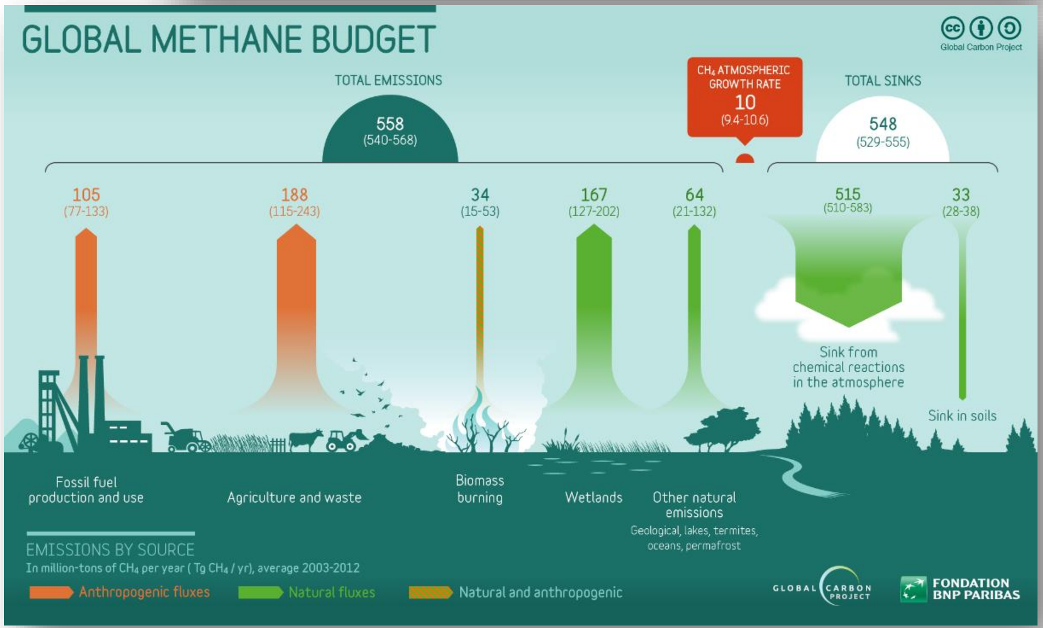
- XCH4 based on the GOSAT-TIR CH_4 profiles agreed within 0.5% of the aircraft XCH_4 values over the tropical ocean (Saitoh et al., 2012);
- Mean misfit in CH_4 between GOSAT and AIRS were 10.3±31.8 and -16.2±25.7 ppbv for the levels of 300 and 600 hPa, respectively;
- Global comparisons of GOSAT-TIR V1 vertical profiles to ACE-FTS on SCISAT and MIPAS on Envisat, as well as 16 NDACC ground stations shows agreement within 20 ppbv, or 1% (Olsen et al., 2017);
- The average bias in CH_4 profile retrieved from GOSAT-TIR spectra with a spectral correction scheme is less than 2% over the full altitude range, when compared with data from MACC scaled to the total column measurements of TCCON (de Lange and Landgraf, 2018).

ACTM (Atmospheric General Circulation Model (AGCM)-based Atmospheric Chemistry Transport model)

- CH4 simulated with MIROC4.0-ACTM [Patra et al., Sola, 2018]:
  - 67 sigma-pressure vertical layers (1000-0.0128hPa)
  - horizontal grid T42 (latitude and longitude ~2.8 × 2.8°)

- The **ch4icca** and **ch4icwh** data are inverted fluxes, based on:
  - **ch4cca**: EDGAR432+GFED4s+Termite+… .+VISIT wetland (Cao scheme).
  - **ch4cwh**: EDGAR432+GFED4s+Termite+… .+VISIT wetland (WH - Walter & Heimann scheme)



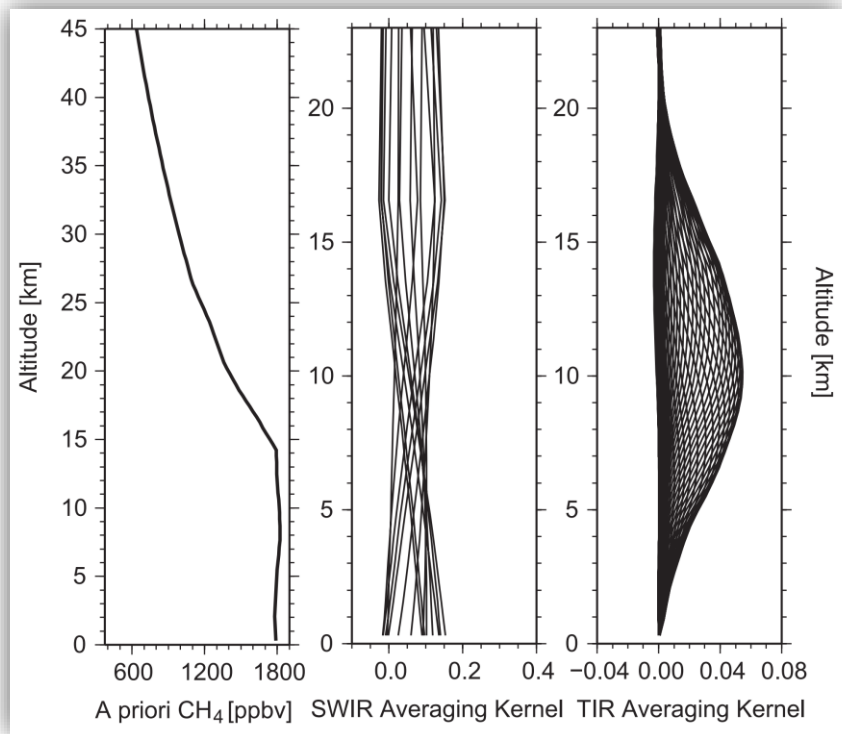


Data processing

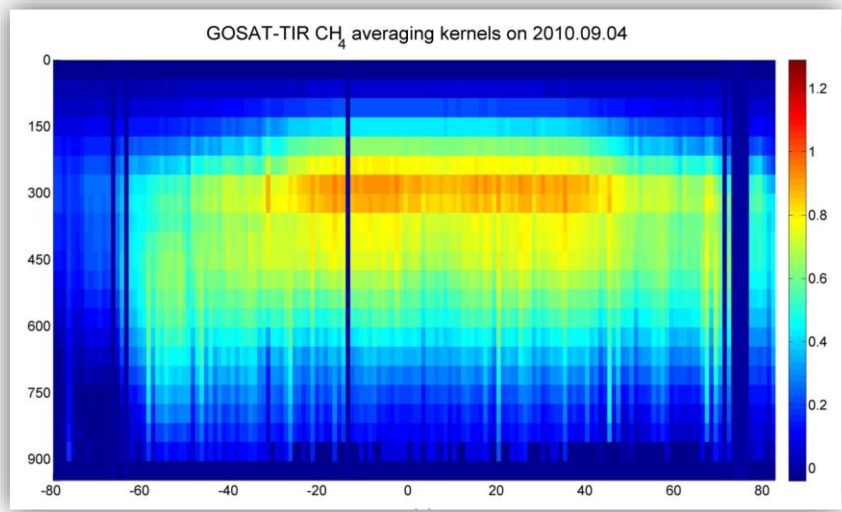
- The ACTM data was collocated with GOSAT observation points:
  - The criteria for the collocation is the nearest model grid cell in space, and the nearest hour in time
  - For vertical profile comparison data was interpolated from the ACTM grid (67 levels) on the GOSAT grid (22 levels)
  - To draw lat/lon plots datasets were remapped on grid 3x3 deg
- We applied TIR CH_4 averaging kernel functions to the corresponding ACTM CH_4 (raw) profile using equation [Saitoh et al., AMT, 2016]:

