Region-dependent seasonal pattern of methane over Indian region as observed by SCIAMACHY

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Abstract

The column averaged mixing ratio (XCH_4) of methane from SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) on-board satellite ENVISAT has been used to study its regional pattern and seasonal cycle over Indian region for the period 2003-2009. XCH_4 varies from 1740-1890 ppbv over Indian region with distinct spatial and temporal features. The peak values are observed in monsoon and post monsoon and minimum in winter months, except over southern Peninsular India which shows the distinctly different seasonal behavior with peak in October/November. The mean background level of XCH_4 over Indian region is estimated as ~1795 ppbv. While regional patterns are strongly associated with livestock distribution, wetland emissions, including rice fields, the seasonal variations in XCH_4 are predominantly associated with the rice cultivation as revealed by analysis of NDVI.

Keywords:

Methane; SCIAMACHY; seasonal variation; Source analysis; regional variation

1. Introduction

Methane (CH_4), the second most leading contributor of global warming subsequent to carbon dioxide (CO_2), with a global warming potential (GWP) of about 25 for 100 year time period (Forster et al., 2007) is emitted from a wide variety of natural and anthropogenic sources. It plays a major role in climate and chemistry of Earth's atmosphere and is a powerful greenhouse gas with a direct forcing of 0.48 W/m^2 in the atmosphere regulated by the Kyoto protocol (Reilly et

al., 1999). Apart from the direct warming, the secondary products of CH₄ oxidation like O₃, CO, CO₂ and H₂O makes an indirect warming of about 0.17 W/m² (Lelieveld et al., 1998). CH₄ is emitted from a wide variety of natural and anthropogenic sources. The natural sources of CH₄ include wetlands (Cao et al., 1998), termites (Sugimoto et al., 1998), hydrates (Bouffaron et al., 2013), ocean (Christopher et al., 1999) and fresh water reservoirs. A major mechanism of CH₄ production is the methanogenic action on organic matter in anoxic environments and the major anthropogenic sources include rice paddies (Minami et al., 1994; Purkait et al., 2005), livestock (Crutzen et al., 1986; Naqvi et al., 2011), mining and burning of fossil fuels (Howarth et al., 2011) and landfills (Chakraborty et al., 2011).

CH₄ in the atmosphere is removed by photochemical oxidation (Saueressig et al., 2001) or by biological oxidation by methanotropic bacteria (Le Mer et al., 2001). About 90% of CH₄ in the atmosphere breaks down by reacting with hydroxyl radical (OH) (Levy 1971). The current global mean mixing ratio of CH₄ is 1.8 ppm, (NOAA/CMDL baseline observatory) which is about 2.5 times greater than the preindustrial concentration (Cunnold et al., 2002). The irregularities in the growth rate of CH₄ and associated warming it produces in the atmosphere are the foremost apprehension for the scientific community.

Ground-based and space-based measurement techniques are available to study the distribution of CH₄ in the atmosphere. The space-based CH₄ studies exploit the near infra-red (NIR) absorption bands in solar spectra or the thermal infra-red (TIR) region of terrestrial radiation to retrieve its abundance in the atmosphere. The instruments like Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) (Bovensmann et al., 1999) and Greenhouse gases Observing SATellite (GOSAT) (Yoshida et al., 2011), utilized NIR based retrieval and Atmospheric Infrared Sounder (AIRS) on-board Aqua (Xiong et al., 2008), Infrared Atmospheric Sounding Interferometer (IASI) in Metop (Crevoisier et al., 2009), and Tropospheric Emission Spectrometer (TES) (Bowman et al., 2006) aboard Aura used TIR based measurements for CH₄ retrieval from space.

Apart from a few campaign mode measurements (Sahu and Lal., 2006; Garg et al., 2011; Baker et al., 2012) and a network station of Commonwealth Scientific Industrial Research Organization (CSIRO), at Cape Rama, Goa (15.08°N; 73.83°E) on the west coast of India, no incessant monitoring is available for the systematic analysis of growth and trends in CH₄ over

this region. This work attempts an analysis of column averaged mixing ratio of CH₄ over Indian region, its seasonal variations using SCIAMACHY measurements. The regional variations in the column mixing ratio of CH₄ over five distinct regions over India along with the respective changes in seasonal patterns were examined in detail. It is attempted to correlate these patterns with the regional distribution of various sources like rice cultivation/agricultural activity, livestock, wetland emissions, biomass burning and petroleum mining and also emission inventory data. In addition, the boundary layer contribution in the seasonal amplitude was delineated. The role of meteorology in controlling the seasonal pattern also was examined.

