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Assessing the impact of forest fires on air quality in Northeast India

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This study investigates the impact of forest fires on air quality in India's northeastern (NE) region, focusing on Guwahati, Tezpur, and Aizawl. The North-Eastern Forest cluster, contributing 36% to the total forest cover, emerges as a hotspot with the highest number of fire detections (40%). Population growth and shifting cultivation practices have intensified the frequency of fires. The study spans 2013–2016, assessing PM_{10}, $PM_{2.5}$, ozone (O_3), carbon monoxide (CO) and nitrogen oxide (NO_x) concentrations in the three NE cities. Guwahati consistently recorded PM_{10} concentrations above National Ambient Air Quality Standards (NAAQS), indicating persistent air quality challenges. Tezpur and Aizawl maintained concentrations below NAAQS, with Aizawl displaying Good to Satisfactory air quality on a significant portion of observed days. During forest fire (FF) events from 2013 to 2016, PM_{10}, $PM_{2.5}$, O_3, CO, and NO_x concentrations rose, suggesting a direct correlation between FF and deteriorating air quality, especially when FF counts were above 100. During these events, a shift in air quality levels was observed, affecting most parameters in Aizawl and varying for other cities. Diurnal patterns during FF events indicated increased pollutant levels. The most prominent change was observed in PM_{10} in all stations. Backward air–mass trajectory analysis confirms the influence of NE-India as a significant pollution source during FF. This study underscores the urgent need for targeted interventions to mitigate the impact of FF on air quality in the NE region, emphasising the intricate relationship between ecological practices, forest fires and atmospheric conditions.

Environmental significance

NE India, though a geographically sensitive region for climate change studies because of its proximity to the Himalayas and also the Bay of Bengal, remains relatively unexplored. Forest fires, primarily originating from naturally falling rocks in the unstable hilly region, ignite the NE forests, with the start of summer, leading to heavy pre-monsoon showers. This study deals with their interaction as seen in the proximity and farther based on three stations' data. This manuscript presents a reliable climatological picture of the forest fires and *in situ* meteorological parameters along with air quality data for 2–4 years, which is extremely rare in this region, revealing how and when the transported pollutants of forest fires from the hills affect nearby and distant lands. Unlike most mainland stations, ozone is the lead pollutant in relatively unpolluted NE hill stations. Fire counts >100 become significant in polluting the air; otherwise, they are insignificant. At Aizawl, a station with the largest number of forest fires, the intensity is reflected in $PM_{2.5}$, CO, and O_3. It worsens air quality further. The effect is seen in PM10 only at the farther stations, Guwahati and Tezpur.

1. Introduction

India, constituting only 2.5% of the global geographical area, yet supporting 16% of the world's population, grapples with a distinctive ecological challenge. The nation's forest cover, comprising 21.7% of its total area, is categorised into 3% very dense, 9.4% moderately thick, and 9.3% open forest. With a mere 1.8% of the global forest area, India's diverse ecosystems bear the weight of a population that substantially demands its natural resources.[1] The prevalence of forest fires (FF) in India is evident, with 380–445 districts out of 647 experiencing annual fires from 2003 to 2016.[2] In 2018 alone, MODIS (MODerate Resolution Imaging Spectroradiometer) satellite data recorded approximately 37 059 fires,[3] highlighting uneven distribution with certain regions facing higher frequencies and severe consequences.

The classification of Indian forests underscores vulnerability, revealing that nearly 4% of the country's forest area is extremely susceptible to fire, while over 6% is highly vulnerable. India can be divided geographically into four clusters – North Himalayan, North-Eastern (NE), Southern, and Central – each representing distinct ecological characteristics. These clusters, housing around 90% of India's total forest cover, witnessed 98% of the detected fire points from 2003 to 2016. The North-Eastern cluster, contributing 36% to the total forest cover, stands out

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with the highest number of fire detections at 40%. The concentration of fires in this cluster is linked to shifting cultivation (jhum), causing repeated burns in specific areas.[4] Population growth has accelerated the frequency of these burns, reducing the ecosystem's resilience from 20–30 years to 2–3 years.[5]

Examining specific cases, Mizoram state, with an 85% forest area dominated by Melocanna baccifera bamboo species, experienced an increased frequency of forest fires in 2007 due to mass flowering in 2006, leading to extensive clearing and burning.[6] This exemplifies the intricate interplay between ecological events and their impact on fire incidence. Biomass burning in India extends beyond crop residue, encompassing forest fires.[7,8] In Mizoram, the high percentage of forest cover (85%) makes the region particularly prone to wildfires. The fires are likely due to a mix of human activities (*e.g.*, shifting cultivation or jhum, which is common in the Northeast) and natural causes. Similarly, in Assam, with 36% forest cover, fires are also common and could be driven by agricultural practices, local land use, and possibly natural causes such as dry conditions and lightning. In Mizoram, the forests are diverse, primarily composed of Secondary Moist Bamboo Brakes (37%) and Cachar Tropical Semi-Evergreen Forests (31%). Other significant types include East Himalayan Moist Mixed Deciduous Forest (31%) and smaller patches of other forest types. The vegetation that burns includes species such as Dipterocarpus turbinatus, Terminalia myriocarpa, and Michelia champaca. In Assam, the primary forest types affected by fires include Cachar Semi-Evergreen Forest (38%) and East Himalayan Moist Mixed Deciduous Forest (18%). Species in the affected forests include Dipterocarpus and Sal (Shorea) trees, which are found in the Assam Valley's tropical wet-evergreen forests and the Kamrup Sal forests, respectively.[4] The Forest Survey of India[3] has identified vulnerable months, primarily from March to May, when high temperatures elevate the risk.

Moreover, natural factors, including lightning, play a role in sparking fires in dry vegetation. As these fires rage, they profoundly impact air quality, releasing pollutants into the atmosphere.[9–11] The resultant degradation in air quality poses significant health risks to the local population and those residing in distant areas. Recognising the pivotal role of open vegetation fires, extensive efforts have been undertaken at both regional and global levels to comprehend their impact on atmospheric chemistry, trace gases and aerosol budgets, earth's radiation balance, and hydrological and biogeochemical cycles.[12–15] Studies examining emissions from open fires and their repercussions have been well-documented across South America, Africa, Southeast Asia, East Asia, and Australia.[16–19] However, research quantifying and characterising emissions from these open fires remains limited in South Asia. In this region, open biomass burning not only contributes to air pollution but also introduces high uncertainty in emission estimates.[20,21] Moreover, the increased pollution levels over South Asia due to open fires, particularly during the pre-monsoon season,[22,23] can potentially impact the summer monsoon.[24] Aerosols, by absorbing and scattering sunlight, modify atmospheric temperature gradients, which can disturb the monsoon system that depends on the temperature contrast between land and ocean to bring rainfall. Since the summer monsoon delivers the majority of South Asia's annual precipitation, any disruption could result in erratic rainfall patterns or drought, severely impacting crop yields and threatening food security throughout the region.