$$X_{ACTM}(AK) = X_{apriori} + A(X_{ACTM}(raw) - X_{apriori})$$

here, A - averaging kernel

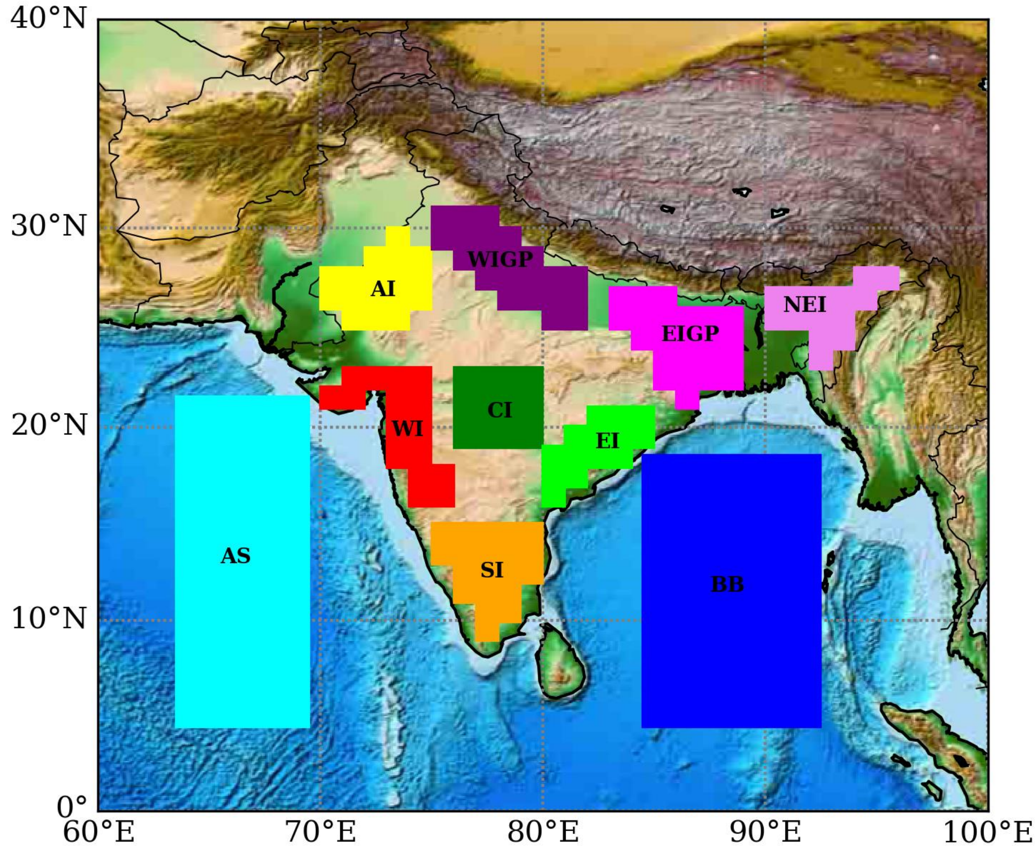


Saitoh, SOLA, 2012



Zou, AMT, 2016

Study domain



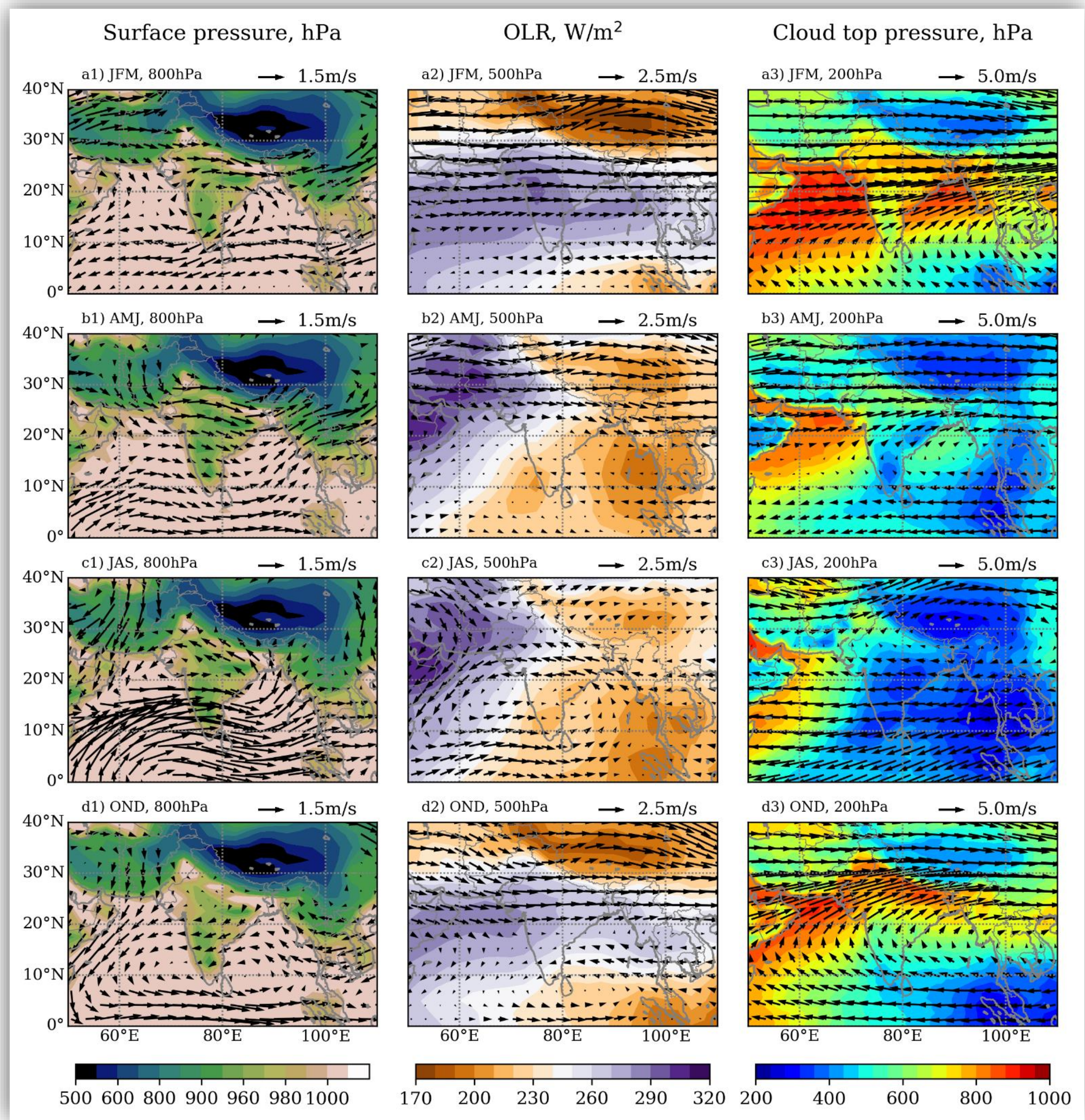
The map of the regional divisions for the analysis, as defined by (Chandra et al., ACP, 2017). The Indian regions from Southwest to Northeast are following: the Arabian Sea (AS), Southern India (SI), the Bay of Bengal (BB), Western India (WI), Central India (CI), Eastern India (EI), Arid India (AI), Western IGP (WIGP), Eastern IGP (EIGP), and Northeast India (NEI).