2. Data and Measurement Technique

The data of column averaged mixing ratio of CH₄ (XCH₄) over Indian region used in the present study is from SCIAMACHY (Schneising et al., 2011), launched on March 2002 and was operational till 2012. The payload was a passive imaging spectrometer with a spectral range from ultraviolet to NIR through visible (214-2386 nm), in 8 channels. It had a spatial resolution of 30 km (along the track N-S) and 60-120 km (across the track E-W) with a swath of 960 km and global coverage achieved within 6 days. The NIR channel 6 (1631-1671 nm) was used for CH₄ measurement and data retrieved using the Weighted Function Modified-Differential Optical Absorption Spectroscopy (WFM-DOAS v2.0.2) algorithm (Buchwitz et al., 2006) was used (<http://www.iup.uni-bremen.de/sciamachy/NIR-NADIR-WFM-DOAS/products>) in the present study. The algorithm estimates XCH₄ as (Schneising et al., 2008);

$$XCH_4 = (VCH_4 / VCO_2) \times CO_{2\text{ mf}} \text{ ----- (1)}$$

Where VCH₄ and VCO₂ are the retrieved CH₄ and CO₂ in the absolute column (in the unit of molecules/cm²) from SCIAMACHY. CO_{2 mf} is the assimilated CO₂ column averaged mixing ratio from carbon tracker (Peters et al., 2007). The simultaneously retrieved CO₂ is chosen as a proxy for air column, assuming a constant mixing ratio. By normalizing with the air column, small variations within the column due to emission are identified in the column averaged mixing ratio. The relative precision in the measurement was about 1.7 % and which reduced to 4% after November 2005 (Schneising et al., 2012). The XCH₄ extracted for Indian region (0°- 40° N and 60°-100° E) for each month from 2003 to 2009 from global data set is used in this study. The spatial resolution of data is 0.5°× 0.5°.

3. Results and Discussion

3.1. Monthly Variation in XCH_4 over Indian region

Fig. 1: Monthly map of XCH_4 in 2004.

The present study on the spatio-temporal variation of XCH_4 as obtained from SCIAMACHY focused on the Indian land mass. The monthly mean spatial maps of XCH_4 were generated from the SCIAMACHY data for the period 2003 to 2009. Fig. 1 shows the typical spatial map of monthly mean XCH_4 for 2004. The mean XCH_4 starts increasing from June onwards and peaks in August/September. The annual pattern is more or less similar for all the years, except for the fact that the month of highest CH_4 levels may shift from August to September. Unlike CH_4 for which the mixing ratio remains more or less similar for wider regions (Fig.1), the spatial patterns of the tropospheric NO_2 , CO etc (Sheel et al., 2010; David et al., 2013; Girach et al., 2014) are characterized by highly localized hot spots.

Fig. 2: The study regions selected for the analysis: IGP, CI, Thar, SPU and SPL region.

Based on the monthly mean maps of XCH_4 over India (shown in Fig.1), the Indian landmass was dissected into five regions, namely Indo Gangetic Plains (IGP), Central India (CI), Thar (an arid region), Southern Peninsular Upper (SPU) and Southern Peninsular Lower (SPL) regions where the spatial patterns are distinctly different (Fig 2). Fig. 3 (a) shows the variation of monthly mean XCH_4 over these regions averaged for the period 2003 to 2009. The overall variation of XCH_4 is 1740-1890 ppbv over Indian region. The highest amplitude of XCH_4 values is observed in the IGP region (reaching 1880ppbv) with slightly less or comparable values over CI and the arid region of Thar (~1860ppbv). Towards south, a clear decrease in XCH_4 is observed with changes in seasonal patterns. Fig 3 (a) reveals two distinct aspects (1) the regional differences in XCH_4 and (2) distinctly different seasonal pattern of XCH_4 over the five regions, which are addressed in the following sections in detail.

