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* Corresponding Author:

tyagib@nitrrkl.ac.in

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Then and Now: COVID-19 Pandemic Lockdown Misfire Atmospheric Methane over India

Manoj Hari , Rajesh Kumar Sahu , MS Shyam Sunder , Bhishma Tyagi *

Department of Earth and Atmospheric Sciences, National Institute of Technology Rourkela,
Odisha 769008, India

ABSTRACT

COVID-19 lockdown resulted in the revival of the environment due to reduced emissions of various pollutants globally. In particular, aerosols, NO_x and SO₂ showed significant reductions at most places. However, the greenhouse gases are not necessarily following this reduction everywhere. In most areas, a decrease in NO_x increases methane (CH₄) concentration by enhancing the lifetime, but also results in decreased concentrations with reduced emissions. Analyzing the atmospheric CH₄ variations during the COVID-19 lockdown over India is crucial as India is one of the regions with high seasonal variability of CH₄. The present study has analyzed the tropospheric CH₄ trends over India during the pre-monsoon season (March–May) for 2003–2021 using AIRS data. The study analyzed the lockdown variations (24 March–31 May) of tropospheric CH₄ over India with the same period of 2019 and 2021 using TROPOMI to find the changes in CH₄ concentrations over different regions of India due to lockdown. Our results capture the undeviating north (low)–south (high) gradient in the CH₄ concentration with anticipated regional intensifications, likely, in the eastern and western coastal regions, with more comprehensive details than it ever has been presented before.

Keywords: Atmospheric methane, NO_x, COVID-19 lockdown, Seasonal variability, TROPOMI

1 INTRODUCTION

With a considerable residence time (7.2–10.1 years, with an average value of 9 years) in the troposphere (Morgenstern *et al.*, 2018), Methane (CH₄) – a potent greenhouse gas (GHG) holds the global warming potential of about 28–36% for a century (Hogan *et al.*, 1991; Forster *et al.*, 2007). Anthropogenic instigation increased the atmospheric CH₄ to 259% higher than the pre-industrial level (Dlugokencky *et al.*, 1994; WMO, 2019). Though the growth rate is slowed down due to strict policies globally (Dlugokencky *et al.*, 1998), the atmospheric concentrations are already too high. Comparatively, CH₄ at global scale exhibit huge interannual annual fluctuations by rapid positive instability in CH₄ sources every year, which notably cause significant uncertainty in regulating the atmospheric CH₄ concentration. Leading which, quantifying the CH₄ budget remains highly elusive, and thus, evaluating the variability is consequential for better projection of atmospheric CH₄.

As the sources of atmospheric CH₄ are both natural and anthropogenic, the global atmospheric CH₄ puts India as one of the top contenders for CH₄ emissions, including natural wetlands, biomass and biofuel burning, agricultural waste and fossil fuels (Saunois *et al.*, 2020). According to a field campaign in 1991, the Indian paddies CH₄ budget average is 4 Tg year⁻¹ (Parashar *et al.*, 1996). The annual values of CH₄ emissions from coastal wetlands of southern India ranged from 3.10 mg m⁻² hr⁻¹ (Bay of Bengal) to 21.56 mg m⁻² hr⁻¹ (Adyar River), apart from the seasonal variations (Purvaja and Ramesh, 2001). Between 2002 and 2003, the estimated average value of CH₄ flux from municipal solid waste landfill areas varied from 146–454 mg m⁻² hr⁻¹ (Rawat *et al.*, 2008). Guha *et al.* (2018) utilized in-situ observations from two tropical Indian stations (Sinhagad and Cape Rama) to analyze the seasonal variability of CH₄, with minimum values associated with

southwest monsoon and maximum values over northeast monsoon. Tiwari *et al.* (2020) also noticed seasonal variability and sub-seasonal variability over these sites using both in-situ and model simulations. Recently, Singh *et al.* (2021) explored the CH₄ variability over India using GOSAT data from 2009–2020 and analyzed the year-wise progression of seasonal and annual CH₄. As expected, the CH₄ concentrations are increasing over India from 2009–2020, with higher concentrations over parts of central, eastern and southwest regions. For the pre-monsoon season (i.e., March–May), the CH₄ variability trends show a gradient from north to south (low to high values) over India. The average values showed that the post-monsoon season experienced the highest concentrations, followed by winter, monsoon and pre-monsoon (Singh *et al.*, 2021). However, the study has not accounted for the year 2020 abnormal variations over the country. For feasibility, some of the selective studies with comprehensive summary and characteristics are listed in Table 1.

