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Forest Fire Induced Air Pollution over Eastern India during March 2021

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ABSTRACT

Being a significant contributor to atmospheric CO₂, forest fires are considered a threat to the terrestrial ecosystems that influence climate change. This study integrates in-situ and earth observation platforms to investigate an episodic forest fire event at the Similipal National Park and the adjacent areas in eastern India and its effect on the ambient atmosphere of the nearby areas in 2021 March. The analysis brings out a substantial rise in the Aerosol Optical Depth (AOD) during this period with apparent anomalies in carbon monoxide (CO) and ozone (O₃). The pronounced increase in the surface concentration of PM_{2.5} was increased by about 12 µg m⁻³. Furthermore, the AOD exhibited a spike of about 56.21% during the fire episode. The pollutants' intensity (except NO₂) was directly proportional to the fire counts, translated across the northern part of the region. The study also employed an emission index to calculate the amount of CO₂ emitted and was pressed against changes in atmospheric XCO₂ concentrations retrieved from OCO-2 during the fire episode.

Keywords: Aerosol, Particulate matter, Pollution exposure, Satellite observation, Wildfire, TROPOMI, OCO-2

1 INTRODUCTION

Natural or anthropogenic induced forest fires devour millions of hectares of forest across the globe every year, cascading multiple direct and indirect threats to communities. Being the fuel pool of the world, the tropical forests hold more carbon stock (Asner and Mascaro, 2014; Hari *et al.*, 2021b) which are susceptible to frequent and intense forest fires. In India, forest fires are a major hazard, with varying intensity, extent and high interannual variability. Forest Survey of India (FSI), 2020 indicates that Indian forests are prone to 54.40% (occasional), 07.49% (moderately frequent) and 2.41% (frequent) fire events every year. It was estimated that around 89053 fire episodes were observed in the fire season (January–June) from 2018 to 2020. To thwart the vulnerability of the ecosystem and society, it is important to monitor and study forest fires. Forest fire events widely attract global attention, as they devastate bio-, geo-, atmo-, hydro-spheres, causing colossal damages to all forms of the biotic system—more importantly by releasing toxic gases and aerosols into the atmosphere, which compromise the quality of air at the higher degree (Cheng *et al.*, 1998; Sastry, 2002).

During forest fire events, the fine particulate matter (PM_{2.5} and PM₁₀), ozone and other greenhouse gases concentration at ground level increase persuasively (Reddington *et al.*, 2021; Zu *et al.*, 2016). With the swing of favourable meteorological conditions to biomass burning, the regionally confined smoke plumes can widely disperse to tens and thousands of kilometres (Hari *et al.*, 2021a; Sahu *et al.*, 2021). More likely, the nitrogen dioxide (NO₂) from combustion acts as a precursor for photochemical reactions to form ozone within the boundary layer (Grennfelt *et al.*, 2020) which also induces acid rain in some regions. Forest fires in the woodland not only degrade the air quality but also rapidly increase carbon dioxide (CO₂). Evidential studies suggest that fire episodes increase the greenhouse gases and mediate its interannual variability, which

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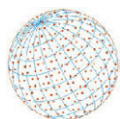
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intercedes the regional climate (Martins *et al.*, 2012; Reddington *et al.*, 2021).

Direct emissions from the plumes of forest fire not only compromise the regional air quality but turns out to be the sources of indirect pollutants that can harm the population miles away. This effect took the spotlight in the international forum when the forest fires of Indonesia smoked out Singapore in September 2019 (Tan-Soo and Pattanayak, 2019). More recently, in August 2020, the Californian wildfires turned San Francisco into a gas chamber (Meo *et al.*, 2021). Close to home, the crop residual fires of Punjab and Haryana blew smoky air towards the south-east, which leaves the Indian capital city, New Delhi, breathless every cropping season (Hari *et al.*, 2021a). With persistent fire episodes in the past years, the Similipal region has joined the club.

Eastern India is a hub for persistent aerosols, particularly due to the industrial clusters (Gogikar *et al.*, 2018; Tyagi *et al.*, 2020). Frequent biomass burning and forest fires intensify the domination of air pollutants. Appending to this, favourable topography and the meteorological conditions exacerbate the prevailing condition. In Odisha, all these factors are harmonised. Being the gateway to the Eastern ghats, Odisha is dominated by dry deciduous forests and provides perfect bowls for forest fires. Due to its high hardwood coverage, nine districts of Odisha fall under highly vulnerable to forest fire, three under moderately vulnerable and one under less vulnerable, where 41–50% of the total population is below the poverty margin who are exposed directly and indirectly to its ramification (FSI, 2020). It is discernibly observed that the crucial period of forest fire occurrence in Odisha is from February 3rd week to April 4th week (Saranya *et al.*, 2016; FSI, 2020).

With the advancement of earth observations and remote sensing, monitoring and analysing the forest fire in real-time is utilised to its full potential, which outdates the traditional investigations, which were dangerous and costly. Here we integrate various remote sensing platforms and in-situ datasets to investigate the forest fire episode and its subsequent emission of pollutants that occurred in 2021 in Similipal National Park, Odisha, primarily along with other nearby forest fire events in eastern India. To analyse the singularity of pollution-induced by forest fire, we also analysed the air quality from 2019 and 2020 as the background. The study aims to bring out the impact and pattern analysis of the short-lived event of forest fire on the regional air quality over eastern India.

2 MATERIALS AND METHODS

2.1 Study Region

Being the cradle of the Eastern Ghats, the Similipal National Park is located in the Mayurbhanj district of Odisha, India, stretches over an area of 84500 ha with a buffer of 212900 ha reserved forest between 21°11'02" and 22°14'09"N latitude and 85°58' 41" and 86°42'37"E longitude (Saranya and Reddy, 2016). The Similipal National Park was declared as a wildlife sanctuary in 1979, as a biosphere reserve in 1994 and came under the focal point of UNESCO's "Man and Biosphere Program" in 2009 (Saranya *et al.*, 2014). The geography of the region is decked with hills, valleys, gorges, plains and plateaus drained by many perennial rivers with mean sea level ranging from 215–1168 m. The region distinctively experiences hot summer from March to May (~32°C) and cold winter from November to February (~2°C) and with maximum precipitation of about ~2109 mm from June to October. The Similipal region is recurrently prone to heatwaves in summer and frost episodes in winter (Hari and Tyagi, 2021). The buffer zone is blended with tropical semi-evergreen and deciduous forests (Mishra *et al.*, 2008). Being the transitional zone, the region ecologically links Lower Gangetic Plains (LGP), Eastern Coastal Plain (ECP), Deccan Plateau (DP) and the Eastern Ghats (EG), harbouring many endangered flora and fauna. Around 65 villages of aboriginals are inhabited within the zone of this biosphere reserve. The spatial domain of Similipal National Park and the eastern states of India analysed in this study is depicted in Fig. 1.