Fig.3: (a) Monthly variation in XCH₄ at IGP, Thar region, CI, SPU and SPL,(b) Regional average of XCH₄, and (c) regional variation of seasonal amplitude of XCH₄-BL.

3.2. Regional variations of XCH₄ and source distributions

Fig. 3 (b) shows the annual mean XCH₄ for the five regions, bringing out the regional differences clearly. The mean XCH₄ remains high over north Indian regions, including the arid Thar region and exhibits a clear decrease towards southern peninsular India. The mean XCH₄ is ~20 ppbv less over southern most part of peninsular India compared to those over the northern counterparts. The atmospheric CH₄ has both biogenic and non-biogenic sources. The major biogenic sources include livestock, rice agriculture and wetlands. Fossil fuel mining and biomass burning constitute the non-biogenic sources. Among these, only agricultural activity, biomass burning and wetland emission have seasonality. Emission from other sources remains more or less steady over a year. A detailed analysis of spatial pattern of XCH₄ obtained from SCIAMACHY and GOSAT together with modeling Bergamaschi et al., (2009); Alexe et al., (2015) has attributed rice cultivation along with other anthropogenic sources to large CH₄ emission in the regions like India, China, and East Asia. The wetland emissions are the major contributor in tropical South America and African region (Bergamaschi et al., 2009). Details of the major sources of CH₄ over Indian region and their regional distributions are presented in the following sections. This analysis was done to see the dependence of source distribution and the emission on the observed regional features of XCH₄.

3.2.1. Rice cultivation

Wetland rice fields are identified as a major source of atmospheric methane in India, (IRRI; 2009). The region wise area of rice cultivation (*Source*: Directorate of Economics and Statistics, India) is shown in Fig 4 (a). It is largest in the IGP, followed by CI and Peninsular Indian regions (SPU and SPL), with minimum over Thar. Thus, the XCH₄ (Fig.3 (b)) and area of rice cultivation are positively correlated (with Thar being an exception), but there is no one to one correspondence. It can be seen that XCH₄ is comparable over IGP, CI and Thar even though there are significant differences in the area of cultivation. It may also be noted that the area of cultivation is significantly less over SPU and SPL are being 12% and 37% of that over IGP with the corresponding reduction in regional mean XCH₄ being ~7 ppbv and ~17 ppbv respectively.

The rice /production is often taken as a proxy for methane emission, rather than the area of cultivation. Fig. 4 (b) shows the region wise rice production. Like the area of rice cultivation, rice production also peaks over IGP, since most of the states which top in rice production (> 10 Million tons) lies in this region where the XCH₄ shows maximum. Even though area of rice cultivation is large over CI and comparable to SPU, the production is less. Over CI and Thar region XCH₄ is almost close to that over IGP, but the rice production is less (< 5 Million tons), implying that the direct emission from rice field is not a dominant contributor of CH₄ over Thar and CI. The comparatively high value of XCH₄ of CI and Thar points out the presence of unaccounted sources/transport/retrieval issue over desert region. The regional patterns of XCH₄ and rice yield are correlated fairly well.

3.2.2. Wetlands

Wetlands contribute to about 36% of the total global CH₄ emission (Pant et al., 2003). The areal extent of wetland is about 15.3million hectares (mha) over Indian region (excluding the area under rice cultivation) (Bassi et al., 2014). The region wise wetland distribution is shown in Fig. 4 (c) (source: National Wetland Inventory and Assessment (NWIA) of Ministry of Environment and Forest (MoEF)). CI has the highest proportion (39%) of the total wetland area followed by SPU and IGP covering about 25% and 22%.

3.2.3. Livestock

India with the largest number of cattle in the world, livestock/ruminants form a major source of CH₄ accounting for ~30% of the total agricultural CH₄ emissions (Sirohi et al., 2007). The region wise livestock population is shown in Fig. 4 (d) (source: Department of Animal Husbandry, Dairying & Fisheries, India). In the livestock distribution also, IGP holds the maximum population of livestock, with CI and SPU come next having equal share and SPL shows minimum. This pattern matches with that of XCH₄.

