Understanding atmospheric methane sub-seasonal variability over India

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HIGHLIGHTS

- Surface CH₄ observations in India show coherence of 30-90 day oscillations.
- Adverted CH₄ signal shows clear northward propagation of anomalies during JJAS.
- The co-evolutions of CH₄, OLR, and OH radicals are presented for the JJAS period.

GRAPHICAL ABSTRACT

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ABSTRACT

Atmospheric methane (CH₄) is considered to be one of the most important greenhouse gases due to its increasing atmospheric concentrations and the fact that it has a warming potential 28 times that of atmospheric carbon dioxide (CO₂). Over the Indian sub-continent, fluxes and transport both contribute towards CH₄ seasonal variability. Its intra-seasonal variability however is more complex as it is additionally influenced by monsoonal activity during the Asian Summer Monsoon (ASM) period. In this study, the intra-seasonal variability of atmospheric CH₄ is examined using ground-based observations at two sites located in the Southern Indian Peninsula, Sinhagad (SNG) and Cape Rama (CRI); and outputs from three different model simulations. Both, the ground based observations and multi-model simulations show that the dominant spectral variability of CH₄ is coherent with 20-90 day oscillations in the dynamics of the monsoon (termed hereafter as Intra-Seasonal Oscillations, ISOs). The multi-model analysis revealed that CH₄ is heavily influenced by advection due to this intra-seasonal variability. The simulations also display a clear northward propagation of CH₄ anomalies over India. The co-evolution of CH₄, outgoing long wave radiation (to represent convection) and OH radicals (proxy to CH₄ sinks) is presented. The study quantifies CH₄ variability at intra-seasonal timescales and also its spatial extent. The results suggest that the effect of ISOs on CH₄ needs to be considered along with the corresponding observations for future inverse modeling.
1. Introduction

Emissions of atmospheric methane (CH₄) are of primary concern in India as it is one of largest emitters in the world (UNFCCC, 2018 database; Ganesan et al., 2017). Quantifying these regional emissions is critical to understand the total effect of CH₄ on the global radiative forcing, which is estimated to be $-0.48 \pm 0.05$ W m $^{-2}$ by the end of the 20th century (Fifth Assessment Report, IPCC, 2013). Atmospheric CH₄ has both natural and anthropogenic origins. Wetlands act as the primary natural source (Cao et al., 1998), while rice paddies (Purkait et al., 2005; Khalil et al., 2008), livestock (Crutzen et al., 1986; Naqvi and Seijan, 2011), landfills (Chakraborty et al., 2011), combustion of fossil fuels, agricultural waste, bio-fuels (Howarth et al., 2011; Leilieveldet al., 1998) are the dominant anthropogenic sources. The main sink of atmospheric CH₄ is its reaction with hydroxyl radicals (OH) in the troposphere (Kirschke et al., 2013; Patra et al., 2014; Ghosh et al., 2015). Although the main sources and sinks of CH₄ are well known, estimating its budget has large uncertainties, especially at regional scales (Patra et al., 2016). Apparently, this difficulty is due to multiple and interconnected sources and sinks as well as transportation from the source areas to the measurement sites, which can vary greatly with seasons. This issue is further complicated by the shortage of observations that can capture these complex variations at a regional scale (Patra et al., 2016).

Guha et al. (2017) and Patra et al. (2016) have discussed in detail the seasonal variability of CH₄ over India. Here, CH₄ concentrations show large variations due to the dramatic seasonal reversals in upper and lower atmospheric circulation during the Asian Summer Monsoon (ASM) season. CH₄ seasonal variability over India is close to 200 ppb, showing a minimum during the ASM season (approx. 1800 ± 20 ppb) and a maximum during the winter season (approx. 2000 ± 30 ppb; Guha et al., 2017). In addition to the seasonal CH₄ variability during the Indian summer monsoon, it is expected that sub-seasonal variability and associated atmospheric dynamics would affect the CH₄ variability over India (Ravi Kumar et al., 2016; Wang et al., 2006; Valsala et al., 2013). Understanding the drivers behind these variability is important considering that observations of CH₄ are used to identify sources and sinks by inverse modeling (Ganesan et al., 2017).