Given this context, the present study focuses on the impact of forest fires in the Guwahati, Tezpur, and Aizawl districts of Assam and Mizoram in the NE region of India. The NE region is recognised as a biodiversity hotspot, boasting rich and diverse forest resources. In NE-India, a close association exists between air pollution and forest fires due to widespread practices of shifting cultivation between February and May each year. Despite this well-known fact, there is limited evidence regarding forest fire incidents and their adverse effects on air quality, particularly in the NE region. For instance, a study conducted by Vadrevu *et al.*[7] suggests that during the dry season of February to May, carbon monoxide (CO) concentration has increased to 439.1 ppbv, coinciding with peak forest fire incidents. Furthermore, a recent study also identifies the role of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) during forest fires in NE-India.[21] Given the absence of knowledge, the present study attempts to evaluate air quality and fire incidence in the three strategic cities of NE-India: Guwahati, Aizawl, and Tezpur.

2. Materials and methodology

2.1. Study area and climate

Guwahati (26°9′11.07″N, 91°39′49.82″E) is the largest city in India's NE state of Assam (Fig. 1). With a total area of 262 sq. km the city lies on the south bank of the river Brahmaputra. The eastern and western regions have vast undulating alluvial plains with varying altitudes of 49.5 m to 55.5 meters.[25] Guwahati experiences a moderate subtropical humid climate with an average temperature of 16.2 °C in winter and about 26.7 °C in summer. The annual average precipitation was recorded as 1724 cm, with very heavy rainfall in June and July. Tezpur (26° 42′3.37″N, 92°49′49.04″E, 73 m) is one of the important towns situated on the north bank of the river Brahmaputra. The town has a total area of 40 sq.km between the foothills of the Himalayas to the north and the river Brahmaputra to the south. The region is characterised by an alluvial flood plain, hillocks, and small red hillocks (90–210 amsl). The climate is typically humid and hot, with annual average temperatures ranging from 9 to 27 °C in winter and about 25–36 °C in summer. The yearly precipitation was recorded as 183.6 cm, with heavy rainfall in June and July. Located in the northern part, Aizawl (23° 43′59.82″N, 92°39′ 55.48″E, 839 m) is the capital city of Mizoram. The town lies on a ridge (1132 amsl) with the Tlawng River Valley to the west and the Tuirial River Valley to the east. The climate is subtropical, with annual average temperatures ranging from 10 to 25 °C during winter and 24–35 °C during summer. The monsoon system influences the region, which has a yearly precipitation of 208 cm, and rainfall is typically higher from May to September.[26]

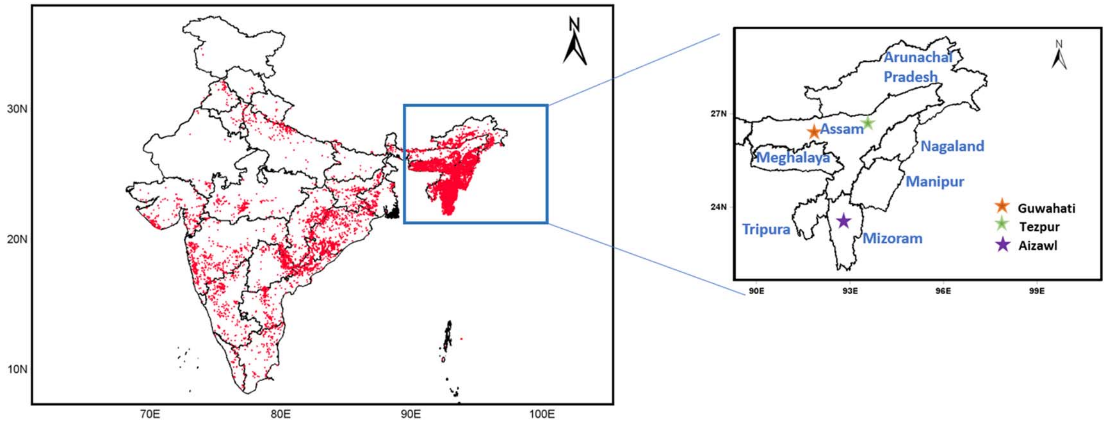

Fig. 1 Fire hotspots (denoted in red) detected in March 2015 by the MODIS satellite in India. Magnified region is North-East India. Stars show the locations of the measurement sites.

2.2. Air quality assessment

The continuous measurements of air pollutants *viz.* ozone (O_3), CO, NO_x, particulate matter with an aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) and particulate matter with an aerodynamic diameter ≤10 μm (PM_{10}) were carried out using online analysers under the Modelling of Atmospheric Pollutants and Networking (MAPAN) program, sponsored by the Ministry of Earth Science, Govt. of India, at Guwahati (Gauhati University; Jan 2013 to Dec 2016), Aizawl (Mizoram University; Jan 2015 to Dec 2016) and Tezpur (Tezpur University; May 2013 to July 2016). The hourly average concentration of O_3 was measured using the UV photometric technique (Ecotech-EC9810), CO was measured using the IR photometric technique (Ecotech-EC9830) and NO_x using an AC32M. $PM_{2.5}$ and PM_{10} measurements were carried out using a Met one Instrument Model BAM-1020 (Beta Attenuation Monitor). Meteorological parameters, *viz.* temperature (Temp.), relative humidity (RH), wind speed (WS), solar radiation (SR) and rainfall (RF), were measured using an Automatic Weather Station (AWS). Air quality was assessed using the standard Air Quality Index (AQI). According to the Central Pollution Control Board, the AQI ranges from 0–500, with 0–50 being good and 400–500 being severe. In the present study, five different parameters, *viz.* PM_{10}, $PM_{2.5}$, CO, O_3 and NO_2, were employed to compute the AQI. In the present study, daily AQI values were calculated from the 24 h mean of $PM_{2.5}$, PM_{10}, and NO_2 concentrations and the maximum 8 h mean of O_3 and CO concentrations following the standard formula.[27]