The unprecedented spread of CO₂ Virus Disease-19 (COVID-19) worldwide in early 2020 forced most of the world to go into a state of lockdown (Karatayev *et al.*, 2020), resulting in a shift in modern lifestyle globally, with a negative response to isolation (Thakur and Jain, 2020) and a positive response to the environment (Muhammad *et al.*, 2020). The revive in the environment is more pronounced over the countries like India, where the ambient air pollution was high and shared a significant burden on health (Balakrishnan *et al.*, 2019; Gautam, 2020; McDonald *et al.*, 2020). The Government of India imposed a lockdown from 24 March–31 May 2020 to combat the COVID-19 spread over the country (<https://www.mygov.in/covid-19>; Bherwani *et al.*, 2020). The global lockdown due to COVID-19 resulted in a significant decrease in aerosols, NO_x and SO₂; however, not in the greenhouse gas (CO₂ and CH₄) concentrations. The reasons for no reductions were decreased ocean uptake of CO₂ and a likely increase in CH₄ lifetime from reduced NO_x emissions. These changes in CO₂ and CH₄ are further moderated by carbon-cycle feedbacks to CH₄ and CO₂ along with background pollutant levels and wildfires apart from other factors (Laughner *et al.*, 2021). Stevenson *et al.* (2021) also supported the increase in CH₄ concentration due to reduced NO_x concentrations globally during the COVID-19 lockdown. However, localized studies across the globe portrayed contradicting results during the lockdown (Rendana *et al.*, 2021; You *et al.*, 2021).

Over the Indian region, the primary focus for analyzing the reduction in atmospheric pollution remains on particulate matter, NO_x and SO₂ (e.g., Sahu *et al.* (2020), Singh *et al.* (2020), Hari *et al.* (2021), Singh and Tyagi (2021), and Tyagi *et al.* (2021)). Limited studies have reported the variations in CH₄ during the lockdown period. Notably, Chauhan and Singh (2021) used AIRS satellite data over six megacities of India, and Behera *et al.* (2021) focused on seven west-east Indian agro-climatic zones by utilizing Sentinel-5P data and highlighted the increased CH₄ concentrations. Behera *et al.* (2021) reported that the seasonal variability of CH₄ was linked to crop-residual burning, and the study defined higher CH₄ values in 2021. Similarly, Dutta *et al.* (2021) argued that the increase in CH₄ over India agreed with the global rise using Sentinel-5P. However, the data gaps in their visualized analysis do not fully support their conclusion. From a global CO₂ and CH₄ perspective, no significant variations of CH₄ were reported concerning lockdown (Sharma and Verma, 2021), which was supported by Tibrewal and Venkataraman (2021) findings, who summarised insignificant variations in CH₄ during COVID-19 lockdowns over India. However, the reported studies over India during the COVID-19 lockdown period did not explicitly explore the lockdown period compared to the previous period/year and afterward concentration. The present study is an attempt to cover this gap by analyzing trends in CH₄ concentrations during the pre-monsoon season for 2003–2021 and comparing the total lockdown period (24 March–31 May 2020) with similar periods in the preceding year (2019) and succeeding year (2021). The study aims to understand the spatial variations in CH₄ during COVID-19 lockdowns over the whole of India. The study highlights the rectilinear behaviour of CH₄ across India and the seasonal trends, which can help to improve the understanding of Indian CH₄ concentrations.

2 DATA AND METHODOLOGY

The study employs multiple earth observation platforms to analyze the intensity and variability of atmospheric column-averaged dry-air mole fractions of CH₄ (XCH₄) over India, detailed in the following sections. The data were pre-processed and filtered by quality assurance for each time step.

Table 1. Comprehensive summary and characteristics of selective studies on CH₄.

Study Characteristics	Spatial Domain	Temporal Domain	Data Source [†]	Study Importance	Source
General	Global	2000–2017		Inventory based ensemble detailing the nature of various sources and sinks of CH ₄	Saunio <i>et al.</i> (2020)
		2020–2021		In-situ based study focused on the changes of trace gases over Toronto, Canada during COVID-19 lockdown	You <i>et al.</i> (2021)
		2016–2020	TROPOMI AIRS	Reviewed various spaceborne platforms advancements in analysing the trace gases during and prior to COVID-19	Dutta <i>et al.</i> (2021)
	National	2009–2014	GOSAT	Detailed the vertical distributions of CH ₄ and its effect on the monsoon cyclones	Belikov <i>et al.</i> (2021)
		2009–2020	GOSAT	Explicitly investigated seasonal variations of CH ₄ and identified the biogenic source of CH ₄	Singh <i>et al.</i> (2021)
		2006–2015		Model based analysis was directed to focus the dynamics of and drivers of seasonal CH ₄	Tiwari <i>et al.</i> (2020)
Special [‡]	Regional	1991		Observational based study in measuring the CH ₄ fluxes from 8 paddy field sites during monsoon and post monsoon	Parashar <i>et al.</i> (1996)
		2006–2013	CARIBIC Aircraft system	Integrated datasets from multiple platforms in identifying the genesis and the atmospheric transport of CH ₄	Guha <i>et al.</i> (2018)
		2000		Site based annual and seasonal analysis on various sources of methane emission from southern wetlands of India	Purvaja and Ramesh (2001)
		2019–2020	GOSAT	Analysed the latitudinal distribution of CO ₂ and CH ₄ across the globe during the initial phase of COVID-19	Sharma and Verma (2021)
		2019–2020	AIRS OMI	Studied the variations of trace gases over major cities in India for the lockdown phase in comparison with 2019	Chauhan and Singh (2021)
		2019–2020	TROPOMI	COVID-19 lockdown air quality over IGP plains was compared with the preceding year	Behera <i>et al.</i> (2021)