Wind variation

Key-components of the climatology in the Indian Ocean and the surrounding areas are the annual migration of ITCZ and seasonal development of the monsoon winds.

1. In boreal spring the ITCZ migrates northward across the Indian Ocean and reaches its northernmost position at approximately 35°N during summer. A strong pressure gradient between the low-pressure zone over the Tibetan Plateau and a high-pressure zone over the Southern Indian Ocean generates a strong near surface monsoonal airflow from July to September (c1-c3).

2. In autumn the ITCZ then retreats southward and reaches its southernmost position at approximately 25°S in January. The reversed pressure gradient during the winter months generates the moderate and dry northeast monsoon (d1-d3).

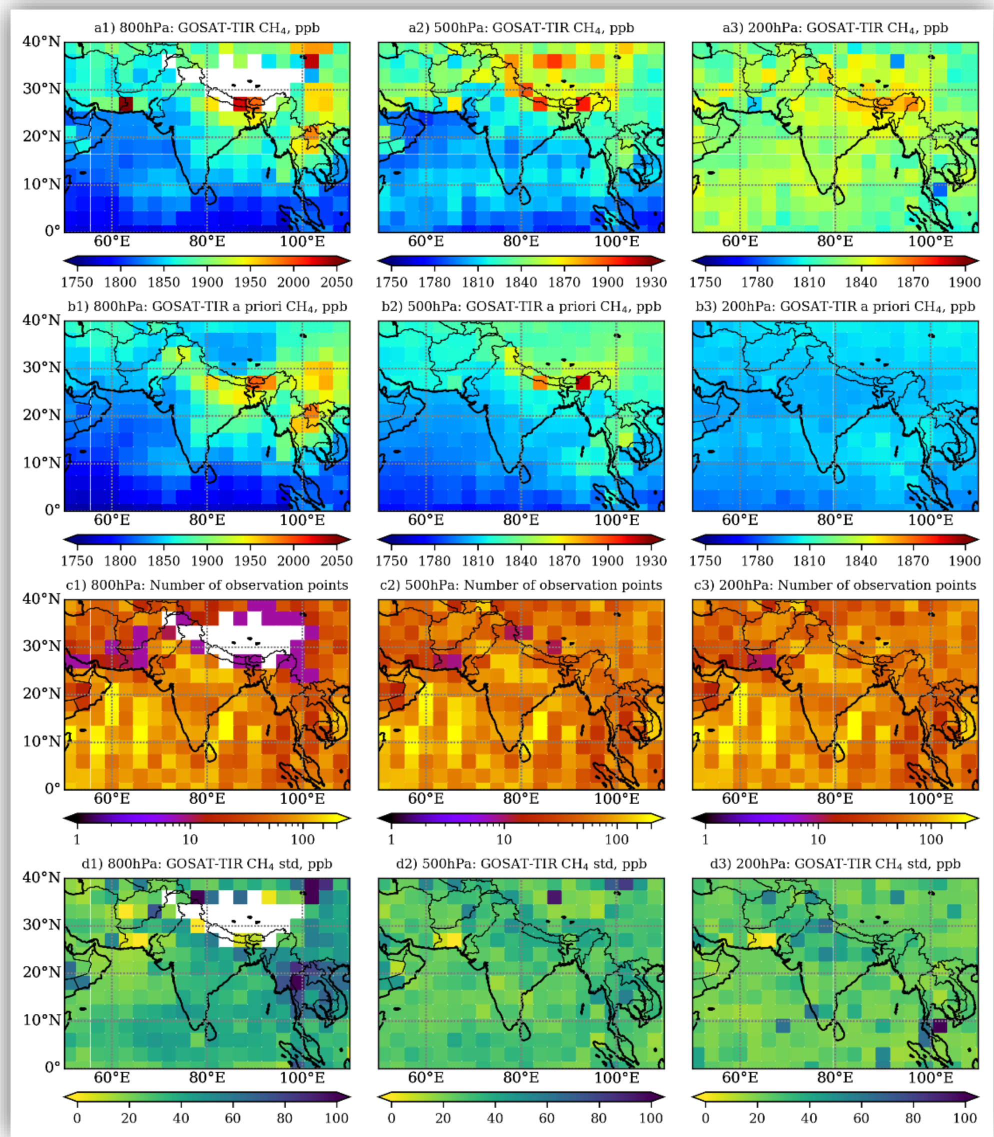


CH_4 over India observed by GOSAT-TIR

- Due to a lack of GOSAT-TIR CH_4 data in cloudy scenes and the influence of the complex orography of the studied area, the number of points used for averaging in each grid cell varies with height over land (d1-d3). This is especially noticeable for the northern regions of India, since a significant part of Tibet and the Himalayas are above the level of 800 hPa (d1).

- Northern India also has large sources of CH_4 with different types of emission. These two factors cause large standard deviations (STD) in CH_4 (e1-e3). For South India and the marine regions the STD values are much lower compared to those over the land.

- In the middle and upper troposphere the perturbations from the heterogeneity of the emissions are smoothed out, the density of observation points increases, therefore, the averaging errors decrease. At a height of 200 hPa, the average STD for GOSATTIR is approximately 25 ppb.