Fig 4: Regional distribution of (a) Area of cultivation, (b) Production of rice (c) wetland area, (d) Livestock population, (e) Fire count from MODIS, (f) Crude oil and Natural gas.

3.2.4. Biomass burning (BB)

Biomass burning is recognized as another source of trace gases, including CH₄ (Koppmann et al., 2005). Biomass burning is effectively identified and assessed by fire detection from space. The MODerate resolution Imaging Spectrometer (MODIS) on board Terra and Aqua satellites provides fire count information based on radiance measurements at the two mid IR bands, 4 μm and 11 μm (Giglio et al., 2006). In this study, the cloud corrected fire count data of the MODIS Aqua (MYD14CM1) during 2003-2009 of 1° × 1° spatial resolution (<http://ladsweb.nascom.nasa.gov/data/>) has been used and the region wise fire count is shown in Fig 4 (e). In terms of fire count, maximum biomass burning is observed at IGP, followed by SPU and CI with minimum in Thar region.

3.2.5. Petroleum and natural gas sector

Petroleum and natural gas mining form the major anthropogenic sources of CH₄ with steady emission even though their contribution is low (4.5%) over Indian region (Garg et al., 2011). The region wise distribution of the oil and gas production is shown in Fig. 4 (f) exhibiting similar pattern. In India, highest production of crude oil is from the Western India and the offshore mining from Bombay High which comes under the CI (Fig. 2) (Source: Ministry of Petroleum and Natural Gas, India) accounting more than 80% of the crude oil share of India.

3.3. Boundary layer Contributions of CH₄

Earth's surface and atmospheric boundary layer (BL) being the source region of CH₄, the contribution of the mixing ratio in the BL was examined. It is taken that the retrieved XCH₄ contributes only 20% the total column and remaining 80% is from boundary layer of ~2km height (up to 800 hpa) since 80% of atmospheric mass exists below 2km, (Hayashida et al., 2013). Based on this assumption the enhancement of XCH₄ in the boundary layer (XCH₄-BL) is estimated as $XCH_4-BL = A/0.2$ where A is the seasonal amplitude of XCH₄. Fig. 3 (c) presents the regional variation of XCH₄-BL. This pattern is slightly different from that of XCH₄ (in Fig.3

(b)). The BL contribution is maximum over IGP, comparable over CI and Thar with minimum over SPL.

3.4. Emission Inventory analysis

In this context, it is worth examining the regional pattern of XCH_4 along with the available emission inventory data. In this study, the CH_4 emission inventory data of EDGAR v4.2 (Emissions Database for Global Atmospheric Research) (<http://edgar.jrc.ec.europa.eu/overview.php?v=42>), Global Fire Emission Data (GFED) version 4s data (<http://www.globalfiredata.org/>) and REAS 2.1 (Regional Emission inventory in Asia) ([http://www.nies.go.jp/REAS/#data sets](http://www.nies.go.jp/REAS/#data%20sets)) were examined on a regional basis. The emission inventory data on livestock, biomass burning/total burning, oil, gas taken from EDGAR and rice data from REAS (emissions estimated in same units as EDGAR). Using GFED emission data, the CH_4 emission from different fire types, was also calculated as follows:

Methane emission= Dry Matter (DM) emission ($\text{Kg DM/m}^2/\text{month}$)* fraction of various sources (Savanna, peat etc.)* Emission factor ($\text{g CH}_4/\text{Kg DM}$) ----- (2)

DM emission and contribution of various sources are taken from GFED and emission factor from Akagi et al., (2011).

Fig. 5 a to f shows the region wise emission of CH_4 from different sources. A comparison of this along with the regional distribution pattern of various CH_4 sources in Fig. 4 reveals that both (statistical data of sources and emission inventory) follow more or less similar pattern, but there are discrepancies even though the inventory data are based on statistical data. In both, the regional peak is seen over IGP for most of the parameters except oil and gas. The regional distribution of livestock population and the CH_4 emission from livestock as per EDGAR are in good agreement. Pattern of rice production and REAS inventory are also more or less in agreement except for SPL. The largest deviation between the two is observed over the Southern peninsular region particularly SPL and the arid region of Thar. Even though the source distributions as well as the emission inventory data show low values, XCH_4 over Thar is relatively high, and comparable to other northern regions (IGP and CI).