Indian summer monsoon is broadly termed as a lower level atmospheric inflow of oceanic air due to the land-ocean contrast established over the Asian-Indian Ocean region during the summer season (June to September). Modulating this mean flow are the intermittent perturbations of northward propagating convection, originating over the oceanic convergence zone near the equatorial Indian Ocean and propagating northward towards the monsoon trough over the land (i.e. Himalayan foothills). When these convections are active, the landmass receives increased rainfall followed by a short spell of break days where the convection and rainfall is weak (Sikka and Gadgil, 1980; Yasunari, 1979; Wang et al., 2006). This oscillation between active and break spells of rainfall over India is termed as Intra-Seasonal Oscillations (ISOs) and is best observed at the CO2 ISOs at these two stations and found that the local biosphere fluxes, in response to monsoon ISOs, determine the CO2 variability (Valsala et al., 2013). Preliminary analysis of CH₄ using the same methodology indicates that dominant peaks of variability between 20 and 90 days are seen in atmospheric CH₄. Therefore, variability in CH₄ concentrations at ISO timescales deserves special attention.

In order to understand the CH₄ ISOs over India, we use model simulations in addition to surface observations in this study. The major foci of this study are to answer (i) what the patterns of atmospheric CH₄ ISOs over India are; (ii) what the associations of CH₄ variability at ISO time scales with the underlying atmospheric dynamics are; and (iii) what the major causes of CH₄ ISOs over India are. Answering the above questions is important considering that at present the observed CH₄ concentrations over India are used for interpreting the sources/sinks by statistical methods. Considering the negligible role of fluxes in controlling the atmospheric CH₄ seasonality over India (Guha et al., 2017), one may anticipate a similar relationship between CH₄ ISOs and fluxes. Hence, it is nontrivial to verify whether the state of the art atmospheric transport models capture such variability.

2. Data and methodology

In this study we have used CH₄ observations from two ground-based stations i.e. Sinhagad (SNG) and Cape Rama (CRI); and CH₄ concentration fields simulated by three different models i) Laboratoire de Météorologie Dynamique (LMDz) model, ii) JAMSTEC’s atmospheric chemistry transport model (ACTM), and iii) the 3D global chemistry Climate Model CAM-Chem. We have also used the Kalpana retrieved OLR dataset to identify the dynamical ISOs. Details of the models and OLR dataset are given in Sections 2.2 and 2.3.

2.1. Surface observations

A facility for measuring ambient mixing ratios of long-lived greenhouse gases (e.g. CO₂, CH₄ etc.), was established in India in 2009. This laboratory is equipped with Gas Chromatograph (GC) instrument, automatic air sampler, glass flasks, and flask evacuating-heating equipment. In this study, we used surface observations from two sites.

1) Sinhagad (SNG) is a mountain site located at the western boundary of India (200 km east of the Arabian Sea: 18.35°N, 73.75°E, 1600 m above mean sea level). Air Sampling location is free from any major vegetation in the vicinity. The prevailing wind speed during the time of sampling (i.e. noon) is comparatively low (0.5–1 m s $^{-1}$). Air samples at SNG are collected from top of 10 m tower at a weekly interval. Collected paired flask samples are analyzed at GC lab located at the Indian Institute of Tropical Meteorology (IITM) Pune. The analysis is calibrated using international standards provided by the WMO Central Calibration Laboratory (CCL) located at the National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory (ESRL)/Global Monitoring Division (GMD), Boulder, Colorado, USA. The repeatability of the instrument was checked at regular interval using NOAA CH₄ calibration standards. To understand the reproducibility in measurement paired flask samples were analyzed in the GC. The reproducibility was found to $\pm 5$ ppb (Guha et al., 2017). The entire monitoring procedure air sample collection to GC analysis, were carefully examined. We made sure that the collected samples are representative of large volume of atmosphere. Samples contaminated by local sources are flagged and excluded from data analysis. Details of sample analysis, data acquisition, and calibration procedures are described in Tiwari et al., 2011; Ravi et al. (2014); Guha et al. (2017). We adopted data analysis and quality control (QA/QC, outlier detection in raw data, etc.) methods described in Dlugokencky et al., 1994. CH₄ concentrations observed at SNG during 2010–2013 are used in this study.