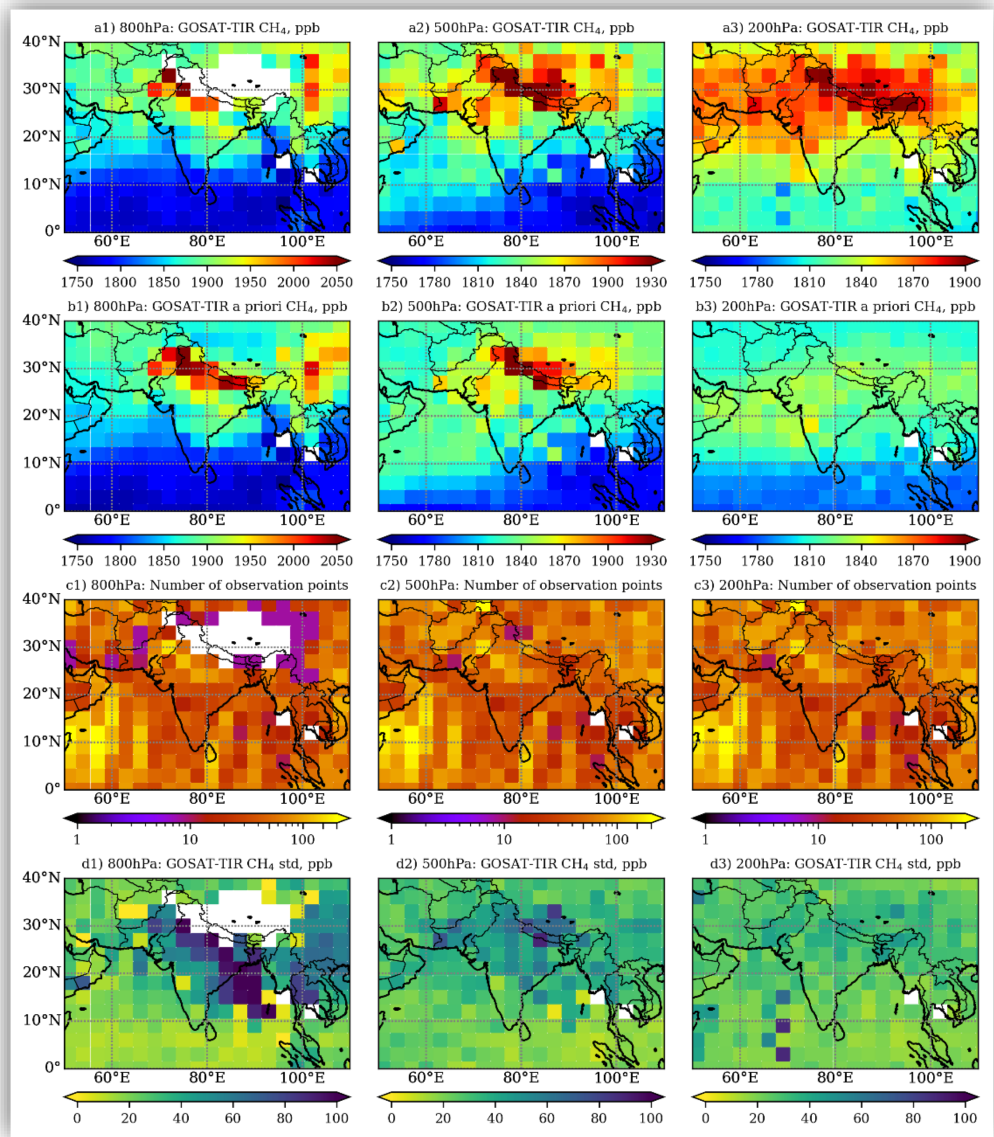
Pre-monsoon (April-May-June) 2011

CH_4 over India observed by GOSAT-TIR

- The density of observation points decreases with the onset of the monsoon season (d1-d3), however, it remains sufficient to detect significant changes in CH_4 concentrations even considering the relatively large STD values there. A significant increase in concentration values is noticeable primarily in the middle and upper parts of the atmosphere (a1-a3), which is due to effect of convective transport.

- After reaching a level near the tropopause, the increased concentrations are distributed by three jets: the lateral (the cross-equatorial circulation) and transverse (flows between the arid regions of north Africa and the Near East and south Asia) monsoons, and the Walker Circulation is extended across the Pacific Ocean.

- The GOSAT- TIR CH_4 product shows vivid differences in CH_4 from the *a priori* values even in the lower part of the atmosphere, where sensitivity is weak (c1-c3).



Monsoon (July-August-September) 2011

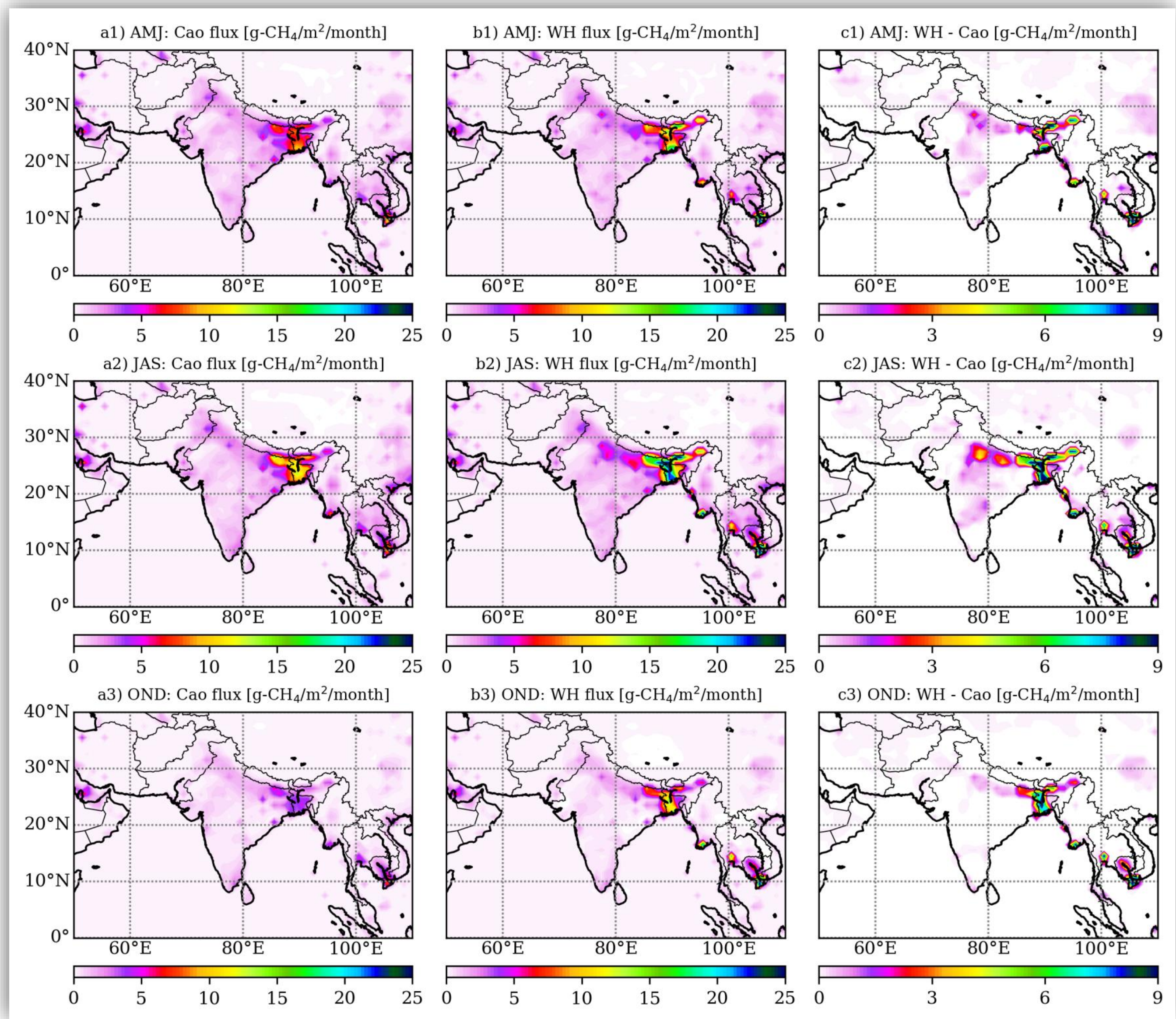
Surface CH_4 fluxes

The surface CH_4 fluxes (g-CH4/m2/month) used for ACTM simulation:

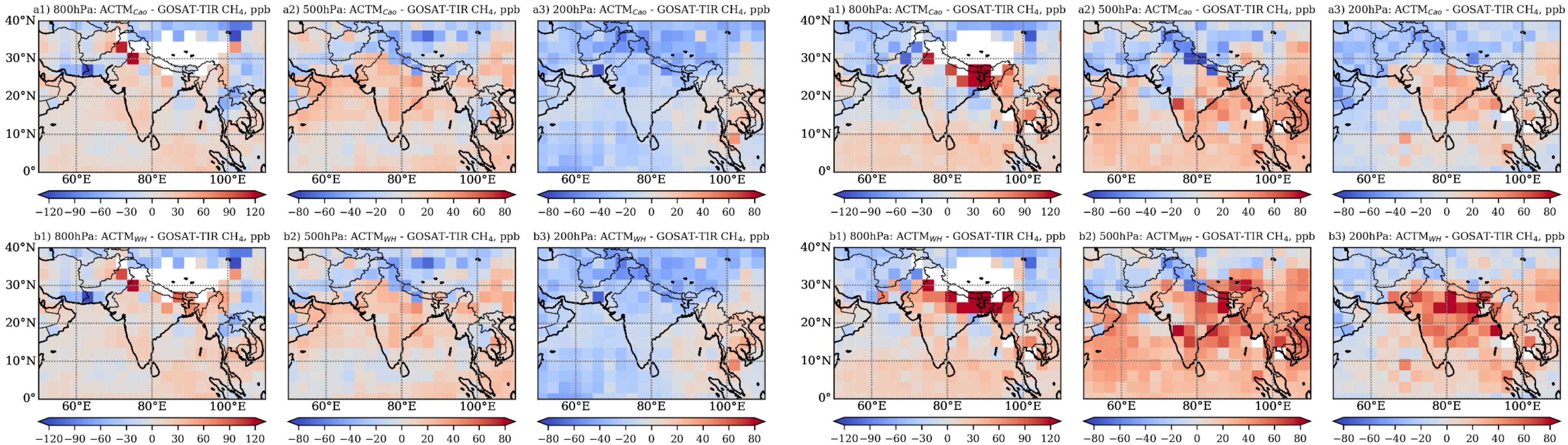
- a1-a3) from Cao scheme,
- b1-b3) from WH scheme, and
- c1-c3) difference between schemes.

In general, the WH scheme fluxes are about 5-10% larger the Cao, excepting the WIGP, EIGP, and NEI regions of India and Bangladesh where the maximum difference reaches 20-40%.

Besides, there are small hot spots in Southeast Asia (e.g. Mekong River Delta).



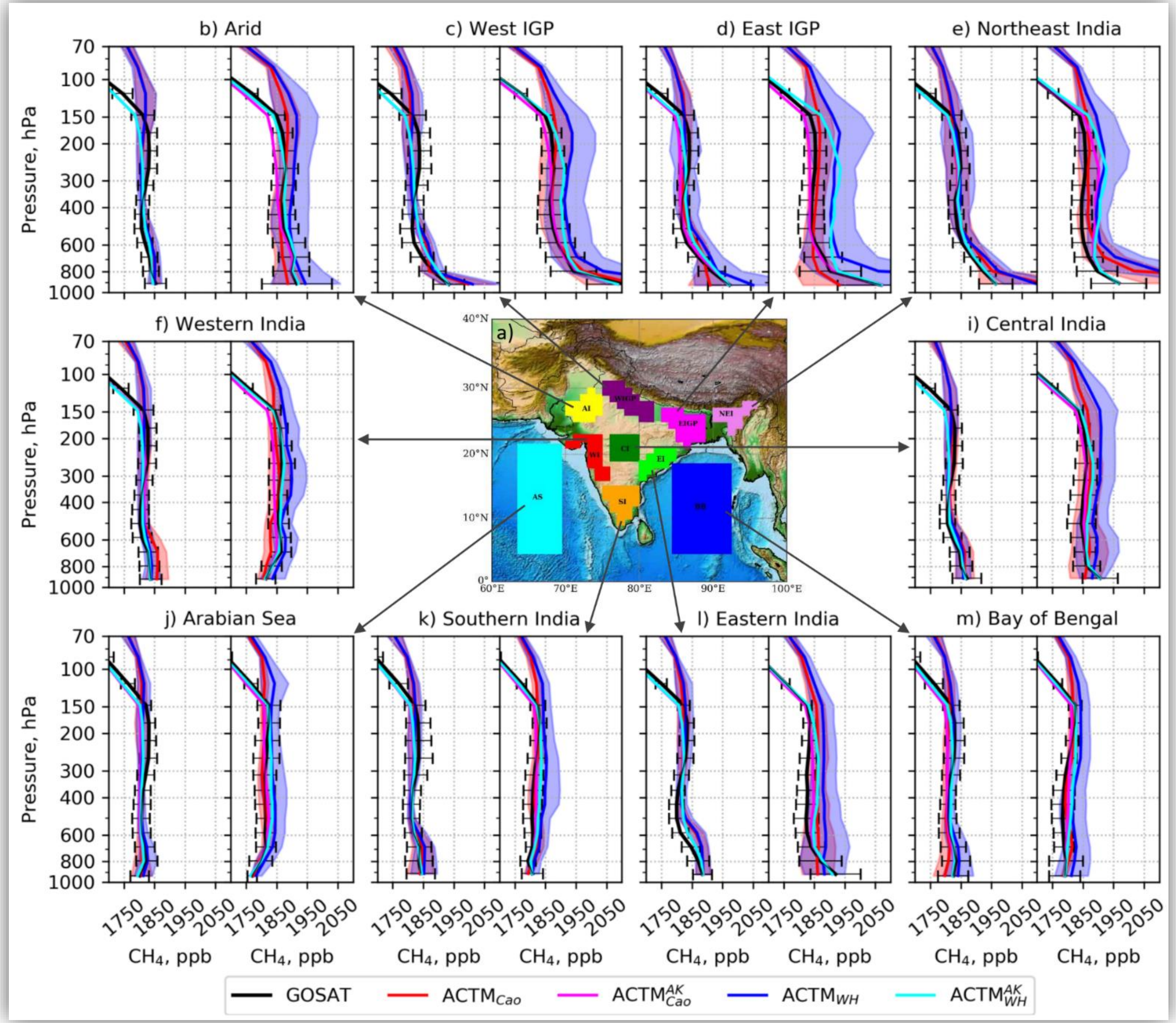
CH_4 simulated by ACTM



Pre-monsoon (April-May-June) 2011 Monsoon (July-August-September) 2011

Since in the pre- and post-monsoon seasons (AMJ and OND) the excess concentration due to additional emission is locked in the boundary layer, we can detect only a slight increase in concentration at the levels selected for the analysis. CH_4 simulated using both emission schemes are consistent with the GOSAT-TIR retrieval with averaged misfit within ±2%, the heterogeneity of which is apparently caused by transport regimes. By analogy to the CH_4 distribution from GOSAT-TIR the increased scatter found in modeled CH_4 over IGP, wherein the enhanced values extend up to the level of 200 hPa. During the monsoon, the difference between emission scenarios becomes significant, as additional CH_4 mass is carried to the middle and upper atmosphere. The larger misfit in comparison with GOSAT-TIR emphasizes the redundancy of CH_4 emission of the WH scheme.