[†] Representing only the spaceborne datasets from the study.

[‡] COVID-19 based studies.

2.1 Sentinel-5P Data

TROPOspheric Monitoring Instrument (TROPOMI) of Sentinel 5P platform traces major air pollutants: CO, CH₄, HCHO, O₃, NO₂ and SO₂ at the top of the Atmosphere (TOA) with a higher spatial resolution of 7.5 km daily (Hari *et al.*, 2021). For this study, level 2 of the CH₄, retrieved by the TROPOMI/WFM-DOAS algorithm, which is limited to cloud-free scenes, was selected and analyzed. TROPOMI yields XCH₄ from spectral bands 0.76 μm (Oxygen-A band) – 1700 μm (SWIR band) and are validated ground-based TCCON and by GOSAT satellite (Hasekamp *et al.*, 2021). XCH₄ from TROPOMI has retrieved measurements including the Planetary Boundary Layer (PBL), proportionate for studies at higher spatial scales. For better analysis, OFFL products were chosen and filtered by quality assurance. To maintain the scope of the article, the study employed the data retrieved for the period of three years: 2019 (pre-lockdown year), 2020 (lockdown year) and 2021 (post-lockdown year). The errors in data acquisition result in the missing data for the analysis period. Most of the analysis details the variability of XCH₄ for the lockdown dates (24 March–31 May), whereas the supplement document expounds the seasonal variations for the aforementioned years.

2.2 Atmospheric Infrared Sounder (AIRS) Data

For this current study, the data is taken from the Aqua-AIRS (Atmospheric Infrared Sounder) satellite, which has a spatial resolution of 1° × 1° and a temporal resolution of 1–2 times per day. This satellite passes through the equator twice a day, and over India, it passes the orbit in the ascending band at 13:30 LT (Local Time) (daytime) and in the descending band at 1:30 LT (nighttime). To analyze the trend over the Indian subcontinent, we isolated the data for the pre-monsoon period from 2003 to 2021.

2.3 Trend Analysis

At the 95% confidence level ($p < 0.05$), the Mann-Kendall test (MKT), a non-parametric statistical test for analyzing patterns in time-series datasets, was applied in the current study (Yue *et al.*, 2002; Asoka *et al.*, 2017; Vissa *et al.*, 2019). The MKT accepted the null hypothesis as the absence of any monotonic pattern in a time series, with pattern values that can be positive or negative. Sen's slope is used to calculate the trends in this trend test (Sen, 1968).

3 RESULTS AND DISCUSSION

3.1 Trend of Tropospheric CH₄

Fig. 1 shows the Mann Kendall trend test for CH₄ from 2003 to 2021 for the pre-monsoon season. Panel-a from Fig. 1 shows the trend for ascending band (during daytime 13:30 local time), Panel-b shows the trend for descending band (during night time 1:30 local time) and Panel-c shows the combination of both the bands. We used this bimodal trend combination to differentiate the CH₄ concentration (expressed in ppb season⁻¹) between day and night. From Fig. 1, we observed an overall positive trend across India (ascending (Fig. 1(a)), descending (Fig. 1(b)) and a combination of both (Fig. 1(c)). In the ascending band's trend analysis, a substantially steady trend was observed over the Indo-Gangetic Plain (IGP) extending from west to east. In contrast, a higher positive trend was observed in the western coasts of Gujarat plains. No trend was found in the northernmost part of India in the ascending band. For the descending band, an overall positive trend was observed across India with higher values, especially over the western and northwestern parts of the country. The trend varied from 3.5 to 5 ppb season⁻¹, which was the highest compared to other regions of the country. The trend in the northern part of the country was in harmony with the ascending band. In the combinational band, the trend was unequivocally positive over India with no trend over the northernmost part. While comparing the northern and southern parts for all the bands, south India exhibited a lesser positive trend than north India, highlighting its pertaining CH₄ concentrations. The CH₄ concentration was higher in the descending band, i.e., during the nighttime compared to the ascending band (daytime) across the country. The MKT analysis exhibited unequivocally statistical significance across the country with $p < 0.05$ for all the bands (Cao *et al.*, 2019).