2.3. Data quality check

Quality control and quality assurance are the major and essential steps performed before using the air pollutant data. The equipment was maintained and operated according to the standard specifications of the supplier. The instruments are US EPA approved and the quality system is certified ISO9001 by Bureau Veritas Certification. We have adopted the US EPA's Standard Operating Procedures for instrument calibration and maintenance. For more information about the calibration procedure refer to Title 40 of the Code of Federal Regulations (CFR) Part 50. **http://www.law.cornell.edu/cfr/text/40/part-50** (**http://www.safar.tropmet.res.in**). The monitoring stations were regularly visited by engineers to ensure that instruments were working properly. Based on drift specification, the instrument environment and other factors, the calibration was done at definite time intervals. The validation is an essential function of technical management. After collecting the data, errors or suspicious data have been flagged by us, which are then checked and corrected by an expert scientific team. Various quality codes are set to observational values based on information relating to the state of the sensor or measurement. The invalid or out of range data are not considered for data analysis.[28]

2.4. Forest fire assessment

Using FIRMS (Fire Information for Resource Management System) data, FF assessments were carried out to determine the daily forest fire incidents in the NE-India (22°–30°N and 88°–98° E) (**https://www.firms.modaps.eosdis.nasa.gov/download/create.php**). The FIRMS dataset was acquired from the MODIS satellite, which is fitted with a multi-spectral sensor with 36 spectral bands from 0.4 to 14.2 μm wavelengths and detects fire at 1 km nominal spatial resolution at nadir using 4 and 11 μm channels.[29]

For a more comprehensive impact assessment of FF on air quality, the January to May period was classified into FF <100 and FF >100 periods based on fire counts. The days on which daily fire counts were fewer than 100 were categorized in the FF <100 period, while those with more than 100 were categorized in the FF >100 period. During this period, only fire counts with a confidence value ≥80% were considered to eliminate the chances of false fire detection. Moreover, to analyse the regional impact of the FF, 72 h backward air mass trajectories (100 m above ground level) at Guwahati, Tezpur and Aizawl were simulated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model based on GDAS (Global Data Assimilation System) meteorological data (1° × 1°).[30]

Table 1 Annual average concentration of pollutants at (a) Guwahati, (b) Tezpur and (c) Aizawl during 2013–2016[a]

Year	2013			2014			2015			2016		
Pollutants	GUW	TZP	AIZ	GUW	TZP	AIZ	GUW	TZP	AIZ	GUW	TZP	AIZ
PM_{10} (μg m^{-3})	98.5 ± 85.2	42.4 ± 38.3	ND	94.6 ± 74.7	51.2 ± 57.1	ND	71.9 ± 55.9	57.7 ± 56.4	43.6 ± 28.9	81.6 ± 50.2	61 ± 63.5	45.9 ± 34.8
$PM_{2.5}$ (μg m^{-3})	53.7 ± 47.6	27.5 ± 29.9	ND	50.2 ± 42	34.8 ± 41.2	ND	31.3 ± 25.3	35.8 ± 38.3	23.2 ± 19.8	39.8 ± 31.2	36 ± 37.5	28.4 ± 27.5
O_3 (ppb)	11.6 ± 11	15.1 ± 9	ND	10.6 ± 8.2	14.6 ± 13.4	ND	10.9 ± 7.5	15.7 ± 10.9	23.4 ± 23.5	10.4 ± 8.5	23.1 ± 14.6	18 ± 11.9
NO_x (ppb)	17.3 ± 14.1	3.4 ± 2.9	ND	19.9 ± 18.6	3.4 ± 3.4	ND	14.6 ± 9.8	4.9 ± 4.5	8.9 ± 6.9	23.7 ± 11.2	8.5 ± 5.7	8.3 ± 5.3
CO (ppm)	0.54 ± 0.3	0.4 ± 0.3	ND	0.51 ± 0.3	0.5 ± 0.2	ND	0.46 ± 0.2	0.4 ± 0.3	0.4 ± 0.2	0.54 ± 0.2	0.5 ± 0.2	0.4 ± 0.3

[a] GUW: Guwahati city; TZP: Tezpur city; AIZ: Aizawl city; ND: no data available.

3. Results and discussion

3.1. Air quality profile

The annual average concentration of PM_{10} in Guwahati was above the National Ambient Air Quality Standard (NAAQS)[31] *i.e.*, 60 μg m^{-3} in all the years (Table 1). The results showed a wide range of variability in PM_{10} concentration, ranging from 71.9 ± 55.9 to 98.5 ± 85.2 μg m^{-3}, with the highest annual average concentration in 2013. As for $PM_{2.5}$, O_3, and CO, their average yearly concentrations ranged from 31.3 ± 25.3 to 53.7 ± 47.6 μg m^{-3}; 10.4 ± 8.5 to 11.6 ± 11.0 ppb; and 0.46 ± 0.2 to 0.54 ± 0.3 ppm, respectively, with the highest concentration in 2013. Notably, only the $PM_{2.5}$ annual average concentration exceeded the NAAQS (40 μg m^{-3}) in 2013 and 2014. Moreover, the NO_x ranged from 14.6 ± 9.8 to 23.7 ± 11.2 ppb, with the highest concentration in 2016. Among 1300 observation days, 34.7% of the days were in the 'Good' category, 28.5% in Satisfactory, 26.4% in the 'Moderate', 6.7% in the 'Poor' and 3.7% in the 'Very Poor' category (Table 2, Fig. 2). The AQI observations revealed that PM_{10} was the lead pollutant on 65.7% of the days. In contrast, on 29.6% of the days, $PM_{2.5}$ was the lead pollutant.

Like Guwahati, a wide range of variability in the annual average concentration of PM_{10} ranging from 42.4 ± 38.3 to 61 ± 63.5 μg m^{-3}, with the highest average concentration in 2016 (Table 1), was observed at Tezpur. The concentrations of $PM_{2.5}$, O_3 and CO ranged from 27.5 ± 29.9 to 36 ± 37.5 μg m^{-3}, 14.6 ± 13.4 to 23.1 ± 14.6 ppb and 0.4 ± 0.3 to 0.5 ± 0.2 ppm, respectively, with the highest concentration in 2016. Moreover, the NO_x ranged from 3.4 ± 2.9 to 8.5 ± 5.7 ppb, with the highest concentration in 2016. Although there is variability in the concentration of particulate matter, their annual average concentration was recorded below NAAQS guidelines (except for PM_{10} concentration in 2016). Further, from 2013 to 2016 (1146 observation days), the AQI of Tezpur city was in the Good category on 47.2% of the days, the Satisfactory category on 33.5% of the days, Moderate on 11.8% of the days, Poor on 4.1% of the days and Very Poor on 3.4% of the days, respectively (Table 2). Among all these AQI categories, $PM_{2.5}$ was identified as the lead pollutant on 48.5% of the days and PM_{10} on 27.6% of the days.