Fig 5: Regional variation of CH₄ emission from (a) Rice [REAS], (b) Livestock [EDGAR], (c) Total burning [EDGAR], (d) Fire [GFED], (e) Oil [EDGAR], and (f) Gas [EDGAR] inventories.

3.5. Correlation analysis

The dependence of regional mean XCH₄ and its boundary layer counterpart XCH₄-BL of the regional distribution of CH₄ sources and emission inventories is examined quantitatively by carrying out the linear regression analysis between the respective parameters. Fig. 6 a to g depicts the scatter plot between XCH₄ against the source parameters livestock, rice production, wetland area, fire count, oil and gas along with regression fitted line. The regression coefficients are listed in Table.1. Statistically significant correlation coefficient ($R > 0.5$) with 95% or above confidence is taken as well correlated.

As observed in figures, livestock population is correlated well with the regional pattern of XCH_4 . The correlation is poor for oil and gas as seen from the figure and the table. The y-intercepts in Table 1 are indicative of background XCH_4 (in the absence of the active sources). The mean background XCH_4 over Indian region is estimated as ~ 1795 ppbv.

Fig 6: Linear regression analysis of XCH_4 and (a) Area of rice, (b) Production, (c) Livestock, (d) Wetland area, (e) Oil, (f) Gas and (g) Fire count.

Statistical/inventory Data of	XCH ₄ & statistical data			XCH ₄ -BL & statistical data	XCH ₄ & inventory data	XCH ₄ -BL & inventory data
	Y-Intercept	Slope	Correlation Coefficient [R]	Correlation Coefficient [R]		
Live stock	1790	0.095	0.78	0.84	0.39	0.60

Area or rice	1794	0.047	0.54	0.68	0.21	0.025
Production of rice	1795	0.015	0.42	0.62	No data	No data
Wetland	1793	2E-6	0.49	0.41	No data	No data
Fire count	1795	0.05	0.45	0.62	0.49	0.69
Gas	1795	0.005	0.45	0.19	0.61	0.50
Oil	1797	0.012	0.43	0.20	0.01	0.08

Table 1: Parameters intercept, slope and correlation coefficients of linear regression analysis

In order to understand the effect of these sources on BL contribution the above regression analysis was repeated for regional XCH₄-BL and the sources and the correlation coefficients shown in Table.1. Correlation coefficients show a significant increase for most of the parameters indicating that changes in sources are more strongly reflected in the BL mixing ratio. The correlation analysis with inventory data presented in Table.1 also indicates a better correlation with XCH₄-BL (except gas).

3.6. Seasonal features of XCH₄

The major seasonal features observed over the different regions include (Fig.3a):

(1) The annual peak occurs in the monsoon month of August over IGP, Thar and CI (North India) after which it decreases till November and broad minimum is observed from November to April/May (2) The seasonal peak is broader for SPU extending till November (3) There is a notable change in seasonal pattern over SPL with, the seasonal peak shifting to November with minimum seasonal amplitude (~1830ppbv) (5) During Oct-Nov, XCH₄ over SPU and SPL is high compared to the IGP, CI and Thar (6) During monsoon (June-Sep) when XCH₄ exhibits high over northern regions it is low over SPU and SPL. The major sources inducing seasonality in CH₄ include, rice cultivation, wetland emission and biomass burning. In addition, the meteorological conditions can also affect the atmospheric CH₄ levels favouring source /sink mechanisms. The agricultural practice in India is dependent on monsoon activity and takes place in two seasons, namely the Kharif (May to October) and Rabi (November to April). CH₄ emissions peak when the majority of rice is grown, which occurs, during the wet season, June to September (Pathak et al., 2005). The region wise area of rice cultivation and rice production during Kharif and Rabi seasons are also shown in Fig.4 (a) and (b). Over IGP, CI and SPU, area of rice cultivation and production is more comparable to SPL and Thar in Kharif season. But during Rabi season, the area of rice cultivation and production over SPU is higher

than those over IGP, CI and Thar. The high value of XCH_4 over IGP, during monsoon can be attributed to maximum CH_4 emission from the vegetative phase of rice cultivation during Kharif. The high value of XCH_4 during post monsoon and winter and the extended peak observed over SPU and SPL (Fig. 3 (a)) is attributed to the cultivation in the Rabi season over the region.