2.2 Data Descriptor

The study employs multiple data platforms to analyse the intensity of forest fire and the regional air quality. The datasets include multiple satellite retrievals and surface measurements projects with various traits. Table 1 describes the characteristics and the nature of the datasets

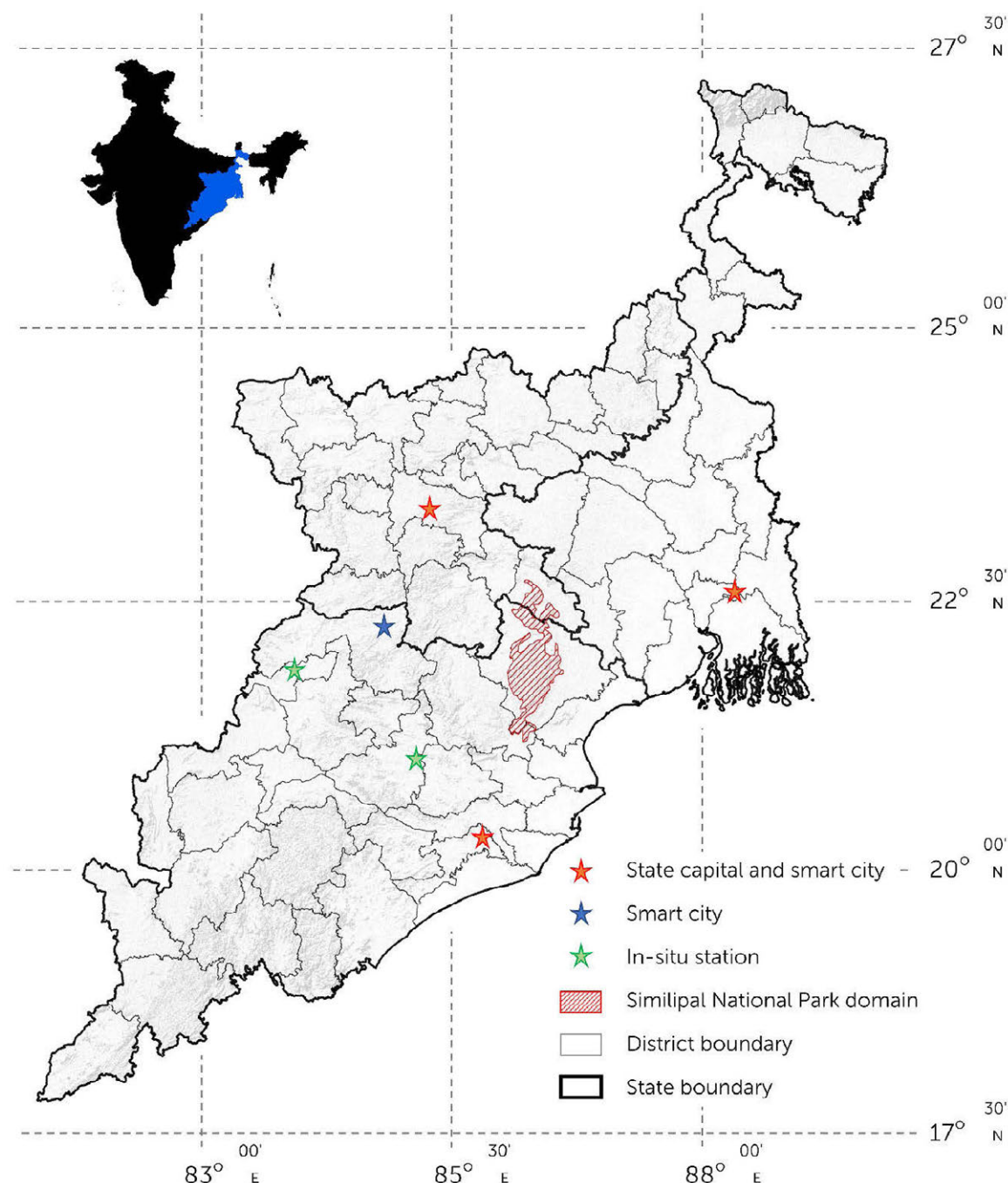
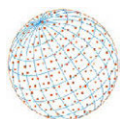
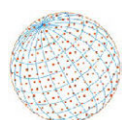


Fig. 1. The spatial domain of Simlipal National Park and the eastern states of India analysed in this study. The red mark indicates the corresponding state capital city (also a smart city), the blue mark indicates the smart city within the proximity of pollution exposure and the green mark indicates the in-situ station.

used in the study, which are detailed in the following sections. To explicitly mark the spatial and temporal changes in the air quality, the satellite datasets were pre-processed and filtered by quality assurance for each time step.

2.2.1 Sentinel-5P

TROPOMI—TROPOspheric Monitoring Instrument of Sentinel-5P platform traces major air pollutants: CO, CH₄, HCHO, O₃, NO₂ and SO₂ at Top of Atmosphere (TOA) with a higher spatial resolution of 7.5 km daily. For this study, level 3 of the major pollutants—CO, O₃ and NO₂ were selected and analysed. The retrieval algorithm for CO is based on Weighting Function Modified

**Table 1.** Notation of data attributes used in the study.

Type	Platform	Dataset	Data code	Spatial resolution	Temporal resolution	Description
Satellite	MODIS	AOD	MCD19A2	1 km	Daily	Level 2 Aerosol Optical Depth at 0.55 μm
		FIRMS	MCD14DL	1 km		Combined Terra and Aqua MODIS thermal hotspots
			VNP14IMGTDL_NRT	375 m		VIIRS active fire hotspots to complement the MODIS dataset
	Sentinel-5P	CO	L3_CO	0.01°	Daily	Level 3 vertically integrated CO column density
		NO ₂	L3_NO2			Level 3 total vertical column of NO ₂
		O ₃	L3_O3			Level 3 total atmospheric column of O ₃
In-situ	CPCB	OCO-2	XCO ₂	2.25 × 1.29 km	16 days	Level 2 bias-corrected XCO ₂ measured by spectrometers in NIR (1.61–2.06 μm) and O ₂ A-Band (0.76 μm)
		PM _{2.5}		Site confined		Hourly averaged surface concentration of PM
		PM ₁₀				
		CO				
		O ₃				

Differential Optical Absorption Spectroscopy (WFM-DOAS) algorithm (Sun *et al.*, 2013), O₃ is based on Convective-Cloud-Differential (CCD) method (Heue *et al.*, 2016) and NO₂ is based on the Dutch OMI NO₂ (DOMINO) method (Zhou *et al.*, 2009). For better analysis, OFFL products were chosen over NRTI, which were then filtered by quality assurance. The errors in data acquisition result in the missing data for the analysis period.

2.2.2 MODIS AOD

NASA's MODIS platform provides the global daily observations of AOD since 1999, which measures the spectrum by scattering and absorption of aerosols. AOD is retrieved by 0.47 μm and 0.66 μm , which are interpolated at 0.55 μm to report the AOD values for analysis. The level 2 AOD properties are retrieved by the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm (Lyapustin *et al.*, 2012; Mhawish *et al.*, 2019). For this analysis, MODIS (Aqua and Terra operational pods combined) level 2 daily Aerosol Optical Depth at 0.55 μm with the spatial resolution of 1 km were used to characterise the spatiotemporal variations of AOD during the forest fire over the Similipal region.