The air quality mapping of Aizawl City (2015–2016) depicts slight variability in the PM concentration (Table 1). For instance, PM_{10} annual average concentration ranged from 43.6 ± 28.9 to 45.9 ± 34.8 μg m^{-3}, with the highest average concentration in 2016. Similarly, for $PM_{2.5}$ and NO_x, the concentration ranged from 23.2 ± 19.8 to 28.4 ± 27.5 μg m^{-3} and 8.3 ± 5.3 to 8.9 ± 6.9 ppb, respectively. The annual average concentration of O_3 ranged from 18 ± 11.9 to 23.4 ± 23.5 ppb. Further, from 2014 to 2015 (630 observation days), the AQI of Aizawl was in the Good category on 50.8% of the days, the Satisfactory category on 44.3% of the days, Moderate on 4.1% of the days, Poor on 0.5% of the days and Very Poor on 0.3% of the days, respectively (Table 2). O_3 was identified as the lead pollutant among all these categories, and its occurrence was repeated from February to May. The occurrence of O_3 as a lead pollutant corroborates with a recent study, which suggests that,

Table 2 AQI variation and leading pollutant at (a) Guwahati, (b) Tezpur and (c) Aizawl during 2013–2016[a]

					No. of days as the leading pollutant														
AQI category		No. of days			$PM_{2.5}$			PM_{10}			CO			O_3			NO_2		
Cities	AQI	GUW	TZP	AIZ	UW	TZP	AIZ	GUW	TZP	AIZ	GUW	TZP	AIZ	GUW	TZP	AIZ	GUW	TZP	AIZ
Good	0–50	451 (34.7%)	541 (47.2%)	320 (50.8%)	44	344	12	351	76	66	7	78	205	38	41	21	11	2	16
Satisfactory	51–100	371 (28.5%)	384 (33.5%)	279 (44.3%)	53	37	74	313	203	56	—	107	146	5	36	3	—	1	—
Mod. Poll.	101–200	343 (26.4%)	135 (11.8%)	26 (4.1%)	156	89	3	187	37	5	—	7	16	—	2	2	—	—	—
Poor	201–300	87 (6.7%)	47 (4.1%)	3 (0.5%)	84	47		3	—	—	—	—	3	—	—	—	—	—	—
Very poor	301–400	48 (3.7%)	39 (3.4%)	2 (0.3%)	48	39	2	—	—	—	—	—	—	—	—	—	—	—	—
Severe	401–500	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Days	—	1300	1146	630	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

[a] GUW: Guwahati city; TZP: Tezpur city; AIZ: Aizawl city.

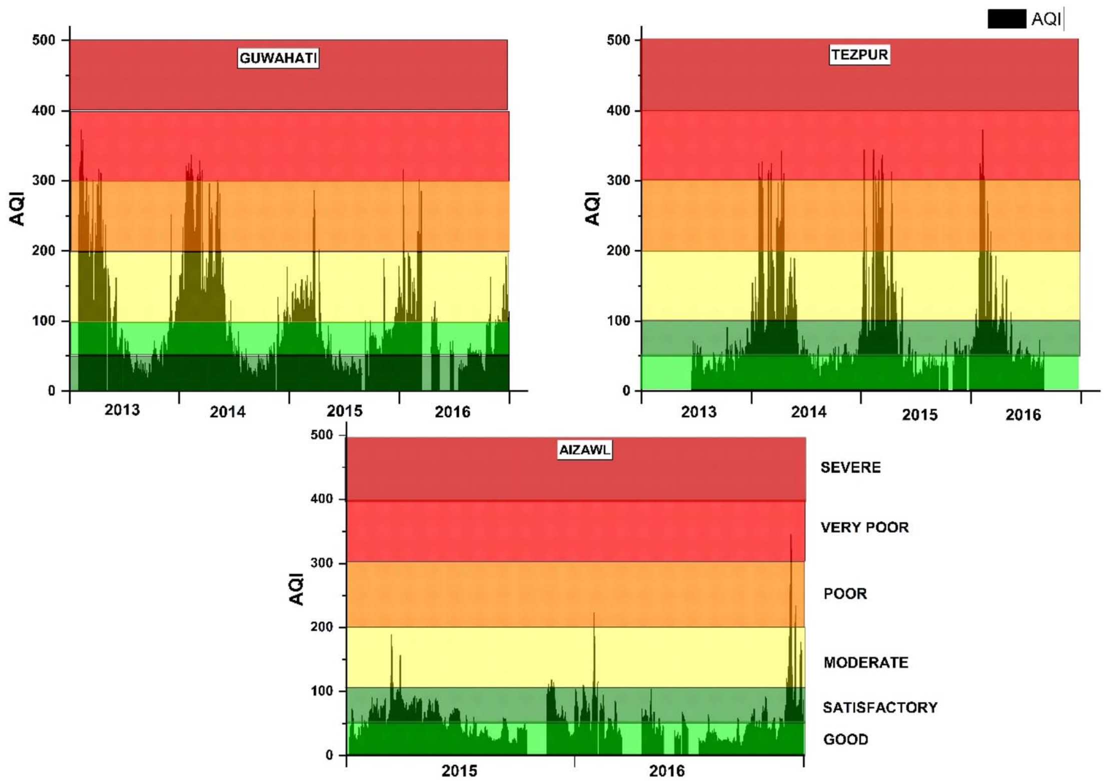

Fig. 2 Temporal variation of the AQI (represented by black lines) at Guwahati, Tezpur and Aizawl from Jan 2013 to Dec 2016.

during March, O_3 has a higher concentration within the proximity of fire hotspots due to its shorter life.[32]

Guwahati city experiences road congestion and vehicular traffic due to the single-lane roads, contributing to higher PM and NO_x concentrations than Tezpur and Aizawl.[33] The study reported by Srivastava *et al.*[34] at Gual Pahari, an urban site in the IGP, observed PM_{10} concentrations similar to those in Guwahati. Tezpur and Aizawl showed similar $PM_{2.5}$ and PM_{10} concentrations reported at Mahabaleshwar (a high altitude site at 1348 amsl).[35] O_3 and CO concentrations observed at all sites were comparable, showing similar variations reported by earlier studies.[26,36]

3.2. Interrelation between forest fire events and air quality

3.2.1. Fire count assessment. During 2013–2016, in all studied locations, the AQI in the Poor and Very Poor categories was observed mainly during the February to May months. This period also coincides with the slash and burning practices in the NE-India, which might be responsible for poor air quality. Thus, comprehensive FF profiling was carried out to investigate the variation of air quality during FF. The result demonstrates an increasing trend of FF observed from mid-February to May, with the maximum fire count in March (Fig. 3). March is one of the most vulnerable months for FF since it is a dry month. Additionally, it has been reported that open forests are more