The Normalized Difference Vegetation Index (NDVI) is a numerical indicator widely used in vegetation studies to infer biomass coverage, plant growth factors, crop yield, etc. Seasonal variation of NDVI is examined to infer the changes of a growing pattern of rice. NDVI, is defined as

$$NDVI = (\rho_{NIR} - \rho_{RED}) / (\rho_{NIR} + \rho_{RED}) \quad (3)$$

Where ρ_{NIR} , ρ_{RED} are the reflectance values in the red and NIR regions of electromagnetic spectrum respectively. In this study, the NDVI monthly data from Goddard earth sciences, data and information service center (GES-DISC) (http://disc.gsfc.nasa.gov/data/collection/MODVI_V005.shtml) (Huete et al., 2002) is used. Fig. 7 (a) shows the mean monthly variation of NDVI for each study region. The seasonal pattern of NDVI is more or less similar to that of XCH_4 (in Fig.3. (a)) showing peak during Aug/Sep over IGP, CI and Thar. Towards south, the pattern starts deviating from this. Peaks start broadening and shifts towards Oct/Nov. The seasonal amplitude also gets reduced. But over SPL, the NDVI is higher than that over IGP, CI, Thar and SPU during most of the month except August/Sep when XCH_4 peaks over the northern regions.

Region	Correlation Coefficient (R) between		
	XCH_4 & NDVI	XCH_4 & FE/FC	XCH_4 & RF
IGP	0.65 (0.89)	0.14	0.84
Thar	0.83 (0.82)	0.46	0.78
CI	0.81 (0.86)	0.45	0.85
SPU	0.71 (0.87)	0.72	0.70
SPL	0.79 (0.82)	0.48	0.34

Table 2: Correlation coefficients (R) between XCH_4 and NDVI, FC, RF, temperature.

The correlation coefficients obtained by linear regression analysis between XCH_4 and NDVI (from Jan-Dec) for each region is listed in Table.2. For all the regions, these two parameters are positively correlated. Since the period of rice cultivation is mostly restricted to Kharif season (agriculturally active period) May to Oct/Nov, the correlation analysis was done in this period and the correlation coefficients are also presented in Table 2 (in bracket). It is observed that the correlation coefficients for the period May to November, drastically increases indicating that the seasonal enhancement in XCH_4 (50 ppbv to 100 ppbv in Fig.3. (a)) is significantly contributed from the rice cultivation.

Fig. 7: Mean monthly variation in the (a) NDVI, (b) total fire counts from MODIS and (C) CH_4 emission from fire using GFED at IGP, Thar, Central, SPU and SPL during 2003-2009.

The monthly variations in the area averaged fire count data, an indicator of biomass burning, over the five study regions along with CH_4 emission from fires estimated as discussed in section 3.4 are shown in Fig.7 (b) and (c) respectively. Both depict a similar seasonal pattern. The peak during the October month over IGP is associated with the burning of agricultural residue after the Kharif season. The correlation coefficients between XCH_4 and FC or FE are insignificant (Table.2) except at SPU ($R \sim 0.72$)

3.7. Low XCH_4 over Southern Peninsular India during monsoon

As discussed above, one notable feature in the seasonal pattern of XCH_4 is that over Southern region, particularly SPL, it drops during May- September, whereas it peaks over other regions. A comparison of seasonal pattern of XCH_4 and NDVI (Fig. 3 (a) and 7 (a) respectively) reveals that over this region, the NDVI is constantly high, throughout the year. The rice production over SPL is also comparable to that over CI and much higher than that over Thar (Fig.4 (b)), but XCH_4 remains low.

Fig. 8: Mean monthly variation in the (a) Temperature, (b) total Rain fall and (C) Vertically integrated moisture transport at IGP, Thar, CI, SPU and SPL during 2003-2009.