Fig. 1. XCH₄ trend isolated for 2003–2021, from AIRS for the pre-monsoon season (MAM) for (a) ascending node (b) descending node and (c) fused, with a significance threshold $\rho < 0.05$.

3.2 Spatial and Seasonal Distribution of CH₄ Concentrations over India: Pre-, During- and Post-lockdown

The XCH₄ concentration for India exhibits a substantial variation in the spatial distribution. The northwestern regions of the country observed the persistence of strong CH₄ episodes with an average of 1924.48 ± 42 ppbv (Fig. 2). Conversely, central India holds a lower XCH₄ concentration with a mean of 1868.59 ± 26 ppbv. India's eastern and western coastal regions share the concentration traits with the central region, which could be inferred to the sea breeze from the Bay of Bengal and Arabian sea, as the vertical air circulations could help in the dispersion of near-surface CH₄ (Belikov *et al.*, 2021). Apart from the natural emissions from the IGP, the south-central region reflects relatively higher variation, an annual mean of 1908.33 ± 33 ppbv, indicating the heterogeneity of XCH₄ concentrations in urban sprawl. The Sundarbans wetland mainly regulates static high concentration over the northeastern coastal region (West Bengal). They were the highest concentrated CH₄ zone by natural source with a mean of 1901.97 ± 19 ppbv, with superimposed XCH₄ concentrations by the nearby thermal power plant hub (Hajny *et al.*, 2019), known to be the fugitive CH₄ emitters. The most intensive hub in the northeastern region, the Sundarbans wetland and forest vegetation in central India hold a steady trend across seasons. Due to the permanent snow cover, the northernmost and easternmost part of India exhibits less XCH₄ concentration.

Fig. 2. TROPOMI XCH₄ averaged for the lockdown period (March 24–May 31) for (a) pre-lockdown year 2019, (b) lockdown year 2020 and (c) post-lockdown year 2021. The box plot highlights the variability of XCH₄ for the corresponding year, and the red dash with shades signifies the mean XCH₄ concentration for India (1883 ± 15 ppbv). Data coverage for the analyzing period accounts for 92.56%, 91.17% and 92.01%, respectively.

The overall spatial distribution of XCH₄ concentrations shows an evident northward propagation with positive amplitude across time with a seasonal shift in the intensity. However, different ecosystems indicate the concentrations at higher significance due to various local drivers such as paddy cultivation, livestock propagation, wetland emissions, thermal power plants, mining.

By decoding the XCH₄ concentrations from the TROPOMI platform, the most noticeable seasonal changes were observed for the winter season (DJF) next to monsoon (JJAS), influenced by meteorological factors. However, due to the minimum data coverage in the monsoon period, distinct seasonal variability remains elusive. The amplitude in the monsoon seasonal shifts the XCH₄ concentrations from north-west to the IGP belt due to the enhanced Kharif seasonal cropping (especially paddy), which redistributes the XCH₄ across the region with almost 50% variability across the season. Fig. S1 in the supplement document signifies this evident shift of the XCH₄ concentrations in the monsoon season. With the monsoon retrieval, the concentrations across the northern regions were suppressed by the shift towards southern and eastern India during post-monsoon. But the winter peak (Fig. S3) corresponds with the dominance of anthropogenic sources from the urban hub, along with a small hike in the concentrations in the northeast is a subset of the spring rice cultivation.

As the present study focuses on the lockdown impact on XCH₄ concentrations, we isolated our AIRS climatological trend analysis to the pre-monsoon season (MAM) but not for the TROPOMI platform. From Figs. S1 and S2 in the supplement document, XCH₄ concentrations peaked during the monsoon and post-monsoon due to the intensive paddy cultivation of the IGP belt, considered to be the high potential emitter of XCH₄. For perpetual cultivation, crop biomass burning practice is maintained across India, further adding the XCH₄ concentrations, especially during the post-monsoon season (Fig. S2), particularly in the IGP belt. Due to the seasonal intensive agricultural zone, the peninsular regions hold maximum concentrations of XCH₄ for pre-and post-monsoon (Figs. 2 and S2). The southern part of India observed a patch of intense XCH₄ during winter (Fig. S3) and pre-monsoon season (Fig. 2), with a peak of +25 ppb than the relative annual mean (1881.97 ± 12 ppbv).