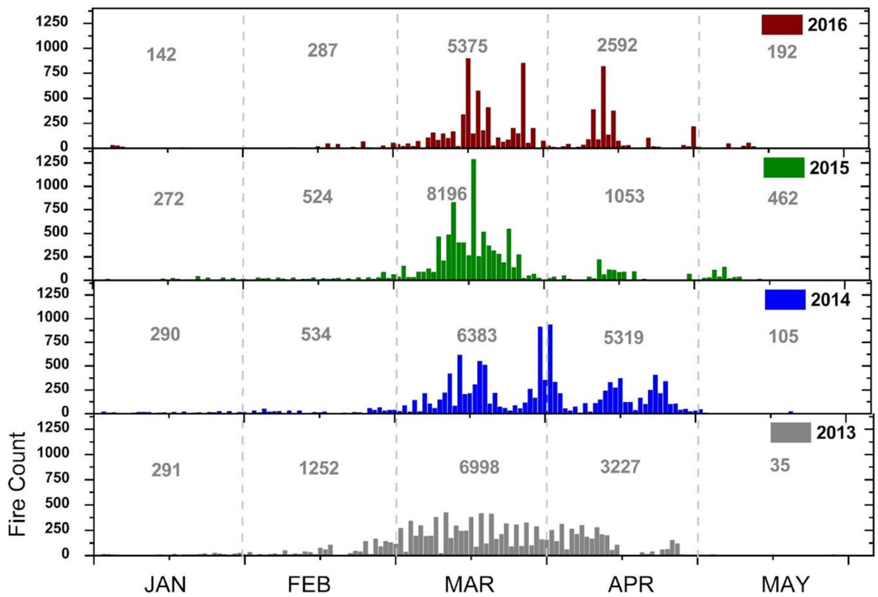

Fig. 3 Temporal variation of daily fire counts (represented by vertical bars) and total monthly fire counts (numbers given in each month) observed in NE-India during Jan to May months in 2013–2016.

Table 3 Variations in the pollutant's concentration and meteorological parameters during forest fire events[a]

	GUW			TZP			AIZ		
Cities	FF<100	FF > 100	% Change	FF < 100	FF > 100	% Change	FF < 100	FF > 100	% Change
CO (ppm)	0.59 ± 0.2	0.63 ± 0.2	6.8	0.5 ± 0.2	0.5 ± 0.2	7.3	0.4 ± 0.1	0.6 ± 0.1	50
NO_x (ppb)	17.2 ± 9.7	21.6 ± 0.5	25.6	9.8 ± 3.8	11.4 ± 4.8	16.3	7.2 ± 2.6	9.2 ± 2.7	27.8
O_3 (ppb)	12.9 ± 5	17.9 ± 7	38.7	22.5 ± 9.1	31 ± 10.1	37.6	37.1 ± 17.2	53.7 ± 21.4	44.7
PM_{10} (μg m^{-3})	121.6 ± 60.1	160.4 ± 58.5	31.9	88.5 ± 50.3	114.5 ± 46.4	29.3	45.8 ± 21	65.1 ± 29.9	42.1
$PM_{2.5}$ (μg m^{-3})	62.2 ± 37	70.8 ± 28.3	13.8	53.4 ± 29.6	58.7 ± 39.4	10	25.4 ± 13.5	36.5 ± 18.4	43.7
Temp. (°C)	21.5 ± 3.7	24.6 ± 1.7	14.4	22.3 ± 3.4	25.1 ± 1.9	12.5	20.8 ± 3.3	23.5 ± 1.4	12.9
RH (%)	81.0 ± 5.1	78.3 ± 5.3	−3.3	79.2 ± 4.2	75.1 ± 5.5	−5.2	77.5 ± 5.2	70.5 ± 5.7	−9.1
WS (m s^{-1})	1.3 ± 0.8	1.6 ± 0.9	23.1	2.2 ± 1.1	2.8 ± 1.1	27.3	4.5 ± 2.9	4.5 ± 2.3	−0.7
SR (W m^{-2})	137.6 ± 59.5	178.9 ± 38.2	30	136.6 ± 53.7	161.4 ± 44.5	18.1	123.8 ± 43.2	136.2 ± 24	10
RF (mm)	0.7 ± 0.7	0.3 ± 0.3	−57.1	0.1 ± 0.4	0.1 ± 0.2	−49.8	1.2 ± 7	0.5 ± 2.5	−146.1

[a] FF: Forest fire; GUW: Guwahati city; TZP: Tezpur city; AIZ: Aizawl city.

prone to FF since higher wind velocity assisted in greater penetration of flames.

Fire count assessment was carried out to decipher the interrelation between the FF and air quality. On a temporal scale, FF days were classified into two groups, *viz.* FF >100 and FF <100 days. Concurrently, during that period, the mean concentrations of pollutants were compared between FF <100 and FF >100 (Table 3). The result shows that during the FF >100 period, total forest fire counts were 4.5 times higher than those during the FF <100 period. The data indicate that $PM_{2.5}$ concentrations were relatively similar between periods FF >100 and FF <100, which could suggest that local sources or background pollution levels contribute consistently to $PM_{2.5}$ concentrations, regardless of fire activity. The fine particulate matter ($PM_{2.5}$) is generally more influenced by combustion-related sources, such as vehicles and biomass burning, which are persistent across both periods. However, slight increases in $PM_{2.5}$ during FF >100 were observed, with concentrations being 43.7%, 13.8%, and 10% higher at Aizawl, Guwahati, and Tezpur, respectively, during fire-affected periods. These increases likely reflect the additional contribution of fire emissions to the overall particulate matter load in these cities.

On the other hand, PM_{10} concentrations showed a more pronounced difference between FF >100 and FF <100 periods, with elevated levels recorded during the fire-affected period. At Guwahati, Tezpur, and Aizawl, PM_{10} concentrations during FF >100 were 160.4 ± 58.5, 114.5 ± 46.4, and 65.1 ± 29.9 μg m^{-3}, respectively, representing increases of 31.9%, 29.3%, and 42.1%. This suggests that larger particulate matter, which includes coarse particles such as dust and ash, is more directly impacted by fire events. The increase in PM_{10} concentrations is more marked because fires release a significant amount of coarser particles, which can travel farther and contribute more visibly to the pollution load.

Furthermore, the fire-affected period (FF > 100) had a notable impact on the AQI based on $PM_{2.5}$, with the AQI shifting from "Good" to "Satisfactory" in Aizawl, and from "Satisfactory" to "Moderate" in Guwahati. No AQI level change was observed in Tezpur, likely due to smaller differences in $PM_{2.5}$ between the two periods. The significant rise in both $PM_{2.5}$ and PM_{10} during FF >100 underscores the deteriorating air quality during periods of high fire activity, with the larger increase in PM_{10} likely reflecting the contribution of coarser particulate matter from fires.