2.2.3 MODIS FIRMS

The thermal anomalies over the study region were collected from NASA's Fire Information for Resource Management System (FIRMS), which collects the fire products from MODIS MCD14DL of resolution 1 km, which was improvised with the integration of 375 m resolution—VIIRS thermal anomalies (Davies *et al.*, 2019). For this study, each thermal pixel was considered as the fire anomaly to distinguish the spatial distribution of the forest fire.

2.2.4 OCO-2

Orbiting Carbon Observatory-2 (OCO-2) level 2 data (Zheng *et al.*, 2020) was extracted for the study domain and was temporally isolated from 20 February–20 March 2021 to extricate the changes in atmospheric CO₂ (XCO₂) during the forest fire period. As OCO-2 was temporally limited, which holds the revisit configuration of 16 days, a single XCO₂ path was attributed for each period (i.e., pre-fire: 20 Feb–02 Mar; during fire: 03–09 Mar; post-fire: 10–20 Mar) was analysed.

2.2.4 Surface data

Hourly averaged surface concentrations of fine particulate matters, CO and O₃ at two available sites (Brajrajnagar and Talcher of Odisha) were acquired from CPCB through the publicly and



freely available site, <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing>. The data were pre-processed and quality checked by removing outliers. CPCB uses Tapered Element Oscillating MicroBalance (TEOM) to measure PM_{2.5} and PM₁₀ (Allen *et al.*, 1997; Cyrus *et al.*, 2001). To analyse and compare the intensification of the pollutants, data for the post period (2019–2020) were selected: under stress (forest fire) and during normal conditions.

2.3 Methodology

Most of the satellite-based pre-processing and quality analyses were processed and computed in the google earth engine (GEE) cloud platform (Hari *et al.*, 2021a). The various targeted post analysis was employed using ArcMap 10.3 and R Studio 3.6.1. Based on the forest fire reports from the forest department—Odisha, the study considered the period from 3 March–12 March 2021 for satellite analysis. Furthermore, to access the atmospheric variation, the period from 9 February–16 March 2021 for in-situ data. Further, to calculate the change in the air quality, the corresponding epoch in the preceding years (2019 and 2020) were considered. As the region of interest falls within the buffer of four smart cities, the extent of the area was perpetuated to state boundary for analysing the pollution concentration and exposure. AOD variations from the satellite data were performed for the aforementioned region and averaged over the area for the equivalent period. The correlation between AOD and fire count was investigated to explore the spatiotemporal variation of fire hotspots and the AOD concertation. The in-situ products were quality screened and used to analyse the change in the regional transport of the pollutants simulated by the forest fire during the case period. Gaps in the satellite image closer to the core region of interest were filled with an average of valid neighbour pixels by a 3 × 3 moving window. While the rest were undisturbed as they were mainly due to cloud contamination and errors in data acquisition. Alongside, we estimated CO₂ emission during the episode with Burned Area (BA) Index using Eq. (1), which is:

$$\varepsilon = A \times B \times \beta \times EF \quad (1)$$

where ε is the CO₂ emission (g), A is the burnt area (m²), B is the average biomass load (kg dry matter⁻¹ m⁻²), β is the burning efficiency (%), and EF is the emission factor (g kg⁻¹). The EF of about 1613 was considered for the Similipal region, which has a dominance of dry deciduous sub-tropical forest and was adapted from Andreae (2019). Similar to the EF , B and β was set to 3.64 kg dry matter⁻¹ m⁻² and 25%, respectively (Saranya *et al.*, 2016) to estimate the ε during the episode.

3 RESULTS

This section outlines the adequacy of remote sensing and in-situ observation in analysing the anomalies in the atmospheric composition induced by the forest fire episode at the Similipal National Park.

3.1 MODIS Derived AOD and Surface Observations

To analyse the spatial intensity of forest fire, we employed MODIS FIRMS to extricate the forest fire situation in this region. Generally, dry atmospheric conditions associated with huge biomass/litter load during this period trigger forest fire (FSI, 2020). The MODIS Burned Area (BA) data estimated that the total burnt area during this fire episode was about 674.21 km² (18.8%) with ~4500 fire events. This introduced various pollutants into the atmosphere of the eastern Indian states. Though fire anomalies apart from the Similipal region were observed on 05–07 March across the whole spatial domain, we confined our fire count to the Similipal domain because of its higher concentrations. From Fig. 2, we can infer the temporal distribution of satellite-derived AOD and the fire anomalies across the domain, where the active fire episode event was marked from 03–09 March. Fig. S1 represents the land use classification which highlights the forest cover for the study domain. This was marked to bring out that the fire events were not bound to the Similipal forest area but also to the adjacent forest areas in the eastern states. Though these fire events were significant, they were localised and short compared to the Similipal episode.

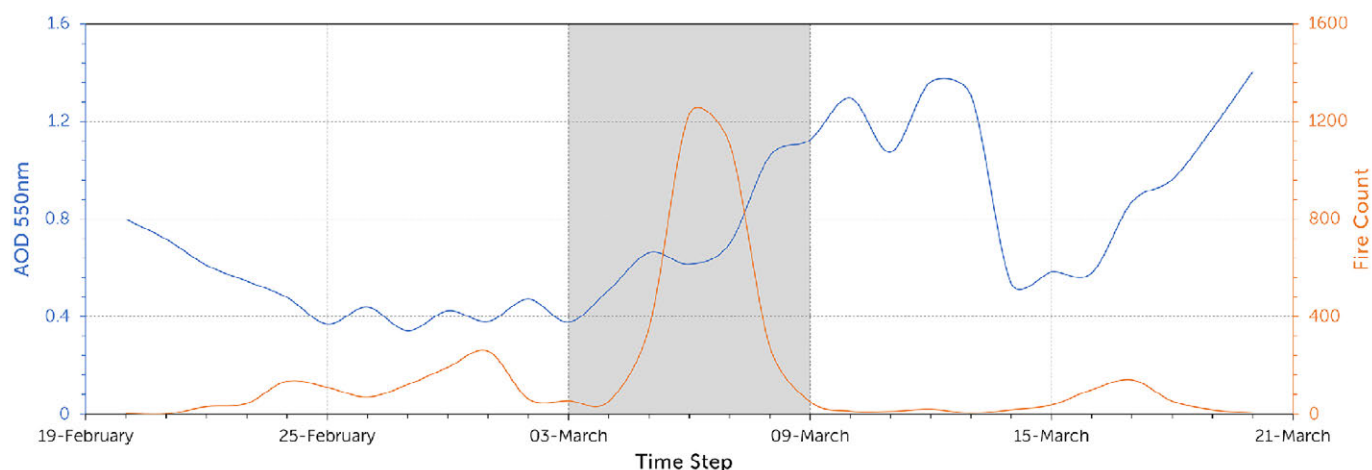
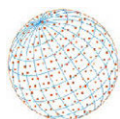


Fig. 2. Spatial averaged MODIS derived AOD and fire count during the fire episode. The shaded region represents the active fire period.