India's XCH₄ concentrations are naturally dependent (with agriculture), mediated by meteorological factors. However, possible anthropogenic sources contribute to a possible extent during the lockdown measures. Fig. 2 provides an outline of TROPOMI XCH₄ over India for the lockdown phase (March 24–May 31) of 2020 (Fig. 2(b)), in comparison to the same temporal step in 2019 (Fig. 2(a)) and 2021 (Fig. 2(c)). Comparatively, the XCH₄ concentrations over India are lower, with evident prominence in the IGP belt. Although, the concentration in the south-central domain appears to be on the positive shift irrespective of the lockdown. As expected, the XCH₄ concentrations during lockdown faced a substantial decline in the agricultural belt and the urban areas. The XCH₄ concentrations were not compromised on the northeastern front during the lockdown year (Fig. 2(b)) due to operational thermal power plants. Significantly, a phase shift in the latitudinal trend was observed during the lockdown year (Fig. 2(b)) with pronounced concentrations over southern India. Being NO_x sensitive regions during the pre-monsoon season, the northern parts of India, particularly the IGP plains, are mostly agriculturally non-intensive. However, the regions in the south (e.g., Telangana and Tamil Nadu) are assimilated to the summer cropping. This, in fact, turns out to be an important reason for the substantial XCH₄ concentration variability across these regions.

Mean XCH₄ concentrations for northern (southern) India was 1925 ± 24 (1873 ± 28) ppbv, whereas the anomaly shift during the lockdown was -29 ($+21$) ppbv, respectively. During the lockdown period, the decline in the XCH₄ concentrations was considerably more significant than the XCH₄ climatology trend (Fig. 1(c)) over the IGP. In contrast, it transcends the climatological trend in the south-central region. Though the climatology over the western front was higher than the threshold (1883 ± 15 ppbv), observations by TROPOMI declined such a trend, especially for the lockdown year. Most of the pollutants and GHGs reflect higher variability in a fading global trend in 2020 as an effect of the COVID-19 pandemic lockdown. But, in agreement with the worldwide studies (Chauhan and Singh, 2021; Dutta *et al.*, 2021; Rendana *et al.*, 2021; Stevenson *et al.*, 2021), our analysis indicates that XCH₄ concentration was progressively increasing with reduced intensity over India, which might be to the reduction in carbon emissions. Before the lockdown face (March 1–March 23), the initial phase of pre-monsoon season, the XCH₄ concentrations remain to follow the year 2019 with an increment of $+11$ ppbv year⁻¹, which can be inferred from Fig. S4

in the supplement document. Being the season for Rabi crops (i.e., wheat, barley), the soil remains aerobic during pre-monsoon, unlike monsoonal season, which favours soil methanogenesis (Dutta *et al.*, 2021).

4 CONCLUSIONS

The enormity of climate change by global warming is daunting. The COVID-19 pandemic lockdown-related fall in the pollutants level is nothing but a mere blip in the long trend, which is not an offset for the changing climate. However, the COVID-19 pandemic reflected the facet of our climate system, which provided us with a platform to understand the changing environment to reach out to a sustained flattening in the climate change curve. To combat the climate crisis, the ability to monitor GHGs across the changing environmental conditions is an essential prerequisite. In light of that, our study underscores the variability and dynamics of CH₄ concentrations over India in the recent past, compared to the COVID-19 lockdown period using satellite atmospheric measurements. The results from the present study can be concluded as follows:

- The XCH₄ trends are increasing over the Indian region. However, the magnitude of rising trends is higher over the western-northern region (including the IGP) compared to southern India.
- South India showed increased in XCH₄ concentrations, whereas the IGP showed a significant decrease. The results show that the 2021 XCH₄ concentrations over IGP are still less than the values of 2019, whereas the south Indian region still has higher concentrations.
- The results advocate that India is showing both reductions and enhancements in XCH₄ concentrations. The north Indian region shows reduced XCH₄ concentrations due to reduced emissions associated with COVID-19 lockdown and subsequent unlock phases. In contrast, south India shows increased XCH₄ concentrations because of increased lifetime due to reduced NO_x emissions.

Needless to say, TROPOMI has facilitated the study by offering extended monitoring potential. However, the lack of data coverage in the analyzing period demands a need for an improved measurement network and focus on CH₄ emissions over India. Being an agrarian country, with rice as a staple cultivated crop, lack of ground-level information on the seasonal cropland emission, especially for the lockdown period, unskeptically induced uncertainties in the analysis. Holding on to this, local scale studies on cropland CH₄ emissions call for further in-depth exploration. Other limitations of the work include analyzing different ecological zones separately for in-depth cause-effect correlation of XCH₄ concentrations, which future regional studies can take advantage of.