During the FF >100 days, the PM_{10} based AQI jumps a level from Good to Satisfactory in Aizawl and Satisfactory to Moderate in Tezpur but shows no shift of level in Guwahati as it is already in the Moderate level and the range for the same is quite extensive. The increase in PM_{10} at all stations connected to FF is similar to that reported by Tarín-Carrasco *et al.*[37] in their study of mortality and wildfires in Portugal. O_3 is another important gaseous pollutant that is emitted from the FF.[38] Results showed that O_3 concentrations during the FF <100 period were 12.9 ± 5, 22.5 ± 9.1 and 37.1 ± 17.2 ppb, respectively, at Guwahati, Tezpur and Aizawl. Conversely, during the FF >100 period, the concentrations of O_3 were reported to be higher: 17.9 ± 7 (38.7% higher), 31 ± 10.1 (37.6% higher) and 53.7 ± 21.4 ppb (44.7% higher), respectively, at Guwahati, Tezpur and Aizawl. A study conducted by Jena *et al.*[39] in NE-India suggested that the surface concentration of O_3 increased by 25–30% due to the burning of forests. During the FF >100 period, O_3 exhibits a level enhancement in the AQI level, deteriorating from Good to Satisfactory, and mostly remains the lead pollutant for the AQI; in the other two stations, the enhancement in O_3 is not so significant. O_3 is a secondary pollutant which showed the maximum enhancement among all pollutants during the FF >100 period, which may be due to the emission of O_3 precursors (CO and NO_x) from FF.[38,40] CO concentrations during the FF >100 periods were 6.8, 7.3 and 50% higher than those during the FF < 100 periods at Guwahati, Tezpur and Aizawl, respectively. A study from the southern Himalayan region suggests that mean CO and NO_x reached up to 958.3 mg m^{-2} per day and 25.3 mg m^{-2} per day during April 2016, which is 110.6% and 132.5% higher than those during the

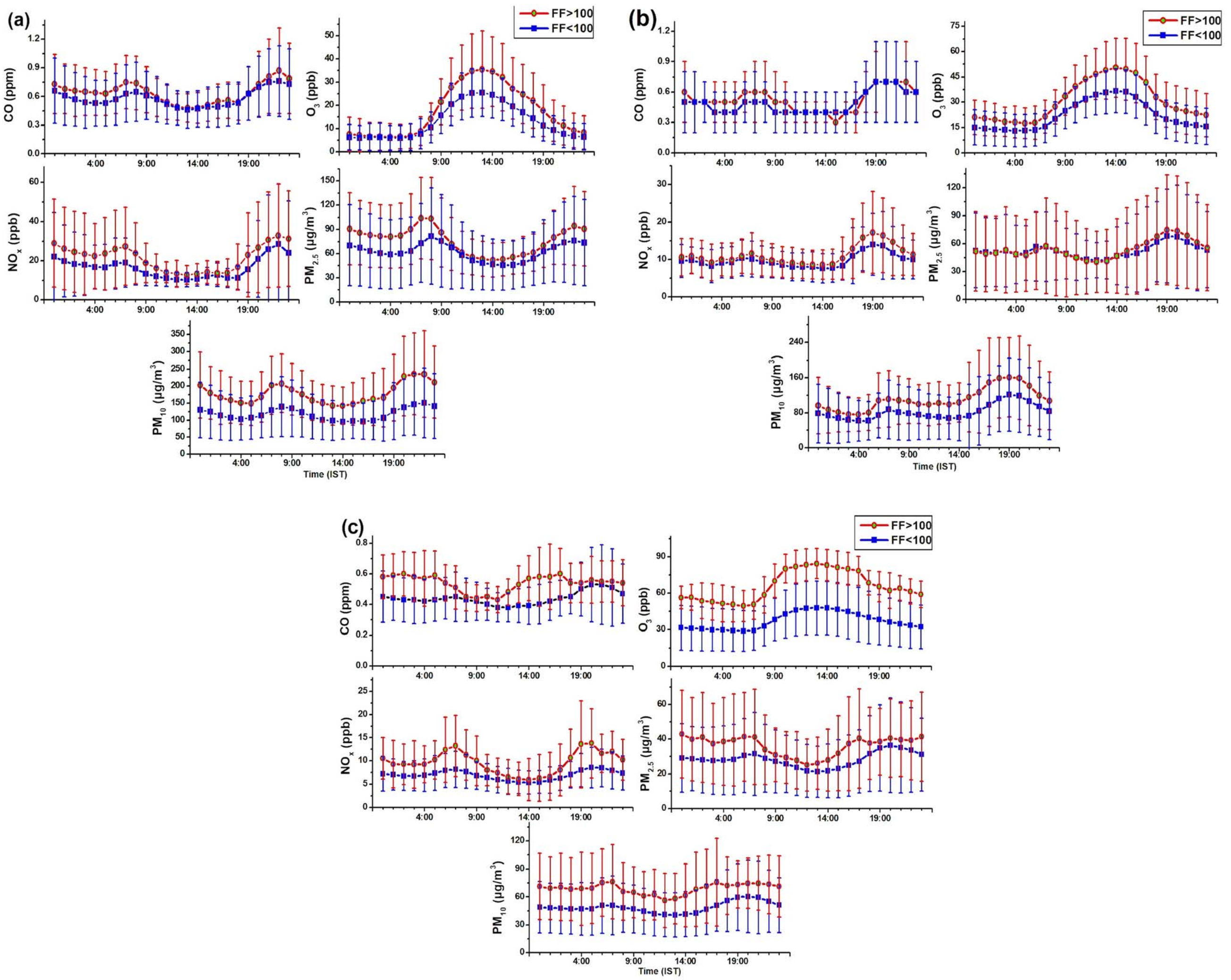

Fig. 4 Variation of average diurnal patterns of pollutants during FF <100 and FF >100 periods at (a) Guwahati, (b) Tezpur and (c) Aizawl.

non-burning period.[41] In the present study, the concentrations of NO_x reported during the FF <100 period were 17.2 ± 9.7, 9.8 ± 3.8 and 7.2 ± 2.6 μg m^{-3} at Guwahati, Tezpur and Aizawl, respectively. Likewise, elevated concentrations of NO_x were reported during the FF >100 period with values of 21.6 ± 10.5, 11.4 ± 4.8 and 9.2 ± 2.7 μg m^{-3} at Guwahati, Tezpur and Aizawl, respectively. The result of the present study is also in close agreement with the maximum emission of PM_{10}, $PM_{2.5}$, CO and NO_x from FF reported at Mizoram.[42]