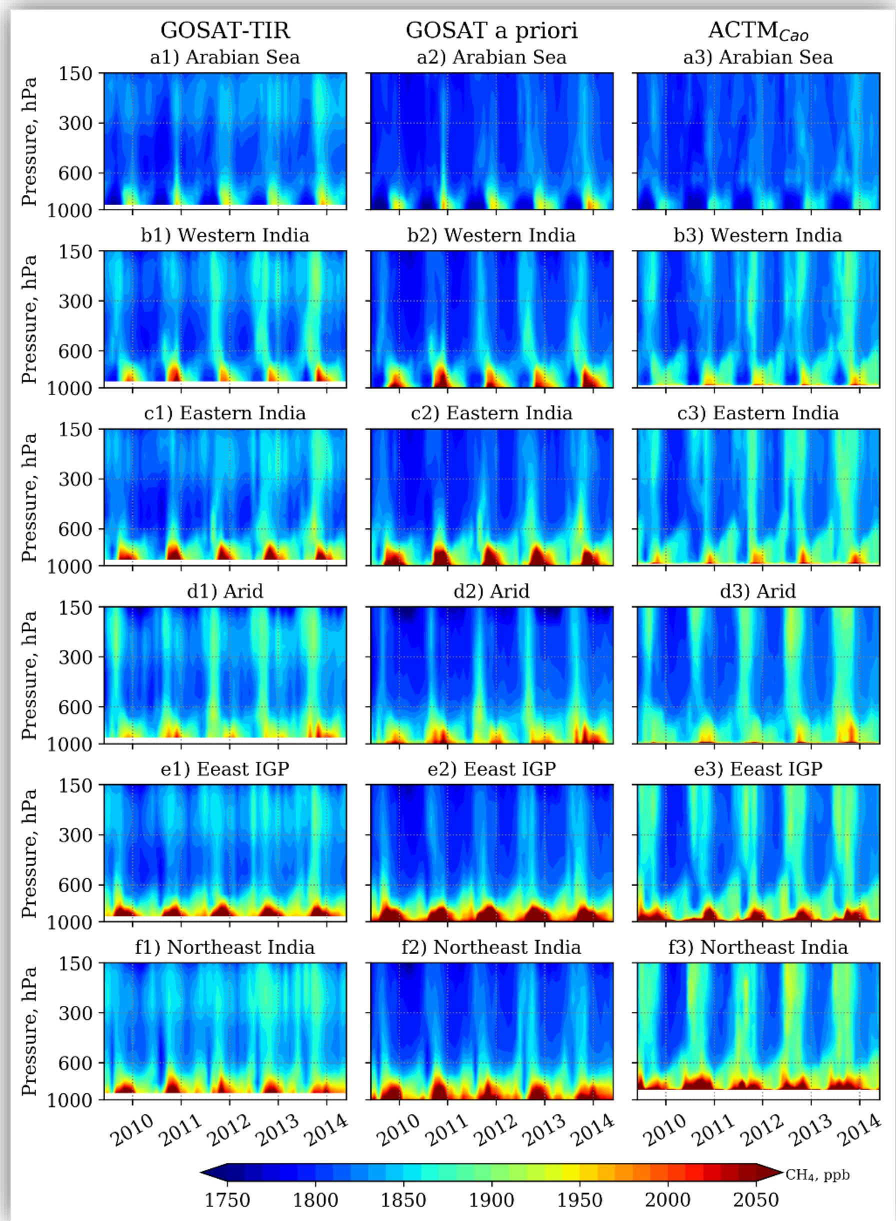
CH_4 vertical profiles

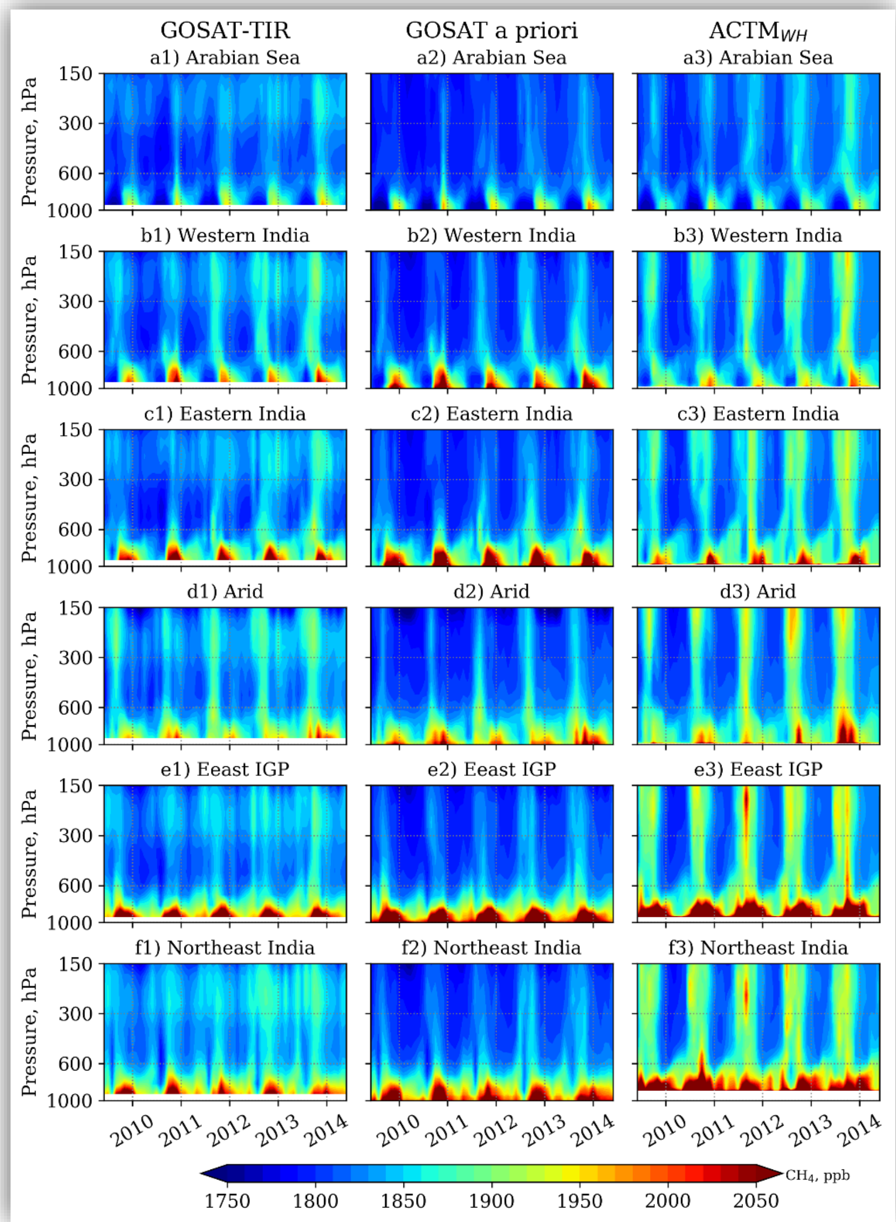


CH_4 vertical profiles

- The sensitivity of GOSAT-TIR measurements (at 22 levels) has a maximum at the level of 300-200 hPa.
- The vertical CH_4 profiles have a characteristic curved shape with two peaks: near the surface, and at the level of 150-200 hPa.
- Reflecting the increase of CH_4 surface fluxes intensity, the vertical gradient between the near-surface and upper troposphere levels increases in the direction from South-West (marine regions have slightly lower concentrations in the boundary layer since the sea is a weak source) to the North-Eastern (where EIGP, WIGP, and Northeast Indian stand out in significant sources due to various natural and anthropogenic sources.
- In both pre- and post-monsoon seasons, we found a significant correspondence between the GOSAT-TIR and model CH_4 profiles up to the level of 150 hPa, above which the CH_4 concentration decreases due to intensive chemical reactions. The sensitivity of GOSAT-TIR there drops sharply and the satellite retrievals strongly follow the *a priori* profiles.
- Monsoons cause a powerful perturbation of concentration along the entire vertical profile up to the level of the tropopause. Two southern regions (the Arabian Sea and Southern India) are located near the entry point of Somali Jet - atmospheric masses with a low CH_4 coming from the Indian Ocean (Findlater, 1969). These regions do not have significant sources of CH_4, and therefore, concentration in the vertical profiles increase with height due to transport from other regions.
- Convolution of modeled profiles with GOSAT-TIR CH_4 averaging kernels smooths the model profiles to fit the GOSAT-TIR vertical resolution and reduce their misfit. When considering the averaging kernel, the model profiles completely coincide with the GOSAT-TIR profile above the level of 150 hPa, which means that there is less information on CH_4 concentration included in the TIR spectra.