ADDITIONAL INFORMATION

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.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Disclaimer

Not applicable.

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SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at <https://doi.org/10.4209/aaqr.210354>

REFERENCES

- Asoka, A., Gleeson, T., Wada, Y., Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nat. Geosci.* 10, 109–117. <https://doi.org/10.1038/ngeo2869>
- Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R.S., Brauer, M., Cohen, A.J., Stanaway, J.D., Beig, G., Joshi, T.K., Aggarwal, A.N., Sabde, Y., Sadhu, H., Frostad, J., Causey, K., Godwin, W., Shukla, D.K., Kumar, G.A., Varghese, C.M., Muraleedharan, P., Agrawal, A., *et al.* (2019). The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: The Global Burden of Disease Study 2017. *Lancet Planet. Health* 3, E26–E39. [https://doi.org/10.1016/S2542-5196\(18\)30261-4](https://doi.org/10.1016/S2542-5196(18)30261-4)
- Behera, M.D., Mudi, S., Shome, P., Das, P.K., Kumar, S., Joshi, A., Rathore, A., Deep, A., Kumar, A., Sanwariya, C., Kumar, N., Chandrakar, R., Seshadri, S., Mukherjee, S., Bhattaram, S.K., Sirivella, Z. (2021). COVID-19 slowdown induced improvement in air quality in India: Rapid assessment using Sentinel-5P TROPOMI data. *Geocarto Int.* <https://doi.org/10.1080/10106049.2021.1993351>
- Belikov, D.A., Saitoh, N., Patra, P.K., Chandra, N. (2021). Gosat CH₄ vertical profiles over the indian subcontinent: Effect of a priori and averaging kernels for climate applications. *Remote Sens.* 13, 1677. <https://doi.org/10.3390/rs13091677>
- Bherwani, H., Nair, M., Musugu, K., Gautam, S., Gupta, A., Kapley, A., Kumar, R. (2020). Valuation of air pollution externalities: Comparative assessment of economic damage and emission reduction under COVID-19 lockdown. *Air Qual. Atmos. Health* 13, 683–694. <https://doi.org/10.1007/s11869-020-00845-3>
- Cao, L., Chen, X., Zhang, C., Kurban, A., Qian, J., Pan, T., Yin, Z., Qin, X., Ochege, F.U., De Maeyer, P. (2019). The global spatiotemporal distribution of the mid-tropospheric CO₂ concentration and analysis of the controlling factors. *Remote Sens.* 11, 94. <https://doi.org/10.3390/rs11010094>
- Chauhan, A., Singh, R.P. (2021). Effect of lockdown on hcho and trace gases over India during March 2020. *Aerosol Air Qual. Res.* 21, 200445. <https://doi.org/10.4209/aaqr.2020.07.0445>
- Dlugokencky, E.J., Masarie, T., K.A., Lang, P.M., Tans, P.P. (1998). Continuing decline in the growth rate of the atmospheric methane burden. *Nature* 393, 447–450. <https://doi.org/10.1038/30934>
- Dlugokencky, E.J., Steele, L.P., Lang, P.M., Masarie, K.A. (1994). The growth rate and distribution of atmospheric methane. *J. Geophys. Res.* 99, 17021–17043. <https://doi.org/10.1029/94jd01245>
- Dutta, V., Kumar, S., Dubey, D. (2021). Recent advances in satellite mapping of global air quality: Evidences during COVID-19 pandemic. *Environ. Sustainability.* 4, 469–487. <https://doi.org/10.1007/s42398-021-00166-w>
- Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Dorland, R. Van (2007). Changes in Atmospheric Constituents and in Radiative Forcing, in: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M.M.B., Miller Jr., H.L., Chen, Z. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, United Kingdom and New York, p. 106. <https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf>