In addition, meteorology was compared between both periods (Table 3). Temperature was 14.4, 12.5 and 12.9% higher during the FF >100 period at Guwahati, Tezpur and Aizawl, respectively. Solar radiation also showed a higher value during the FF >100 period (30, 18.1 and 10% at Guwahati, Tezpur and Aizawl). However, relative humidity and rainfall were lower in the FF >100 period. This suggests that the higher O_3 concentration during the FF >100 period may be due to enhanced photochemical production in the increased precursor concentration.[40]

For a more comprehensive study, the average diurnal patterns of the pollutants were compared between FF >100 and FF <100 periods (Fig. 4). O_3 showed a unimodal diurnal pattern with a daytime peak. A similar pattern was observed between both periods; however, the magnitude of the daytime peak was comparatively higher (9.8, 14.1 and 37.3 ppb more than those during the FF <100 periods at Guwahati, Tezpur and Aizawl, respectively) in the FF >100 period. It was observed that the rate of O_3 formation (d[O_3]/dt) was 1.5, 1.4 and 3.4 ppb h^{-1} higher during FF >100. This fine observation confirms the role of the FF, as it generates large amounts of O_3 precursors, which enhance the photochemical production of O_3. CO, NO_x, PM_{10} and $PM_{2.5}$ showed bimodal diurnal patterns with peaks during

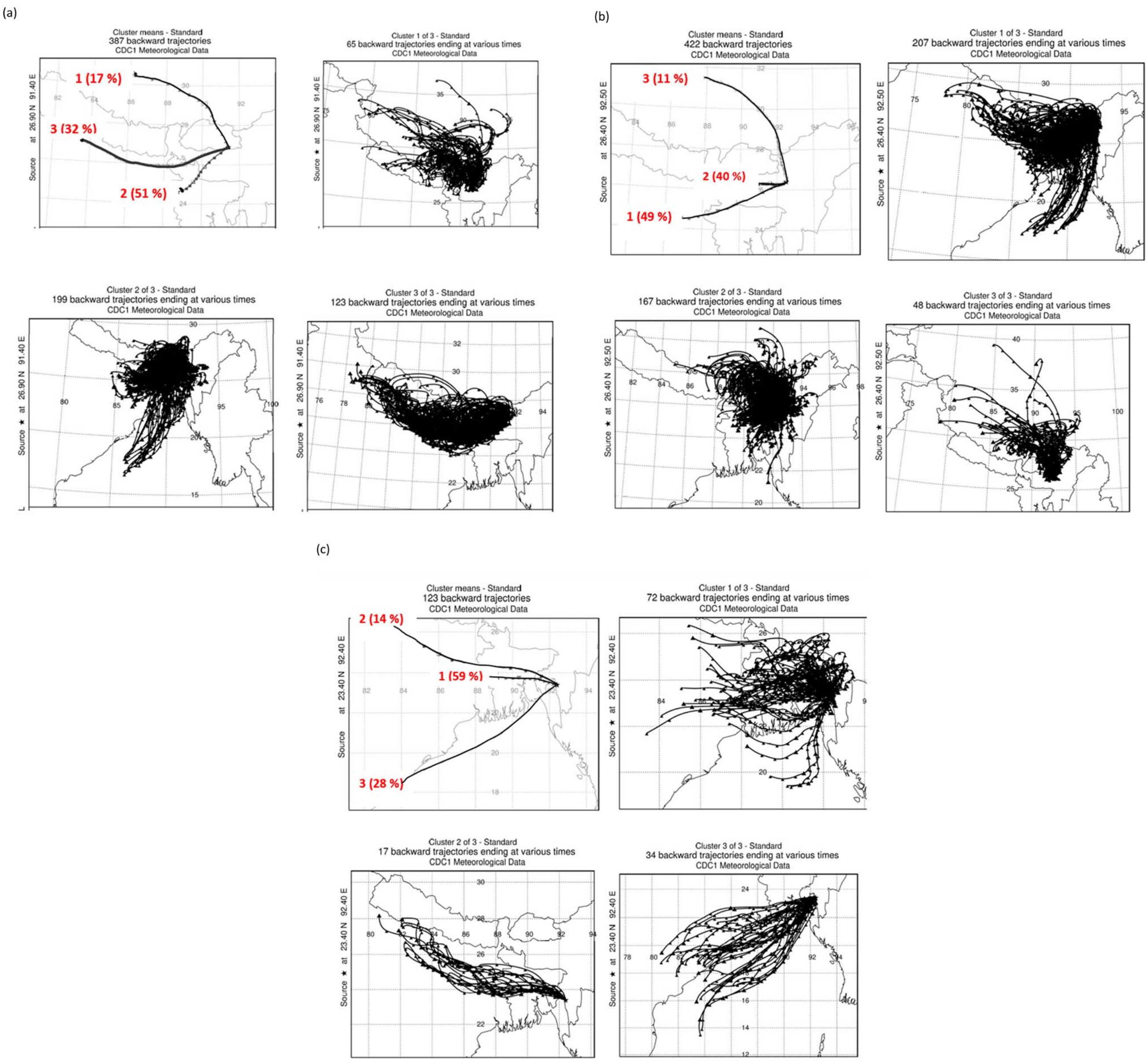

Fig. 5 72 h backward air mass trajectories arriving at 100 m agl during the FF >100 period at (a) Guwahati, (b) Tezpur and (c) Aizawl.

traffic hours. Like O_3, other pollutants also showed higher diurnal values during FF >100. The diurnal NO_x, PM_{10}, and $PM_{2.5}$ values showed maximum enhancement at Guwahati (7.7 ppb, 90.7 μg m^{-3} and 30.8 μg m^{-3}, respectively) during the FF >100 period. However, the maximum enhancement of CO was observed at Aizawl (0.2 ppm) in the FF >100 period. Mehra *et al.*[43] reported the impact of forest fires from the Chitwan Air Quality Monitoring Station situated in Nepal during the pre-monsoon season (February to May 2016). The average concentrations of PM_{10}, $PM_{2.5}$ and CO were found to be 156.4 ± 68.2 μg m^{-3}, 95.9 ± 49.0 μg m^{-3} and 713.4 ± 476.6 ppbv. The concentrations are similar to values observed at Guwahati.

3.2.2. Backward air-mass trajectory assessment. To determine the pathway of air masses arriving at Guwahati, Tezpur and Aizawl during the FF >100 period, a 3 day backward trajectory analysis was carried out (Fig. 5). The air masses were classified into 3 clusters based on Eigenvalues. At Guwahati, 3 clusters of trajectories were observed: one from China-Bhutan (17%), another passing through the southern states of NE India up to the Bay of Bengal (51%) and the last extending into the Indo-Gangetic Plain (IGP) (32%). Most of the air masses passed the southern region of North East India, where MODIS detected maximum FF activity. A similar pattern was observed at Tezpur with maximum air mass trajectories (49%) traversing through southern states of NE-India and another cluster limited to the eastern end of the IGP. At Aizawl, 59% of the trajectories were confined to NE-India and Bangladesh, 28% originated from the northwest coast of the Bay of Bengal, and 14% arrived from deep within the IGP. This indicates that the major portion of the incoming air traversed through the most fire-affected regions of NE India.