2) Cape Rama (CRI) is a coastal site in the state of Goa (15.08°N, 73.83°E, elevation = 50 m above mean sea level). CRI was maintained by the Commonwealth Scientific and Industrial Research Organization
Laboratoire (Laboratory), air sampling was conducted from February 1993 until
(February 1993 until
CSIRO) Atmospheric Research GASLAB (Global Atmospheric Sampling
Y.K. Tiwari et al. 2011 ). The observations between July 2009 and January 2013 from CRI
(2009, 2011a, 2016)
and Chandra et al. (2017).
c) NCAR Community Earth System Model with Chemistry (CAM- Chem) (version 4) (Lamarque et al., 2012) included in the CESM framework, was used in this study to estimate the CH₄ and OH tropospheric mixing ratios, as well as their temporal and spatial evolution. The simulation employed in this work is based on the Chemistry Climate Model Initiative – Reference Experiment (CCMI-REFC1) setup (Hegglin et al., 2014; Fues et al., 2016), and includes an updated halogen chemistry scheme (chlorine, bromine and iodine; Saiz Lopez et al., 2012, 2014, 2016). Lower boundary conditions (LBC) for long-lived gases as well as the anthropogenic gas-phase emissions are equivalent to Fernandez et al. (2017). This model uses a horizontal resolution of 1.9’x 2.5’ and 56 sigma-pressure levels in the vertical. The model was run in Specified Dynamic (SD) mode (Lamarque et al., 2012) using real meteorological fields from the Modern-Era Retrospective analysis for Research and Applications (MERRA) reanalysis database (Rienecker et al., 2011). OH concentrations are simulated in real time during the model run. Although data from 2006 to 2014 were employed in this work, the model run started from 2005 to reach steady state conditions.

To perform a thorough comparison between the observations and model simulations, the simulations are sampled at the same location and time as the SNG and CRI observations. The main differences between the LMDz, ACTM, and CAM-Chem are: first, the spatial resolution, with ACTM and CAM-Chem having coarser resolution than LMDz; second, all three models use different surface fluxes as inputs; and third, the meteorological fields used to solve model transport equation differ between the models. Thus, using such diverse models provides a thorough test of model-observation comparisons.

2.3. Satellite retrieved outgoing long-wave radiation (OLR)

The OLR data used in this study are from the Indian satellite Kalpana-1 (formerly METSAT-1) from 2006 to 2014. Kalpana-1 consists of a very high resolution radiometer (VHRR) used for meteorological applications. OLR values are an indicator of deep convection and are used for precipitation estimation (Xie et al., 1998). OLR data were estimated at a three hourly basis with a spatial resolution of 0.25’x 0.25’ from the observed radiances of Kalpana-1 VHRR. More details about the OLR data estimation from Kalpana-1 satellite are available in previous publications (Mahakur et al., 2013; Prakash et al., 2015).

2.4. Data analysis

In order to identify the dominant periodicties at sub-seasonal timescales, power spectrum analysis was done on the de-trended and de-seasonalized observed data from the two stations (SNG, CRI) and daily output from the three model simulations at the two selected stations. From this we have noted the dominant power spectra peaks at sub-seasonal time-scales. For further analysis of model CH₄ concentrations at these sub-seasonal timescales, we have done the following: First, the annual (365 days) and semi-annual (180 days) cycles were removed from each year by employing harmonic filtering and the processed data were sampled for 121 days from 1st June to 30th September (JJAS) (Ravi et al., 2016). The JJAS days of each year were then stitched together into a single series (i.e. from 2006 to 2014 comprising a total of 1089 data points in time) and only the 20–90 day cycles were extracted by using harmonic filtering. Further details of the data analysis can be

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found in our past publications (Ravi et al., 2016).

In order to show the 20–90 day modes in the summer monsoon convection and associated dynamics, lead-lag spatial maps of OLR anomalies were produced (40°E - 120°E, 10°S - 40°N). This was obtained by regressing a central India averaged OLR index (from 20 to 90 day filtered OLR data as above) onto OLR anomalies for all the grid-points in the above domain with a lead or lag applied to OLR index within a range of −20 to +20 days. This processed data is used to understand the propagation of CH₄ anomalies at ISO scales during both active and break phases of the ASM. This analysis is defined as the ‘lead-lag propagation’. The first day of the active spell is considered as day0 and the lead-lag analysis is done −20 to +20 days from this benchmark. The dates for active rain spells for the years were identified from the OLR anomalies averaged over the Indian region using the method as in Pillai and Sahai (2016). A composite mean of all such events was used to delineate a −20 to +20 day evolution of OLR, CH₄ and OH anomalies and their coherent structures. Similar composite evolutions of break spells were also calculated.