The surface observations of pollutants, i.e., $PM_{2.5}$ and PM_{10} (for the stations selected within the proximity of the Similipal National Park), exhibited a positive correlation with the intensity of the fire events, whereas the spatially aggregated satellite observed pollutants showed a lag correlation. Correspondingly, the AOD load over the region was spiking throughout the episode, with an interestingly lower load on the northern part of the study region. Relatively, the southern and the central part highlights the consistent AOD trend, inferred from Fig. 3, where AOD across the regions spurred its spiking with fire episode. On analysing the same for the past years (2019–2020), the pollutants load was non-substantial with negligible fire counts due to the crop residual burning (Hari *et al.*, 2021a). Fig. S2 depicts the surface variations of $PM_{2.5}$ and PM_{10} for the selected station that brings out the variations of atmospheric pollution composition during the fire episode period across years. The PM concentrations clearly show a peak during the fire episode with a day lag across Brajraj Nagar, whereas the Talcher does not exhibit any significant peak during the event.

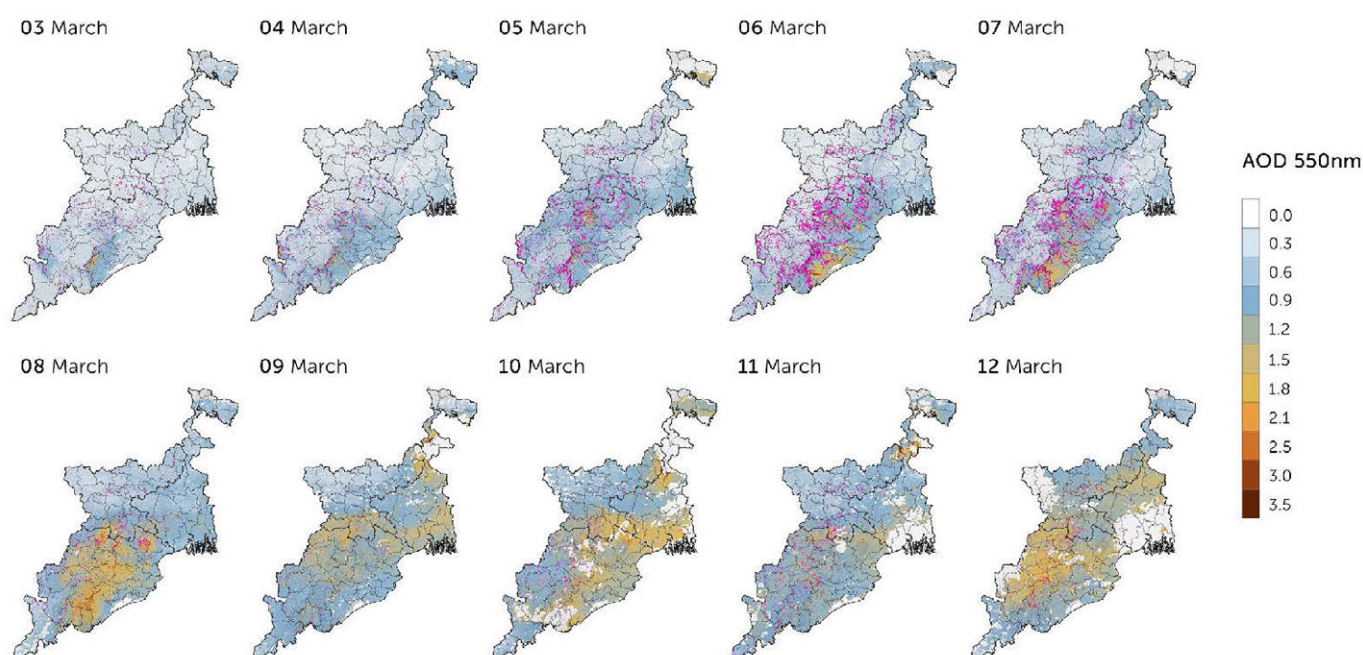
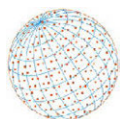


Fig. 3. Spatial and temporal distribution of AOD during the fire episode. The pink stippling represent the spatial distribution of fire counts for the corresponding date.

**Table 2.** Temporal distribution of various pollutants over the eastern states during the Similipal forest fire event. Surface CO (O₃) and satellite CO (O₃) are represented in mg m⁻³ (μg m⁻³) and mole m⁻².

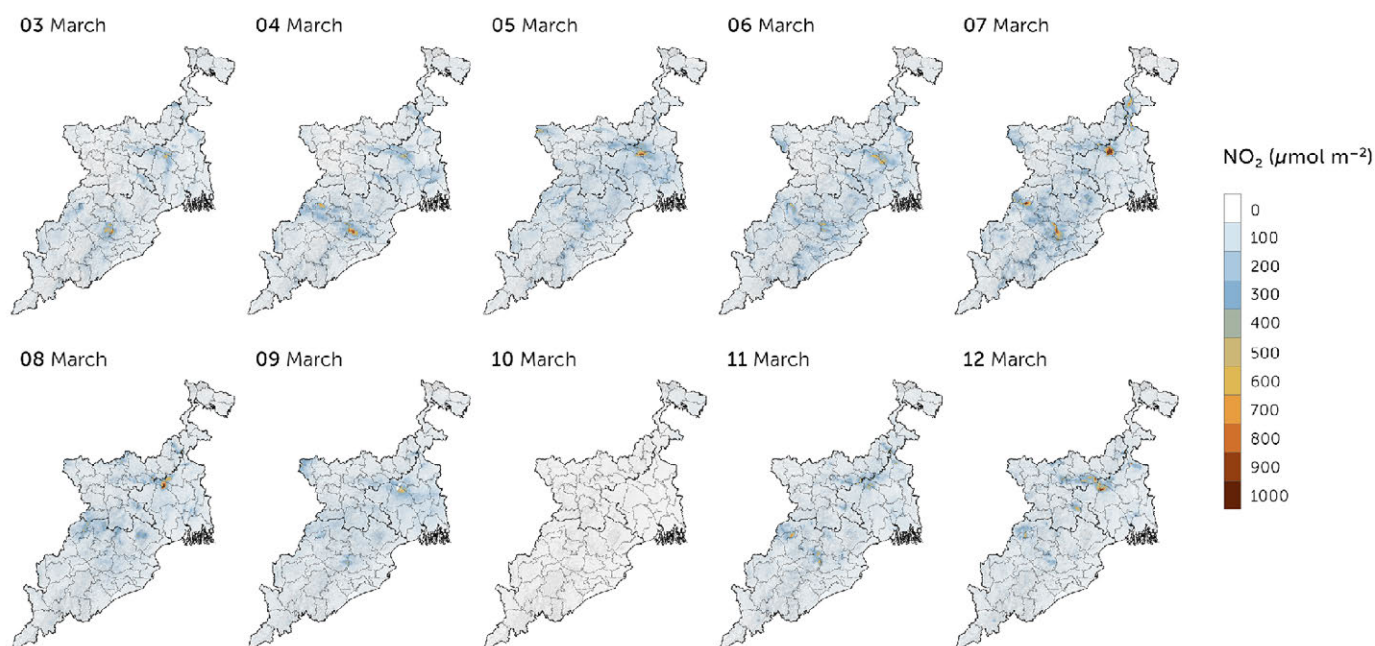
Date	AOD	PM [†]		CO		O ₃	
		PM _{2.5}	PM ₁₀	Surface [†]	Satellite [‡]	Surface [†]	Satellite [‡]
03 Mar	0.38	140	105	14	0.04	34	0.12
04 Mar	0.51	172	120	16	0.05	36	0.12
05 Mar	0.66	174	110	21	0.06	31	0.13
06 Mar	0.62	171	107	20	0.05	31	0.12
07 Mar	0.71	193	105	16	0.06	27	0.13
08 Mar	1.06	176	101	14	0.07	30	0.14
09 Mar	1.12	120	65	15	0.06	23	0.12