4. Discussion

This study highlights the significant impact of forest fire events on air quality in the north-eastern Indian cities of Guwahati, Tezpur, and Aizawl. During periods of intense fire activity (FF > 100), PM_{10} concentrations reached alarming levels of 160.4 ± 58.5 μg m^{-3} in Guwahati, 114.5 ± 46.4 μg m^{-3} in Tezpur, and 65.1 ± 29.9 μg m^{-3} in Aizawl, marking increases of 31.9%, 29.3%, and 42.1%, respectively. The study also found slight increases in $PM_{2.5}$ concentrations during these fire-affected periods, with Aizawl experiencing a 43.7% rise, Guwahati 13.8%, and Tezpur 10%. These results indicate a direct link between forest fires and deteriorating air quality, particularly in Aizawl. O_3 concentrations similarly spiked during FF >100 periods, rising from 12.9 ± 5 ppb in Guwahati, 22.5 ± 9.1 ppb in Tezpur, and 37.1 ± 17.2 ppb in Aizawl to 17.9 ± 7 ppb (38.7% higher), 31 ± 10.1 ppb (37.6% higher), and 53.7 ± 21.4 ppb (44.7% higher). This trend underscores the role of forest fires in enhancing photochemical O_3 production due to elevated levels of precursors like VOCs and nitrogen oxides (NO_x). CO concentrations also increased during FF >100 periods, with levels recorded at 6.8 μg m^{-3} in Guwahati, 7.3 μg m^{-3} in Tezpur, and a significant increase in Aizawl. Notably, NO_x levels rose from 17.2 ± 9.7 μg m^{-3} in Guwahati, 9.8 ± 3.8 μg m^{-3} in Tezpur, and 7.2 ± 2.6 μg m^{-3} in Aizawl during FF <100 to 21.6 ± 10.5 μg m^{-3}, 11.4 ± 4.8 μg m^{-3}, and 9.2 ± 2.7 μg m^{-3}, respectively, during FF >100.

These findings align with previous research. Sahu *et al.*[32] highlighted the severe impact of the 2021 Similipal forest fire episode on atmospheric pollutants across eastern India, where hazardous levels of $PM_{2.5}$ (300–400 μg m^{-3}), PM_{10} (400–500 μg m^{-3}), and CO (5–7 mg m^{-3}) were recorded, underscoring the widespread influence of fire events on air quality in urban regions. Similarly, Yarragunta *et al.*[44] documented elevated levels of gaseous pollutants in Uttarakhand during fire episodes, with CO concentrations reaching 2–3 ppm and O_3 levels spiking to 60–80 ppb, further indicating the significant role of forest fires in exacerbating air pollution. The findings of Mehra *et al.*[43] on the Himalayan foothills also support these observations, demonstrating a marked increase in pollutant levels during forest fire events, with $PM_{2.5}$ levels surging from 30–50 μg m^{-3} to 100–150 μg m^{-3}. Yin *et al.*[45] reported similar trends in Indonesia, where $PM_{2.5}$ concentrations exceeded 500 μg m^{-3} during forest fires, and Filonchyk *et al.*[46] noted significant increases in $PM_{2.5}$ and CO levels in the United States during the 2020 wildfires. Zhao *et al.*[47] further corroborate these findings, noting substantial increases in $PM_{2.5}$ and CO levels during wildfire events across various regions in China. Collectively, these studies highlight the critical need for improved forest management practices and early warning systems to mitigate the impact of forest fires on air quality.

While government policies in India have made strides in monitoring pollutants and fire records, there remains a significant data gap regarding air quality measurements in Northeast India. This lack of data complicates efforts to study the intricate relationship between air quality and prolonged fires in the region. The results of the present study contribute valuable insights into the atmospheric dynamics affecting air quality in Mizoram and Assam, driven by forest fires in the northeastern states. Thus, coordinated efforts between local governments and environmental agencies are essential for preventing and managing such fire events effectively.

5. Conclusion

• The air quality profiles of Guwahati, Tezpur, and Aizawl revealed notable variations in PM_{10} and $PM_{2.5}$, O_3, CO, and NO_x concentrations over the 2013–2016 period. Guwahati consistently exceeded the NAAQS for PM_{10}, with $PM_{2.5}$ surpassing the limit in 2013 and 2014, suggesting improving air quality over the years. Tezpur and Aizawl reported lower PM concentrations below NAAQS guidelines.

• Tezpur displayed consistently good to satisfactory air quality over 47% and 33.5% of the observed days, respectively, from 2013 to 2016. Aizawl exhibited a good air quality distribution on 50.8% of the days from 2015 to 2016. The lead pollutants in Aizawl, Guwahati and Tezpur were O_3, PM_{10} and $PM_{2.5}$, respectively.

• Interrelations between forest fire (FF) events and air quality were explored, particularly during the vulnerable period from February to May. During FF >100 periods, the concentrations of pollutants, including PM_{10}, $PM_{2.5}$, O_3, CO, and NO_x, were higher compared to those during FF <100.

• $PM_{2.5}$ concentrations during FF >100 were 43.7%, 13.8%, and 9.1% higher in Aizawl, Guwahati, and Tezpur, respectively, indicating the potential contribution of FF to deteriorating air quality. O_3, a critical secondary gaseous pollutant, showed higher concentrations during FF >100 (37.6–44.7% higher), emphasising the role of FF in enhancing photochemical O_3 production.

• In Aizawl, the FF >100 is enough to cause a level shift in the AQI for PM_{10}, $PM_{2.5}$, and O_3, indicating the proximity and more intensity of FF. In contrast, the same is seen only in PM_{10} at the farther stations, Tezpur and Guwahati.

• Diurnal patterns of pollutants revealed higher values during FF >100 periods, further supporting the influence of FF on air quality. Based on back trajectories, it may be said that fire activities were the primary source of air pollution in all three locations.

Data availability

Data were collected as part of the MAPAN network established by the Ministry of Earth Sciences, India. Though not available in the public domain, it can be provided for collaborative research or on specific demand.

Author contributions

Sonal Kumari: conceptualisation, visualisation, methodology, investigation, and original draft writing. Latha Radhadevi: conceptualisation, supervision, methodology, and writing: editing and review. Nihal Gurje: formal analysis and data curation. Nageshwar Rao: formal analysis and data curation. Murthy Bandaru: project administration, resources, and review.

Conflicts of 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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