Correlations between OLR and the processed CH₄ data for all 1089 time steps are calculated over the same domain (40°E-120°E, 10°S-40°N) at lead or lag for a range of days from −15 to 15. This has resulted in a total of 31 spatial correlation maps (and for each vertical level in the model). In order to identify the dominant correlation patterns between CH₄ and OLR, an empirical orthogonal functions (EOF) analysis over these 31 correlation maps was conducted (but only for LMDZ model as a test case). This helped to conclude on the meaningful dominant correlation patterns between CH₄ variability (at each grid point) and OLR (proxy for convection) at ISO timescales and provided information on how they oscillate with a specific lead or lag between them.

3. Results and discussions

Fig. 1 shows the measured surface CH₄ at the two observational sites, Sinhagad (SNG) and Cape Rama (CRI) along with the with model simulation outputs from the three models mentioned above. The correlation coefficient Pearson’s r indicates that model simulations are in close agreement with the observations (Fig. 1). CH₄ concentrations start increasing from September and peak in January, followed by a decreasing trend from February, reaching a minimum in August. An increasing trend is observed from 2009 to 2013. The trend and seasonal cycle show similar patterns in the three models as well. A strong seasonal variation, with a peak-to-peak amplitude of about 300 ppb at SNG and 200 ppb at CRI is observed. SNG is located in the mountains (1600 m above mean sea level) whereas CRI is located closer to the coast with low vegetation in the vicinity. Lin et al. (2018) evaluated the LMDz model performance using various surface observations, including Indian sites SNG, CRI, Hanle, Pondicherry, and Port Blair, over South and South East Asia. Results show that the model simulations agree with the observations on an annual and seasonal scale. Further, Bhattacharya et al. (2009) and Tiwari et al. (2011) evaluated the ACTM model capabilities over India using surface observations at CRI, again showing a good match between observations and model simulations.

The power spectrum presented in Fig. 2, indicates that there are clear spectral peaks at 27, 89 and 116 days for observations at SNG. For CRI, the spectral peaks at 70 and 114 days are clearly visible. The corresponding model outputs at SNG show spectral peaks at 91, 122 and 183 days (for LMDZ); 19, 23 and 122 (for ACTM); 32, 91 and 122 (for CAM-Chem). The model outputs at CRI show spectral peaks at 28, 39 and 112 days (for LMDZ); 27, 31 and 112 (for ACTM); 28, 37 and 112 (for CAM-Chem). These analyses indicate that atmospheric CH₄ is embedded with an ISO signal with a predominating 20–90 day cycle. Similar ISO structures in atmospheric CO₂ were identified earlier (Ravi Kumar et al., 2016). However, one of the reasons for that was the corresponding variability in fluxes rather than in atmospheric dynamics (Valsala et al., 2013). In case of CH₄, the ISOs are expected to be dominated by atmospheric dynamics rather than fluxes because flux variability is not a determining factor in the seasonal cycle of atmospheric CH₂O over India (Guha et al., 2017). Moreover, all the models here are run with climatological monthly mean CH₄ fluxes and therefore the inherent ISO variability in model CH₄ concentrations cannot origin from the fluxes but would be driven more by dynamics or from atmospheric chemistry.

Fig. 3 depicts the lead-lag regressions for OLR anomalies based on an index of OLR averaged over the Indian region (Fig. 3). Here, the negative OLR anomalies stand for convection and organized rain. As time progresses from −20 to +20 days, convection from the equatorial oceanic region appears to move northward and the cycle terminates by +20 days over land. The corresponding CH₄ anomaly propagations are represented as latitude-time plots of composite CH₄ evolutions for active and break rainy spells (see Section 2.4 for details) for three different vertical levels (Fig. 4). The area averaged for these plots is over a region between 55° E and 110° E and shown for the surface (1000 mb), middle troposphere (650 mb) and upper troposphere (230 mb) for each of the three models considered here.