- Gautam, S. (2020). The influence of COVID-19 on air quality in India: A boon or inutile. *Bull. Environ. Contam. Toxicol.* 104, 724–726. <https://doi.org/10.1007/s00128-020-02877-y>
- Guha, T., Tiwari, Y.K., Valsala, V., Lin, X., Ramonet, M., Mahajan, A., Datye, A., Kumar, K.R. (2018). What controls the atmospheric methane seasonal variability over India? *Atmos. Environ.* 175, 83–91. <https://doi.org/10.1016/j.atmosenv.2017.11.042>
- Hajny, K.D., Salmon, O.E., Rudek, J., Lyon, D.R., Stuff, A.A., Stirm, B.H., Kaeser, R., Floerchinger, C.R., Conley, S., Smith, M.L., Shepson, P.B. (2019). Observations of methane emissions from natural gas-fired power plants. *Environ. Sci. Technol.* 53, 8976–8984. <https://doi.org/10.1021/acs.est.9b01875>
- Hari, M., Sahu, R.K., Tyagi, B., Kaushik, R. (2021). Reviewing the crop residual burning and aerosol variations during the COVID-19 pandemic hit year 2020 over North India. *Pollutants* 1, 127–140. <https://doi.org/10.3390/pollutants1030011>
- Hasekamp, O., Lorente, A., Hu, H., Butz, A., Brugh, J. de, Landgraf, J. (2021). Algorithm Theoretical Baseline Document for Sentinel-5 Precursor Methane Retrieval. Germany. p. 63. <https://sentinel.esa.int/documents/247904/2476257/Sentinel-5P-TROPOMI-ATBD-Methane-retrieval>
- Hogan, K.B., Hoffman, J.S., Thompson, A.M. (1991). Methane on the greenhouse agenda. *Nature* 354, 181–182. <https://doi.org/10.1038/354181a0>
- Karatayev, V.A., Anand, M., Bauch, C.T. (2020). Local lockdowns outperform global lockdown on the far side of the COVID-19 epidemic curve. *Proc. Natl. Acad. Sci. U.S.A.* 117, 24575–24580. <https://doi.org/10.1073/pnas.2014385117>
- Laughner, J.L., Neu, J.L., Schimel, D., Wennberg, P.O., Barsanti, K., Bowman, K.W., Chatterjee, A., Croes, B.E., Fitzmaurice, H.L., Henze, D.K., Kim, J., Kort, E.A., Liu, Z., Miyazaki, K., Turner, A.J., Anenberg, S., Avise, J., Cao, H., Crisp, D., de Gouw, J., *et al.* (2021). Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change. *Proc. Natl. Acad. Sci. U.S.A.* 118, e2109481118. <https://doi.org/10.1073/pnas.2109481118>
- McDonald, A.J., Balwinder-Singh, Jat, M.L., Craufurd, P., Hellin, J., Hung, N. V., Keil, A., Kishore, A., Kumar, V., McCarty, J.L., Pearson, P., Samaddar, A., Shyamsundar, P., Shirsath, P.B., Sidhu, H.S., Singh, A.K., Singh, S., Srivastava, A.K., Urban, E., Malik, R.K., *et al.* (2020). Indian agriculture, air pollution, and public health in the age of COVID. 135, 105064. *World Dev.* <https://doi.org/10.1016/j.worlddev.2020.105064>
- Morgenstern, O., Stone, K.A., Schofield, R., Akiyoshi, H., Yamashita, Y., Kinnison, D.E., Garcia, R.R., Sudo, K., Plummer, D.A., Scinocca, J., Oman, L.D., Manyin, M.E., Zeng, G., Rozanov, E., Stenke, A., Revell, L.E., Pitari, G., Mancini, E., Di Genova, G., Visionsi, D., *et al.* (2018). Ozone sensitivity to varying greenhouse gases and ozone-depleting substances in CCMI-1 simulations. *Atmos. Chem. Phys.* 18, 1091–1114. <https://doi.org/10.5194/acp-18-1091-2018>
- Muhammad, S., Long, X., Salman, M. (2020). COVID-19 pandemic and environmental pollution: A blessing in disguise? *Sci. Total Environ.* 728, 138820. <https://doi.org/10.1016/j.scitotenv.2020.138820>
- Parashar, D.C., Mitra, A.P., Gupta, P.K., Rai, J., Sharma, R.C., Singh, N., Koul, S., Ray, H.S., Das, S.N., Parida, K.M., Rao, S.B., Kanungo, S.P., Ramasami, T., Nair, B.U., Swamy, M., Singh, G., Gupta, S.K., Singh, A.R., Saikia, B.K., Barua, A.K.S., *et al.* (1996). Methane budget from paddy fields in India. *Chemosphere* 33, 737–757. [https://doi.org/10.1016/0045-6535\(96\)00223-8](https://doi.org/10.1016/0045-6535(96)00223-8)
- Purvaja, R., Ramesh, R. (2001). Natural and anthropogenic methane emission from coastal wetlands of South India. *Environ. Manage.* 27, 547–557. <https://doi.org/10.1007/s002670010169>
- Rawat, M., Singh, U.K., Mishra, A.K., Subramanian, V. (2008). Methane emission and heavy metals quantification from selected landfill areas in India. *Environ. Monit. Assess.* 137, 67–74. <https://doi.org/10.1007/s10661-007-9729-8>
- Rendana, M., Idris, W.M.R., Rahim, S.A. (2021). Atmospheric methane condition over the South Sumatera peatland during the COVID-19 pandemic. *Aerosol Air Qual. Res.* 21, 210072. <https://doi.org/10.4209/AAQR.210072>
- Sahu, S.K., Tyagi, B., Beig, G., Mangaraj, P., Pradhan, C., Khuntia, S., Singh, V. (2020). Significant change in air quality parameters during the year 2020 over 1st smart city of India: Bhubaneswar. *SN Appl. Sci.* 2, 1990. <https://doi.org/10.1007/s42452-020-03831-7>