Cross-section of CH_4





Cross-section of CH_4

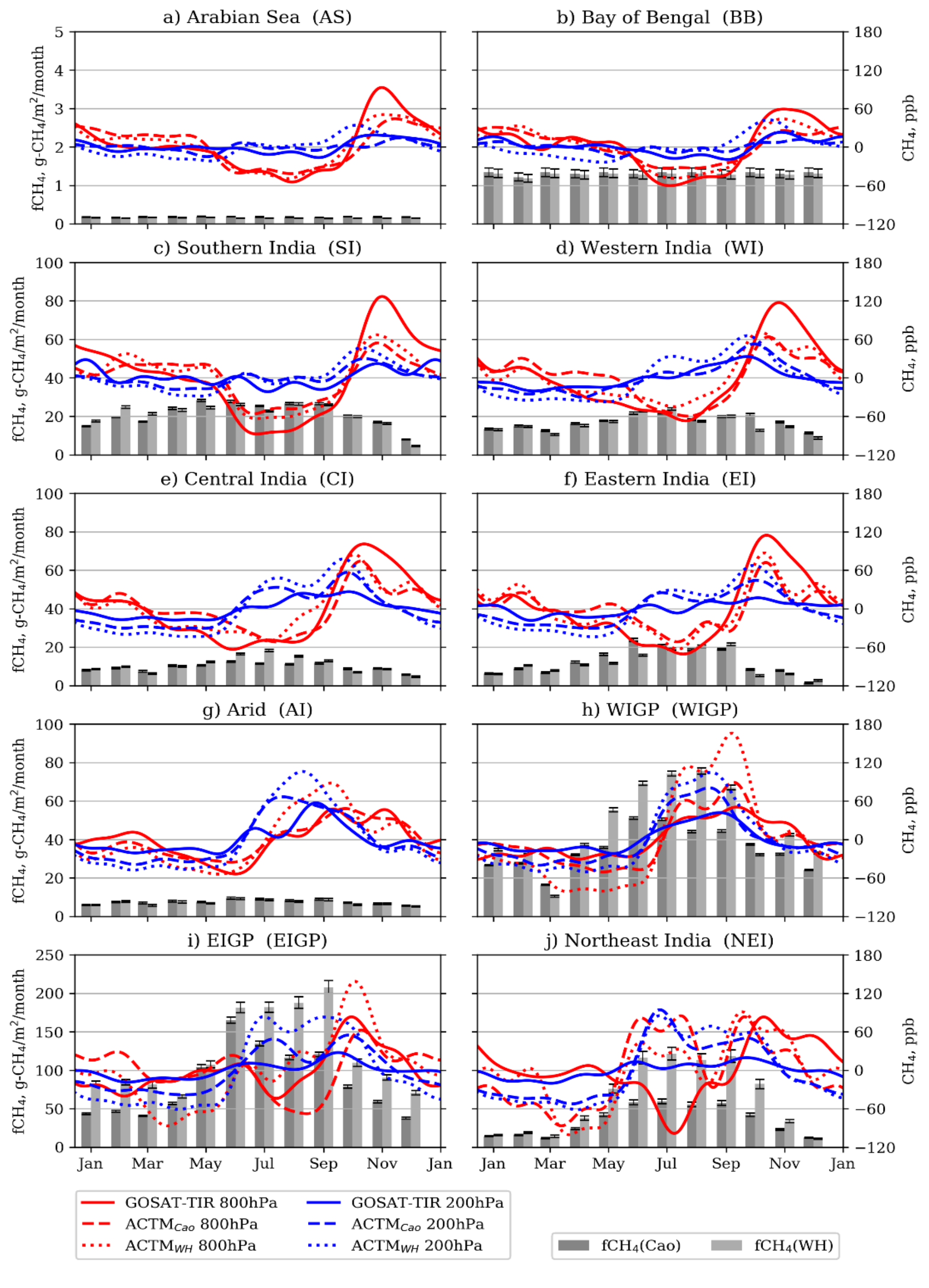
- The monsoon anticyclone shows substantial intra-seasonal oscillations, which are connected to variable forcing from transient deep convection over the Indian subcontinent and the Bay of Bengal. This variability is typically associated with active/break cycles of the monsoon with timescales of ~10–20 days. Significant correlations exist between outgoing longwave radiation and circulation within the monsoon region, such that the entire balanced anticyclone varies in concert with convective heating: enhanced convection leads to warmer tropospheric temperatures, stronger anticyclonic circulation, and colder lower stratospheric (and tropopause) temperatures. This causes a significant heterogeneity of the flux transported upward and CH_4 concentration in the upper layers during Asian monsoon.

- The Indo-Gangetic Plain (IGP) located in the foothills of the Himalayas is one of the most densely populated regions on the globe, with consequent large emissions of greenhouses gases (Kar et al., 2010; Chandra et al., 2017). This region experiences intense agricultural activity, hosts many coal-fired thermal power plants and industries. The use of traditional biofuels is common in the rural areas. In the winter months the IGP is often enveloped by thick fog and haze (Gautam et al., 2007). The prevailing winds at low altitudes (surface to ~850 hPa) are northerly to northwesterly with low wind speeds (<5 m/s) and the eastern parts of the IGP are impacted by a localized area of strong subsidence in winter (Dey and Di Girolamo, 2010). These conditions tend to trap the pollution at low altitudes (Kar et al., 2010).