[†] Mean of two surface observation sites represented in μg m⁻³ (PM), mg m⁻³ (CO) and μg m⁻³ (O₃).[‡] Spatial mean for the eastern states represented in mole m⁻².

Other pollutants such as CO, O₃ and NO₂ exhibited a parallel trend to AOD. These pollutants showed higher values within the proximity of fire hotspots, possibly due to their shorter life. The difference between the surface and the satellite observations was significant but are temporally homogenous. These temporal variations of surface O₃ and CO can be inferred from Table 2, highlighting the intensity peak during 07–09 March. Deviating from the AOD distribution, the CO and O₃ shown in Fig. S3 indicated that the pollutants were mainly locally emitted from the fire and not transported. Though the surface data underestimate the variations in the onset of fire episodes, the peak in the later days indirectly exhibits their validity. In the later period (from 10 March), CO was widespread across the southern domain, which degraded the air quality considerably. Despite the fire intensity in the mid-period of the episode, O₃ was almost stable across the spatial domain.

3.2 TROPOMI Observed Pollution Covariates

Fig. 4 highlights the NO₂ dispersal during the Similipal forest fire event over eastern India. The NO₂ concentrations are spatially and temporally homogeneous across the study domain. However, they leave with some unequivocally higher values with the concentrations of more than ~837 μmol m⁻² for the parts of central and western Odisha (especially over Angul, Sambalpur and Jharsuguda districts); north-western West Bengal (over Paschim Bardhaman, Murshidabad and

**Fig. 4.** Spatial and temporal distribution of NO₂ retrieved from TROPOMI during the fire episode.

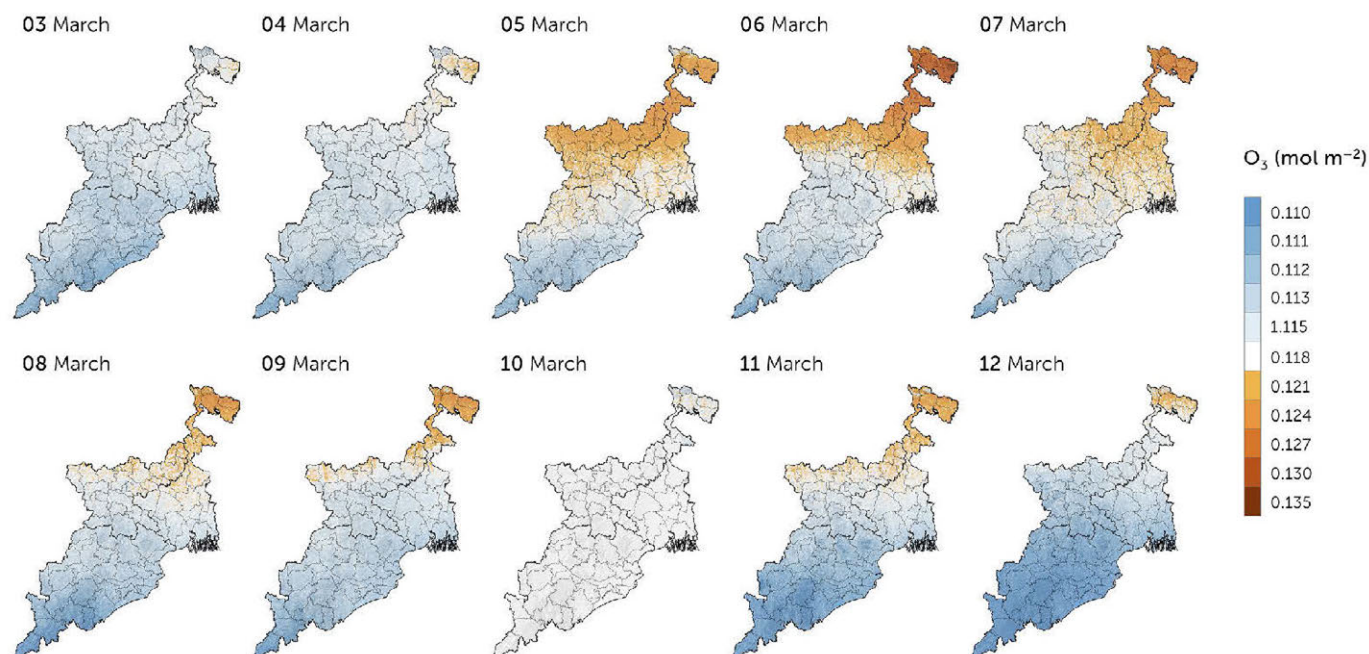
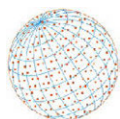


Fig. 5. Spatial and temporal distribution of O_3 retrieved from TROPOMI during the fire episode.

Malda districts) and eastern and south-eastern Jharkhand (over Saraikela Kharsawan, Bokaro, Dhanbad and East Singhbhum districts) during the Similpal forest fire event.

The spatial and temporal distribution of O_3 for the study domain during the Similpal forest fire event is shown in Fig. 5. Unlike other pollutants, O_3 distribution was spatially biased towards the north, where the states of West Bengal and Jharkhand experienced significantly higher concentrations than Odisha. Similar to the spatial trend, the O_3 was temporally lenient for the later phase of the fire episode, where the maximum concentration was observed between 05–07 March with a spatial average of $\sim 0.12 \text{ mol m}^{-2}$. Spatially, the highest concentration of O_3 was observed over the northern West Bengal region (especially over Cooch Behar, Jalpaiguri, Darjeeling, Alipurduar and Kalimpong areas) on 06 March, with the mean concentration of $\sim 0.12 \text{ mol m}^{-2}$.