A conspicuous feature revealed in the composite analysis is a clear northward propagation of CH₄ anomalies with an amplitude of ±10 ppb and at a speed of approximately 1.5° latitude per day. On the day that the active spell commences (i.e. at zero on the time axis), the CH₄ concentration anomalies switch from positive to negative at the surface, middle and upper troposphere. This is visible in the three model outputs analyzed here, although with some differences from model to model. During the active spells over the land, the convection is at its peak and CH₄ appears to reduce in concentration at the surface and is also slightly lower in the middle troposphere but hardly any change is seen in the
upper troposphere. This phenomenon continues from 0 to +15 days. This indicates that due to convection, oceanic air masses that have less CH$_4$ get transported from the lower troposphere to the middle troposphere over India. At the upper troposphere (230 mb) the CH$_4$ anomalies during and following the active phase are rather weak. An opposite trend in CH$_4$ anomalies is visible during the break phase as expected (Fig. 4). On the day that the break spell commences and during its progression from 0 to +10 days, the CH$_4$ concentration anomalies at the surface switch from negative to positive. This is also visible in the middle troposphere and more distinctly in the upper troposphere. The background mean CH$_4$ concentrations over India during summer have been previously reported by Guha et al. (2017). According to their study, during the summer monsoon season over India, surface CH$_4$ is lower than in the upper troposphere, which indicates a dilution effect of CH$_4$ due to the advection of oceanic air-masses from the near-equatorial region towards the Indian continent (see also Patra et al., 2016). Convection during the active period transports these air masses with low CH$_4$ aloft. However, during the break period large scale subsidence over India brings the upper tropospheric air-mass downwards. These air masses are enriched in CH$_4$ as compared to the surface air. This explains the strong CH$_4$ anomalies in the upper and middle troposphere during break period compared to the surface. Therefore, the active and break composite responses of CH$_4$ appear as a see-saw pattern vertically (compare Fig. 4, panel ‘a’ and ‘f’ in all three models).

The atmospheric CH$_4$ budget is controlled by the surface fluxes, transport and sinks, mainly due to hydroxyl radicals (OH). Therefore the role of OH in modulating the intra-seasonal signal of CH$_4$ has to be quantified and we calculate the active-break composite of CAM-Chem simulated OH (Fig. 5) using the same method as used for CH$_4$. It is observed that OH does not show an ISO variability similar to that of CH$_4$. Thus, it appears that OH does not have any discernible impact on the CH$_4$ variability at ISO timescales. This is an expected result since a change of ±10 ppb in CH$_4$ would not be expected to have a large impact on the oxidizing capacity of the troposphere on such short timescales. Further, we estimated the loss of CH$_4$ through reactions with OH (k = 1.85 × 10$^{-12}$ e$^{(-1690/T)}$; Atkinson et al., 2004) during the ASM season (JJAS). The CH$_4$ lifetime is approximately 782 days assuming the mean OH concentrations above the Indian sub-continent during the ASM (0.06 pptv). To cause a reduction of about 10 ppb, it would take about 4 days. This result indicates that the change in CH$_4$ during the active and break spells is within the oxidation timescale and hence OH oxidation could play a role in addition of transport of different air masses. However, the lack of a large difference in the OH concentrations between the active and break spells indicates that the difference in CH$_4$ between the two spells is most probably driven by transport rather than oxidation chemistry, as can be seen through the OH and CH$_4$ ISOs.