- Saunio, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K., Ciais, P., Arora, V.K., Bastviken, D., Bergamaschi, P., Blake, D.R., Brailsford, G., Bruhwiler, L., Carlson, K.M., Carrol, M., Castaldi, S., *et al.* (2020). The global methane budget 2000–2017. *Earth Syst. Sci. Data* 12, 1561–1623. <https://doi.org/10.5194/essd-12-1561-2020>
- Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *J. Am. Stat. Assoc.* 63, 1379–1389. <https://doi.org/10.1080/01621459.1968.10480934>
- Sharma, L.K., Verma, R.K. (2021). Latitudinal fluctuation in global concentration of CO₂ and CH₄ from shortwave infrared spectral observation by GOSAT during COVID-19. *Int. J. Digit. Earth.* 14, 882–1896. <https://doi.org/10.1080/17538947.2021.1980126>
- Singh, A., Kuttippurath, J., Abbhishek, K., Mallick, N., Raj, S., Chander, G., Dixit, S. (2021). Biogenic link to the recent increase in atmospheric methane over India. *J. Environ. Manage.* 289, 112526. <https://doi.org/10.1016/j.jenvman.2021.112526>
- Singh, J., Tyagi, B. (2021). Transformation of air quality over a coastal tropical station chennai during COVID-19 lockdown in India. *Aerosol Air Qual. Res.* 21, 200490. <https://doi.org/10.4209/aaqr.200490>
- Singh, V., Singh, S., Biswal, A., Kesarkar, A.P., Mor, S., Ravindra, K. (2020). Diurnal and temporal changes in air pollution during COVID-19 strict lockdown over different regions of India. 266, 115368. *Environ. Pollut.* <https://doi.org/10.1016/j.envpol.2020.115368>
- Stevenson, D., Derwent, R., Wild, O., Collins, W. (2021). COVID-19 lockdown NO_x emission reductions can explain most of the coincident increase in global atmospheric methane. *Atmos. Chem. Phys.* [preprint] <https://doi.org/10.5194/acp-2021-604>
- Thakur, V., Jain, A. (2020). COVID 2019-suicides: A global psychological pandemic. *Brain Behav. Immun.* 88, 952–95. <https://doi.org/10.1016/j.bbi.2020.04.062>
- Tibrewal, K., Venkataraman, C. (2021). COVID-19 lockdown closures of emissions sources in India: Lessons for air quality and climate policy. *J. Environ. Manage.* 302, 114079. <https://doi.org/10.1016/j.jenvman.2021.114079>
- Tiwari, Y.K., Guha, T., Valsala, V., Lopez, A.S., Cuevas, C., Fernandez, R.P., Mahajan, A.S. (2020). Understanding atmospheric methane sub-seasonal variability over India. *Atmos. Environ.* 223, 117206. <https://doi.org/10.1016/j.atmosenv.2019.117206>
- Tyagi, B., Choudhury, G., Vissa, N.K., Singh, J., Tesche, M. (2021). Changing air pollution scenario during COVID-19: Redefining the hotspot regions over India. *Environ. Pollut.* 271, 116354. <https://doi.org/10.1016/j.envpol.2020.116354>
- Vissa, N.K., Anandh, P.C., Behera, M.M., Mishra, S. (2019). ENSO-induced groundwater changes in India derived from GRACE and GLDAS. *J. Earth Syst. Sci.* 128, 115. <https://doi.org/10.1007/s12040-019-1148-z>
- World Meteorological Organization (WMO) (2019). World Meteorological Organization (WMO) Greenhouse Gas Bulletin: Greenhouse gas concentrations in atmosphere reach yet another high.WMO. 8. https://library.wmo.int/doc_num.php?explnum_id=10100
- You, Y., Byrne, B., Colebatch, O., Mittermeier, R.L., Vogel, F., Strong, K. (2021). Quantifying the impact of the COVID-19 pandemic restrictions on CO, CO₂, and CH₄ in downtown toronto using open-path fourier transform spectroscopy. *Atmosphere* 12, 848. <https://doi.org/10.3390/atmos12070848>
- Yue, S., Pilon, P., Cavadias, G. (2002). Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.* 259, 254–271. [https://doi.org/10.1016/S0022-1694\(01\)00594-7](https://doi.org/10.1016/S0022-1694(01)00594-7)