The spatial distribution of CO marginally followed AOD, where the highest concentration was observed in the southern part of the domain with a maximum being $\sim 0.13 \text{ mol m}^{-2}$ on 07 March. Unlike the NO_2 pattern, CO was defined with horizontal (west–east) distribution, where the western front of Odisha during the later phase dominated with moderately higher distributions which surpassed the concentrations in the eastern front during the initial phase. The spatial and temporal distribution of CO is highlighted in Fig. 6.

3.3 Carbon Emissions during the Event

Relatively, with the CO_2 emission estimation, our results exhibit that the Similpal deciduous forest emitted about $0.41 \text{ Tg year}^{-1}$ during the 2021 fire episode. This outlines the amount of CO_2 emitted during a single fire episode for a generalised forest type, but the extricated classification of the emission level may significantly improve the estimation of pollutants emitted during the forest fires. But then, this was generally supported by the retrieval of XCO_2 from the OCO-2 satellite, which is detailed in the following section. The estimated emission quantity may vary considerably due to the higher spatial resolution (each 1 km pixel was considered as a burnt area). Thus, the derived estimation may not represent the burnt area in the field.

3.4 Satellite Footprint of XCO_2 from OCO-2

The column-averaged XCO_2 retrieved from OCO-2 during the study period is shown in Fig. 7. Due to the limited temporal resolution, an overpass of OCO-2 across the whole study domain is considered to extricate the changes in atmospheric CO_2 composition during the fire episode. From the analysis, it was observed that the mean XCO_2 observed during the fire episode was

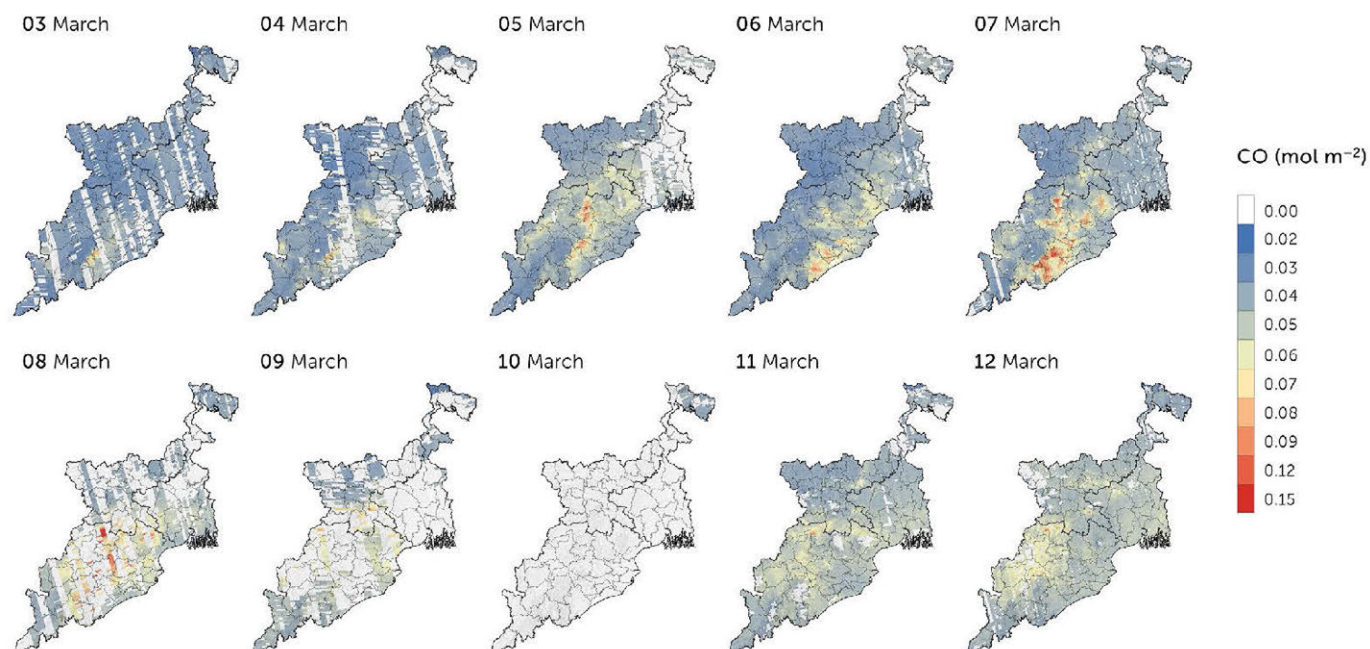


Fig. 6. Spatial and temporal distribution of CO retrieved from TROPOMI during the fire episode.