In order to understand the spatio-temporal locking of CH$_4$ variability in relation with convection, a correlation between OLR and CH$_4$ anomalies at each grid point over the analyzed domain was conducted (see Section 2.4). OLR lead-lag analysis spanning −15 to +15 days with respect to the CH$_4$ data was conducted and the correlations for each lead-lag was analyzed. A side-by-side analysis of all lead-lag at all levels of spatiotemporal correlations appears as chaotic in space and time, because of which we employ EOF analysis on correlation maps (see Section 2.4). CH$_4$ variability in the 20–90 day mode in the model simulations (also in the observations) is connected to the convection and its northward movement as per the dynamics of the ASM. At each lead and lag from −15 to +15 days, the CH$_4$ and OLR are correlated in space and thus there are 31 maps of correlations for each level above the surface. To summarize how the correlation itself changes from a lead-lag of −15 to +15 days, a correlation spatial pattern analysis (CSPA) was conducted (see Section 2.4).
to +15 days, EOF analysis of correlations is presented. Fig. 6 thus enables us to conclude the joint spatio-temporal variability of the 20–90 day mode in CH$_4$ oscillations in connection with the Asian monsoon. Fig. 6 shows the dominant mode EOFs of correlation coefficients (EOF-1 and EOF-2) in space and their principle component in time composed of -15 to +15 days of lead-lag axis. Here the -15 means that the OLR lags CH$_4$ by 15 days and +15 means that the OLR leads CH$_4$ by 15 days. At the surface level (1000 mb), the EOF-1 pattern of correlations is positive over India with negative limbs over the Bay of Bengal and north-western region of India (Fig. 6, Panel ‘a’). The patterns are largely organized in space indicating that a large-scale feature exists between CH$_4$ and convection. The pattern of surface level (1000 mb) PC-1 peaks at a lag of -6 days (i.e. OLR lagged CH$_4$ by 6 days). However, the reason for such a lag is not clear from the present analysis. It changes sign at a lead of +9 days (Fig. 6, lower left panel). Overall the cycle completes in ~50 days as the quasi-sine wave shape seen in principle components (PC). EOF-2 (Fig. 6, Panel ‘d’) has an entirely different structure, with negative correlations accumulated over the Indian land mass extending all the way to the northern part of the domain, with a positive patch over the north Arabian Sea. The PC-2 (Fig. 6, lower left panel) suggests that the pattern peaks in this shape at almost zero-lag between CH$_4$ and OLR. The cycle of this mode also completes a quasi-cosine wave shape in about 50 days. The correlation between PC-1 and PC-2 is almost zero indicating that the modes are orthogonal. Both modes are of significant variances.

In the upper atmosphere (230 mb), the EOF-1 correlations are widespread through an east-west direction over the land. The corresponding PC-1 (Fig. 6, ‘lower right’ panel) indicates that this is an in-situ correlation between CH$_4$ and OLR because the pattern peaks when the lead-lag is zero. A possibility could be that in the presence of moisture in the lower atmosphere, the CH$_4$-OLR coupling has a lag of 6 days, which is close to zero in more dry conditions such as the upper atmosphere (230 mb). Whether the role of absorption bands of CH$_4$ and water vapor are interlinked or not is unclear from this study. EOF-2 in the upper troposphere (230 mb) shows more chaotic features (Fig. 6f).

4. Summary and conclusions

The main inferences derived from this study can be summarized in the following six points. (i) Atmospheric CH$_4$ has short term variability over India during the monsoon period. The power spectrum analyses of observations and models indicate that atmospheric CH$_4$ is broadly embedded with a 20–90 day ISO signal. (ii) Monsoon dynamics control the atmospheric CH$_4$ ISOs. (iii) Active to break and break-active transitions of monsoon ISOs as revealed in the OLR anomalies are equally imprinted on the atmospheric CH$_4$ variability over India, with negative (positive) CH$_4$ anomalies from the date of onset of active (break) to next 15 days. (iv) The strengths of CH$_4$ ISO anomalies are stronger (weaker) at surface (upper atmosphere) for active (break) periods. (v) There is as clear northward propagation of CH$_4$ anomalies at an amplitude of ±10 ppb and at a speed of approximately 1.5° latitude per day. (vi) OH does not have a controlling impact on the CH$_4$ variability of amplitude ±10 ppb in the atmosphere at ISO timescales.
Fig. 4. Active-break composite evolution of atmospheric CH$_4$ anomalies (ppb) over India, as simulated by models LMDz (upper left panel), ACTM (upper right panel), and CAM-Chem (lower panel). The data was averaged from 55°E to 110°E and is shown from the equator to 30°N.

Author contributions

Y.K.T., V.V, T.G. conceived the study, performed the analysis and prepared the manuscript. A.S.L., C.U., R.P.F., A.S.P. performed model simulations and data analysis. T.G., Y.K.T, and V.V provided additional contribution in data analysis and figures preparation. All co-authors contributed to the interpretation of the results and drafting of the manuscript for publication.
Fig. 5. Active-break composite evolution of OH radical anomalies (ppt) over India as simulated by the CAM-Chem model (averaged from 55°E to 110°E and shown from equator to 30°N).

Fig. 6. EOFs of correlation coefficients (EOF-1 and EOF-2) between OLR and CH$_4$ anomalies at: (a,d) surface (1000 mb); (b,e) middle troposphere (650 mb); and (c,f) upper troposphere (230 mb). Their principle components (PC-1, PC-2) (lower Panels: left 1000 mb, mid 650 mb, right 230 mb) in time composed of −15 to +15 days of lead-lag axis are also shown.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2019.117206.

References


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