This reduced XCH₄ over Southern India in spite of high rice production needs investigation. It could be due the stronger sink action controlled by meteorology or decreased emission to the atmosphere from the source. In this context the seasonal variation of temperature (Climate Research Unit (CRU) time series version 3.22) and rainfall (<https://data.gov.in/catalog/all-india-area-weighted-monthly-seasonal-and-annual-rainfall-mm>) is examined (Fig.8 (a) and (b)). Both temperature and RF exhibit different seasonal behavior over the northern regions and southern regions. While RF is higher over SPU and SPL during June to Sep, compared to the IGP and CI, temperature is lower there during this period. The CH₄ emission from the rice fields is significantly influenced by the temperature, precipitation and water level (Marani et al., 2007). In general RF is favourable for CH₄ emission from rice fields. This is evident from the positive correlation between XCH₄ and RF (Table.2.). But water level >16.5cm in the soil is not favorable for CH₄ emission (Mallick et al., 2009). The high precipitation over southern peninsular regions may cause this condition and may inhibit/reduce methane emission leading to decreased XCH₄. The poor correlation between XCH₄ and RF over SPL supports this. In fact SPL experiences another less pronounced peak in RF over SPL during October. This favours the agricultural activities over Southern India and hence CH₄ emission. The overall temperature over SPL remains in the range 25°-30°C which is the optimum range for CH₄ emission through methanogenesis (Mallick et al 2009). The high XCH₄ during post monsoon and winter over this region can be attributed to this, in addition to high precipitation. On the other hand temperature is significantly lower over northern regions during this period and hence weak CH₄ production. But precipitation and water level in soil will be favourable here. Even though temperature and precipitation over SPL favour CH₄ production during monsoon also, XCH₄ remains low, indicating that some sink mechanism is active over there. This aspect is discussed below.

The monsoonal circulation from the Indian Ocean and Arabian sea during June to Sep, transport huge amounts of water vapour over to Indian land mass. It is also known that OH radical source of which is water vapour can cause depletion of CH₄. In this context, the seasonal pattern of the transported flux of water vapour variability in the column was estimated on a monthly basis as given below and shown in Fig. 8 (c).

$$\text{Transported flux of integrated water vapour} = 1/g \left[\int_{p_1}^{p_2} q U dp \right] \text{----- (4)}$$

q- Specific humidity and U – total wind [$\sqrt{u^2 + v^2}$], g – acceleration due to gravity.

q, and u, v the (wind components) are obtained from ECMWF Re-Analysis ERA- Interim (<http://www.ecmwf.int/en/research/climate-reanalysis/era-interim>). The transported water vapour is highest over SPL and SPU during monsoon and hence there is possibility of depletion of CH₄ during this period.

4. Conclusions

XCH₄ retrieved from SCIAMACHY was analyzed over Indian region to investigate its spatio-temporal variations at five distinct regions such as Indo Gangetic Plains (IGP), Thar (arid region), CI, Southern Peninsular Upper (SPU) and Southern Peninsular Lower (SPL) regions. Major results are summarized below:

- The spatio-temporal variation of XCH₄ over Indian region is 1740–1890 ppbv during the period 2003-2009, with significant regional differences. Highest XCH₄ values were observed during monsoon and post monsoon in the northern regions. Southern peninsular regions exhibit distinctly different seasonal behavior with seasonal peak late in October-December month and low values during monsoon.
- These regional variations in XCH₄ are closely associated with the source distribution of sources like livestock population (with highest correlation coefficient), followed by rice cultivation, wetland, biomass burning and oil and gas mining. The boundary layer fluctuations in XCH₄ show stronger correlation with sources.
- Setting apart the seasonal increase, the background XCH₄ over Indian region is estimated as 1795±1.4ppbv.
- Comparison of Statistical data on source distribution and emission inventory revealed reasonable agreement between the two, but no one-to-one correspondence.
- Seasonal variation of XCH₄ over Indian region (~100 ppbv) is controlled by agricultural activities, mainly the rice cultivation as revealed by NDVI analysis. Emission from wetlands and biomass burning also plays a role over IGP and CI.
- Over Thar even though sources and emission inventory data shows low, XCH₄ is comparable to that over IGP and CI. This could be due to transport from nearby source regions and emission from some unaccounted sources. At SPL even though sources are

active XCH₄ shows low. The peculiar meteorological conditions, high precipitation and high water vapour content over the region reduce the XCH₄.

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