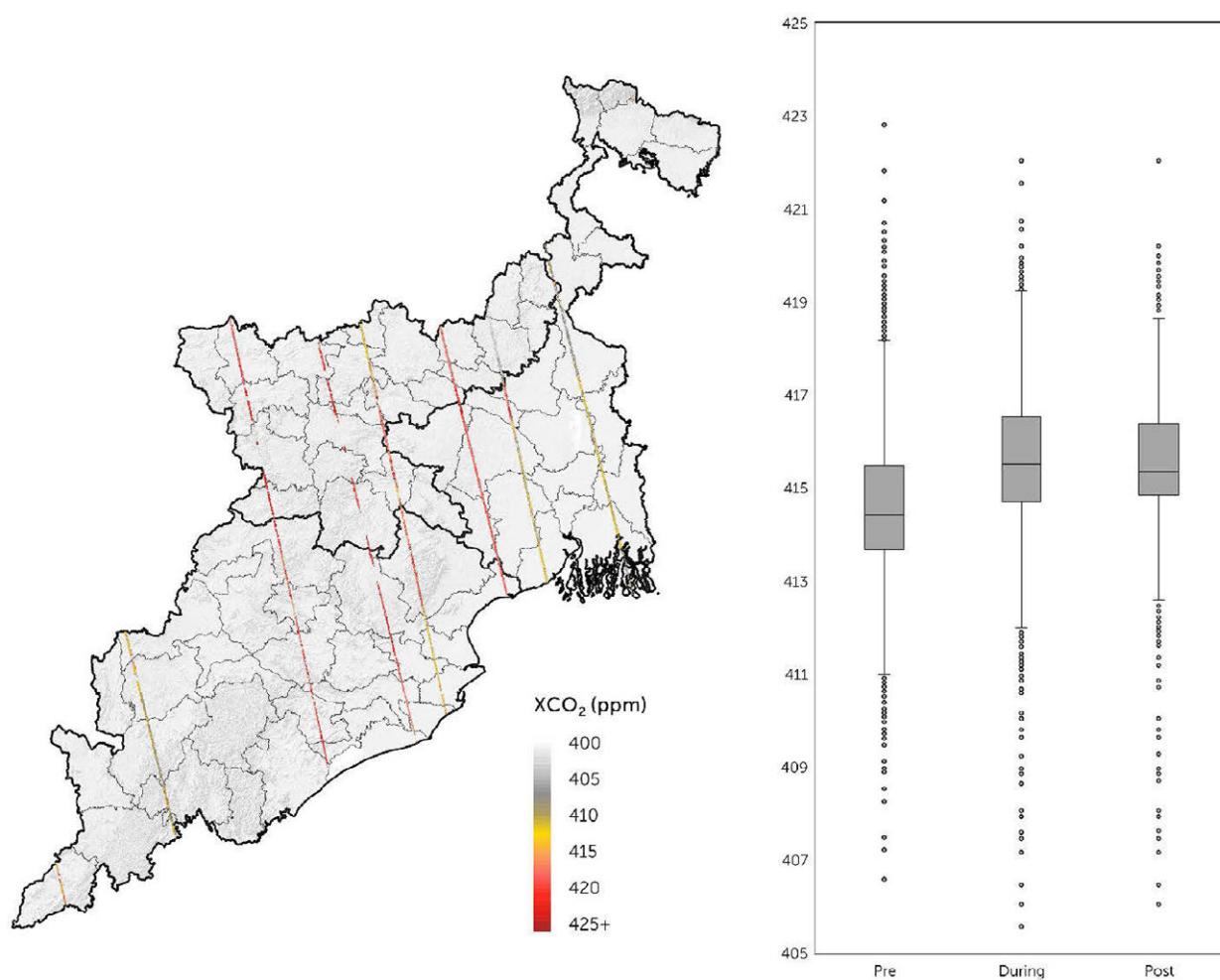


Fig. 7. XCO₂ concentration observed from OCO-2 during the study period. Box plot representing the spatial average of XCO₂ distribution for pre (20 Feb–02 Mar), during (03–09 Mar) and post (10–20 Mar) fire events.



415.49 ppm (with maximum and lowest being 422.04 and 402.59 ppm, respectively). Spatially, the higher and lower concentrations were distributed from central regions (in the buffer of the Similipal region), alike AOD and CO. During the pre- and post-fire events, the mean XCO₂ was observed to be 414.56 and 415.10 ppm, respectively. On the spatial domain, the average concentration of XCO₂ within the Similipal buffer (red lineation from Fig. 1) exceeds the overall concentration, where the observed value was 422.56 ppm.

4 CONCLUSIONS

The present study analysed the influence of the 2021 Similipal forest fire episode on the distribution of atmospheric pollutants over the eastern states of India. With the earth observation, the burnt area was estimated to be 674.21 km² (18.8%) with ~4500 fire events. This fire episode injected various air pollutants, further degrading the air quality of eastern India. Our study also draws inference in understanding the regional carbon emissions emitted through forest fires in the study area with the emission factor. The results indicated that the fire episode induced pollutants climbed (CO and O₃: 4 mg m⁻³) significantly that mostly dominated the southern region of the domain, where they reached a maximum on 04 March. Similarly, the CO₂ emitted from the episode was estimated to be 0.41 Tg year⁻¹. For the aerosols, AOD and PM concentrations were increased precipitously (~18 µg m⁻³) after 06 March, signifying the massive load of aerosols emitted from the fire episode. In contrast to other pollutants, NO₂ anomalies are considerably lower with little change in the spatial aspect. Similar to AOD, the XCO₂ concentration was distinct for the fire episode. Although, we anticipate that the actual emission was larger than the represented due to other active fire zones. AOD dominates the spatial distribution of the other pollutants, where the Similipal forest fire episode possibly threatens the air quality across the eastern states. In light of that, smoke from the fire has reduced the visibility considerably. Due to the strapping wind pattern, the smoke from the Similipal fire would have compromised the air quality of major cities (Rourkela, Bhubaneswar, Kharagpur, etc.) of the states. However, the absence of real-time monitoring stations in these cities impedes the better monitoring of short-lived pollutants to gauge the impact. But then, the overall picture of this study is clear that the seasonal fire episodes in the Similipal domain push the air quality in Odisha beyond its limit. The present case study helps to understand the expansion of very poor air quality at a regional scale initiated by the forest fire events for a shorter period over eastern India, which demands the exigency of the establishment of a proper in-situ network to fill the void in the scientific understanding on the life cycle of such pollutants.

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ADDITIONAL INFORMATION AND DECLARATIONS

Data Availability Statement

The datasets utilised in this article are freely accessible through the following sites: <https://earthdata.nasa.gov/> and <https://scihub.copernicus.eu/>. The in-situ data used for the study is acquired from <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing>. All other analysed datasets generated for this study are included in the article.

Conflict of Interests

The authors have declared no conflicts of interest for this article.



Disclosure

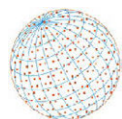
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Supplementary Material

Supplementary material for this article can be found in the online version at <https://doi.org/10.4209/aaqr.220084>

REFERENCES

- Allen, G., Sioutas, C., Koutrakis, P., Reiss, R., Lurmann, F.W., Roberts, P.T. (1997). Evaluation of the TEOM® method for measurement of ambient particulate mass in urban areas. *J. Air Waste Manage. Assoc.* 47, 682–689. <https://doi.org/10.1080/10473289.1997.10463923>
- Andreae, M.O. (2019). Emission of trace gases and aerosols from biomass burning - An updated assessment. *Atmos. Chem. Phys.* 19, 8523–8546. <https://doi.org/10.5194/acp-19-8523-2019>
- Asner, G.P., Mascaro, J. (2014). Mapping tropical forest carbon: Calibrating plot estimates to a simple LiDAR metric. *Remote Sens. Environ.* 140, 614–624. <https://doi.org/10.1016/j.rse.2013.09.023>
- Cheng, L., McDonald, K.M., Angle, R.P., Sandhu, H.S. (1998). Forest fire enhanced photochemical air pollution. A case study. *Atmos. Environ.* 32, 673–681. [https://doi.org/10.1016/S1352-2310\(97\)00319-1](https://doi.org/10.1016/S1352-2310(97)00319-1)
- Cyrus, J., Dietrich, G., Kreyling, W., Tuch, T., Heinrich, J. (2001). PM_{2.5} measurements in ambient aerosol: Comparison between Harvard impactor (HI) and the tapered element oscillating microbalance (TEOM) system. *Sci. Total Environ.* 278, 191–197. [https://doi.org/10.1016/S0048-9697\(01\)00648-9](https://doi.org/10.1016/S0048-9697(01)00648-9)
- Davies, D., Ederer, G., Olsina, O., Wong, M., Cechini, M., Boller, R. (2019). NASA's Fire Information for Resource Management System (FIRMS): Near Real-Time Global Fire Monitoring Using Data from MODIS and VIIRS. NASA Tech. Reports GSFC-E-DAA-TN73770. 1–20. <https://ntrs.nasa.gov/citations/20190032007>
- Forest Survey of India (FSI) (2020). Rapid Assessment of Fire affected Forest Areas in the Country based on MODIS-detections following a Sampling Approach. Forest Survey of India Technical Report. 1–28. http://weblines.co.in/fsi-result/technical_information_series_vol2_no2.pdf
- Gogikar, P., Tyagi, B., Padhan, R.R., Mahaling, M. (2018). Particulate matter assessment using in situ observations from 2009 to 2014 over an industrial region of eastern India. *Earth Syst. Environ.* 2, 305–322. <https://doi.org/10.1007/s41748-018-0072-8>
- Grennfelt, P., Engleryd, A., Forsius, M., Hov, Ø., Rodhe, H., Cowling, E. (2020). Acid rain and air pollution: 50 years of progress in environmental science and policy. *Ambio* 49, 849–864. <https://doi.org/10.1007/s13280-019-01244-4>
- Hari, M., Sahu, R.K., Tyagi, B., Kaushik, R. (2021a). 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>
- Hari, M., Srinivasan, S., Rajasekaran, A., Tyagi, B. (2021b). Above ground carbon stock mapping over Coimbatore and Nilgiris Biosphere: A key source to the C sink. *Carbon Manag.* 12, 411–428. <https://doi.org/10.1080/17583004.2021.1962979>
- Hari, M., Tyagi, B. (2021). Investigating Indian summer heatwaves for 2017–2019 using reanalysis datasets. *Acta Geophys.* 69, 1447–1464. <https://doi.org/10.1007/s11600-021-00603-8>
- Heue, K.P., Coldewey-Egbers, M., Delcloo, A., Lerot, C., Loyola, D., Valks, P., Van Roozendaal, M. (2016). Trends of tropical tropospheric ozone from 20 years of European satellite measurements and perspectives for the Sentinel-5 Precursor. *Atmos. Meas. Tech.* 9, 5037–5051. <https://doi.org/10.5194/amt-9-5037-2016>
- Lyapustin, A.I., Wang, Y., Laszlo, I., Hilker, T., G.Hall, F., Sellers, P.J., Tucker, C.J., Korkin, S.V. (2012). Multi-angle implementation of atmospheric correction for MODIS (MAIAC): 3. Atmospheric correction. *Remote Sens. Environ.* 127, 385–393. <https://doi.org/10.1016/j.rse.2012.09.002>
- Martins, V., Miranda, A.I., Carvalho, A., Schaap, M., Borrego, C., Sá, E. (2012). Impact of forest fires on particulate matter and ozone levels during the 2003, 2004 and 2005 fire seasons in Portugal. *Sci. Total Environ.* 414, 53–62. <https://doi.org/10.1016/j.scitotenv.2011.10.007>