2020-05-06

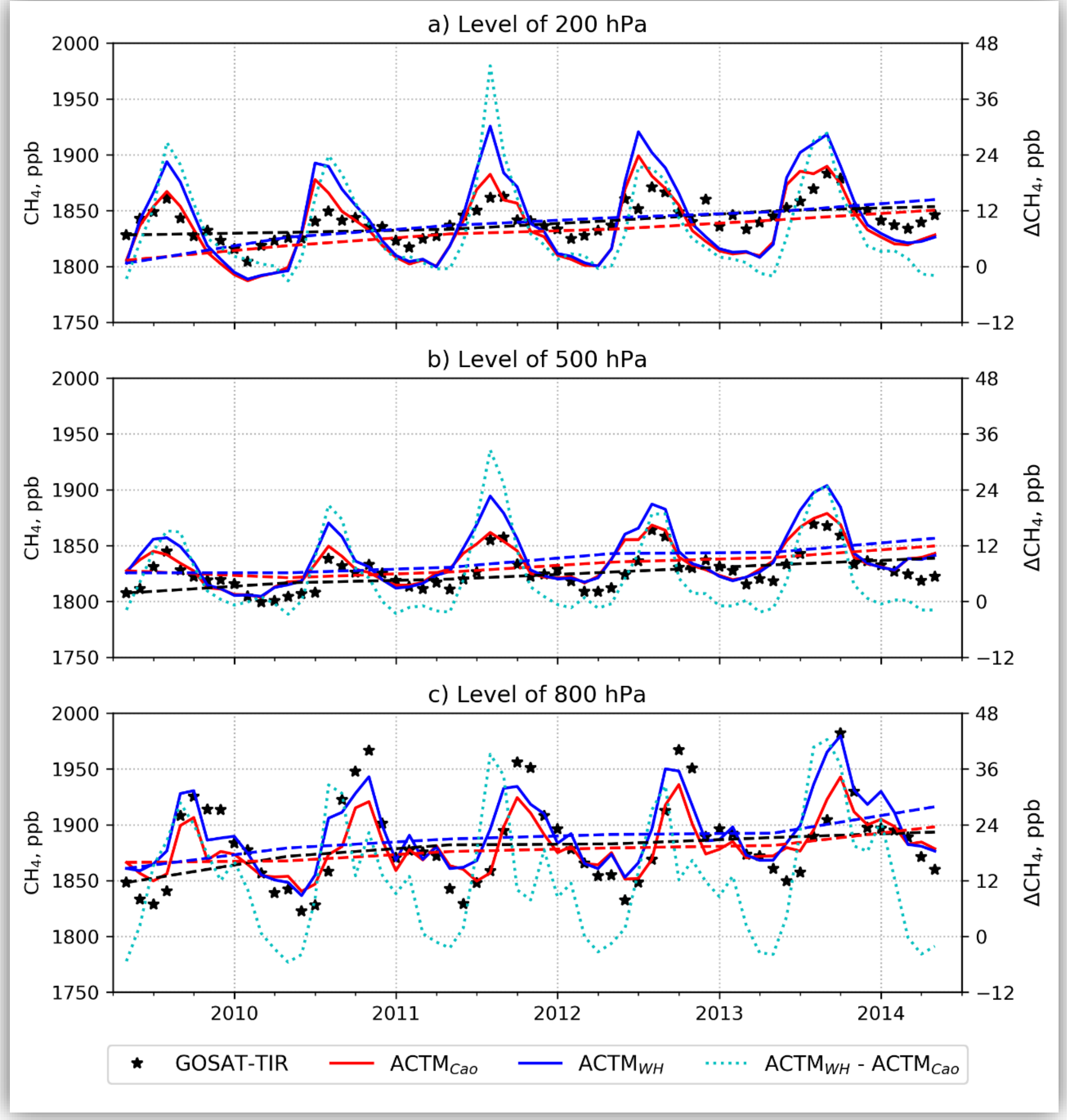
Seasonal variation of CH_4

- Seasonal changes are controlled primarily by meteorological parameters, so the most noticeable effect is determined by the summer monsoon. During this season enhanced transport redistributes CH4 along all layers of the troposphere. The minimum CH_4 seasonal variation is found in the lower troposphere (800 hPa), while the maximum occurs in the upper part.
- The amplitude of seasonal changes is determined by the net amount of the sources; therefore, it increases from south to north from marine regions to the most densely populated areas.
- With the onset of autumn, the deep convective transport is suppressed, therefore under the influence of the Hadley cell circulation the slow outflow of air masses is started in the opposite south-west direction. At this moment the peak of concentration is at 800 hPa, and slowly moves from the northern regions (over EIGP in October) to the southern (over Arabian Sea in the late November).



Seasonal variation of CH_4

- At the level of 800hPa GOSAT-TIR shows significant inter-seasonal variability, which can be greatly influenced due to the large spread of individual samplings.
- In UTLS the strong summer peak in the ACTM CH_4 is associated with excessive vertical transport, which, apparently was not completely resolved upon the transition to the new (MIROC-4.0) meteorology.
- In the middle troposphere a good consistency in phase is found and the $ACTM_{Cao}$ to $ACTM_{WH}$ concentration misfit is strongly associated with the flux difference.
- For the South Asia region for the period the Cao flux combination account 65.7 ± 2.1 Tg yr^{-1}. This confirm the assessment made by Patra et al. (2016), indicating that the EDGAR inventory (version 4.2FT2010) overestimated the South Asia regional emission by 10-15 Tg yr-1.



Conclusion

1. GOSAT-TIR observations provide data coverage and density suitable to study detailed horizontal features of CH_4 from the top of the atmospheric boundary layer up to upper troposphere.
2. The GOSAT-TIR product shows vivid differences in CH_4 from the a priori values even in the lower part of the troposphere, where sensitivity of the TANSO-FTS sensor is relatively weak.
3. Distinct seasonal variations of CH4 have been observed at the different levels of the troposphere over northern and southern regions of India corresponding to the southwest monsoon (July–September) and early autumn (October–December) seasons.
4. If no averaging kernel incorporated, the mean ACTM and GOSAT-TIR misfits are within 50 ppb, except for the level of 150 hPa and upward, where the GOSAT-TIR sensitivity becomes very low.
5. Convolution of the modeled profiles with retrieval a priori and averaging kernels reduce the misfit to below uncertainty. However, the influence of the a priori profiles becomes too large.
6. An additional analysis with aircraft observations is necessary to analyze the GOSAT-ACTM misfit found above the level of 150hPa.
7. Using the Cao emission combinations, the annual mean emission for the South Asia region is estimated to 65.7 ± 2.1 Tg yr-1 for the period 2010-2014.
8. Overall, the ACTM simulations of CH4 in the Indian regions compare favorably with the GOSAT-TIR samplings, in terms of seasonality and global variability. Inconsistencies seen in the GOSAT-ACTM comparisons could provide opportunities for further flux optimization with inverse modeling methods.