- Meo, S.A., Abukhalaf, A.A., Alomar, A.A., Alessa, O.M., Sami, W., Klonoff, D.C. (2021). Effect of environmental pollutants PM-2.5, carbon monoxide, and ozone on the incidence and mortality of SARS-COV-2 infection in ten wildfire affected counties in California. *Sci. Total Environ.* 757, 143948. <https://doi.org/10.1016/j.scitotenv.2020.143948>
- Mhawish, A., Banerjee, T., Sorek-Hamer, M., Lyapustin, A., Broday, D.M., Chatfield, R. (2019). Comparison and evaluation of MODIS Multi-angle Implementation of Atmospheric Correction (MAIAC) aerosol product over South Asia. *Remote Sens. Environ.* 224, 12–28. <https://doi.org/10.1016/j.rse.2019.01.033>
- Mishra, R.K., Upadhyay, V.P., Mohanty, R.C. (2008). Vegetation ecology of the Similipal biosphere reserve, Orissa, India. *Appl. Ecol. Environ. Res.* 6, 89–99. https://doi.org/10.15666/aeer/0602_089099
- Reddington, C.L., Conibear, L., Robinson, S., Knote, C., Arnold, S.R., Spracklen, D.V. (2021). Air Pollution From Forest and Vegetation Fires in Southeast Asia Disproportionately Impacts the Poor. *GeoHealth*. 5, e2021GH000418. <https://doi.org/10.1029/2021GH000418>
- Sahu, S.K., Mangaraj, P., Beig, G., Samal, A., Chinmay Pradhan, Dash, S., Tyagi, B. (2021). Quantifying the high resolution seasonal emission of air pollutants from crop residue burning in India. *Environ. Pollut.* 286, 117165. <https://doi.org/10.1016/j.envpol.2021.117165>
- Saranya, K.R.L., Reddy, C.S., Rao, P.V.V.P., Jha, C.S. (2014). Decadal time-scale monitoring of forest fires in Similipal Biosphere Reserve, India using remote sensing and GIS. *Environ. Monit. Assess.* 186, 3283–3296. <https://doi.org/10.1007/s10661-014-3619-7>
- Saranya, K.R.L., Reddy, C.S. (2016). Long term changes in forest cover and land use of similipal biosphere reserve of India using satellite remote sensing data. *J. Earth Syst. Sci.* 125, 559–569. <https://doi.org/10.1007/s12040-016-0685-y>
- Saranya, K.R.L., Reddy, C.S., Rao, P.V.V.P. (2016). Estimating carbon emissions from forest fires over a decade in Similipal Biosphere Reserve, India. *Remote Sens. Appl. Soc. Environ.* 4, 61–67. <https://doi.org/10.1016/j.rsase.2016.06.001>
- Sastry, N. (2002). Forest fires, air pollution, and mortality in Southeast Asia. *Demography* 39, 1–23. <https://doi.org/10.2307/3088361>
- Sun, Y.W., Xie, P.H., Xu, J., Zhou, H.J., Liu, C., Wang, Y., Liu, W.Q., Si, F.Q., Zeng, Y. (2013). Measurement of atmospheric CO₂ vertical column density using weighting function modified differential optical absorption spectroscopy. *Acta Phys. Sin.* 62, 13070. <https://doi.org/10.7498/aps.62.130703> (in Chinese)
- Tan-Soo, J.S., Pattanayak, S.K. (2019). Seeking natural capital projects: Forest fires, haze, and early-life exposure in Indonesia. *PNAS* 116, 5239–5245. <https://doi.org/10.1073/pnas.1802876116>
- Tyagi, B., Singh, J., Beig, G. (2020). Seasonal progression of surface ozone and NO_x concentrations over three tropical stations in North-East India. *Environ. Pollut.* 258, 113662. <https://doi.org/10.1016/j.envpol.2019.113662>
- Zheng, B., Chevallier, F., Ciais, P., Broquet, G., Wang, Y., Lian, J., Zhao, Y. (2020). Observing carbon dioxide emissions over China's cities and industrial areas with the Orbiting Carbon Observatory-2. *Atmos. Chem. Phys.* 20, 8501–8510. <https://doi.org/10.5194/acp-20-8501-2020>
- Zhou, Y., Brunner, D., Boersma, K.F., Dirksen, R., Wang, P. (2009). An improved tropospheric NO₂ retrieval for OMI observations in the vicinity of mountainous terrain. *Atmos. Meas. Tech.* 2, 401–416. <https://doi.org/10.5194/amt-2-401-2009>
- Zu, K., Tao, G., Long, C., Goodman, J., Valberg, P. (2016). Long-range fine particulate matter from the 2002 Quebec forest fires and daily mortality in Greater Boston and New York City. *Air Qual. Atmos. Health* 9, 213–221. <https://doi.org/10.1007/s11869-015-0332-9>