Atmospheric Environment 343 (2025) 120974

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Assessing air quality during India's National Clean Air Programme (NCAP): 2019–2023

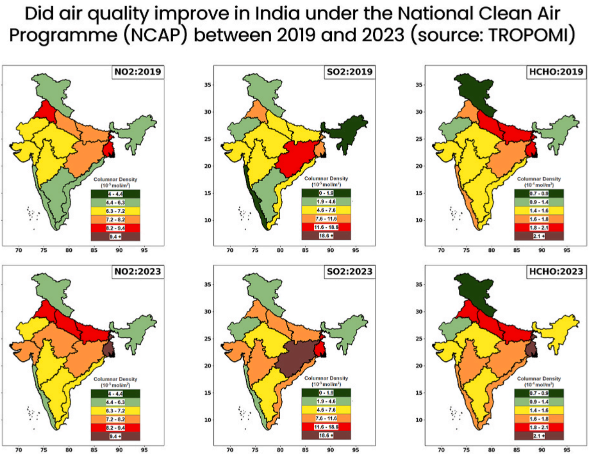
Sarath K. Guttikunda [a,b,*], Sai Krishna Dammalapati [b], Gautam Pradhan [c]

[a] TRIP-Centre, Indian Institute of Technology, New Delhi, India
[b] Urban Emissions Information, Goa, India
[c] Earthmetry Solutions, Bengaluru, India

HIGHLIGHTS

- India's ambient monitoring capacity increased 3–4 times between 2019 and 2023.
- Air Quality Index dropped 13% from 2019 to 2023 per daily bulletins, which cannot be accorded to a single pollutant.
- PM_{10} as the conditional pollutant in AQI bulletins doubled, contrary to reports of NCAP cities improving PM_{10} levels.
- TROPOMI satellite retrievals for gaseous species NO_2, SO_2, and HCHO show an increase in regional averages from 2019 to 2023.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Particulate matter
$PM_{2.5}$
PM_{10}
Air quality
India
NCAP
Progress report

ABSTRACT

Did air quality improve during India's National Clean Air Programme (NCAP)? Since its inception in 2019, 131 cities were designated as non-attainment cities, requiring comprehensive data collection on ambient concentrations, emission sources, emission intensities, and source contributions. Clean air action plans were developed with the goal of achieving a 40% reduction in PM_{10} pollution by 2026 compared to 2017 annual averages or reaching the national standard. Central government funding significantly boosted ambient monitoring capacity in all cities, increasing it by 3–4 times through the installation of at least one manual or continuous monitoring station per city to track pollution levels. The unitless air quality index from the daily bulletins recorded a drop of 13% between 2019 and 2023, which cannot be accorded to a single pollutant. Presence of PM_{10} as the conditional pollutant in the daily AQI bulletins doubled during this period, in contrast to reports saying 95 of the 131 cities have improved PM_{10} pollution levels. Delhi, the most polluted capital city in the 2023 world rankings, showed no significant change in annual average $PM_{2.5}$ concentrations. An agro-climatic airshed level assessment of TROPOMI satellite retrievals shows an increase in the atmospheric loading of gaseous SO_2 and NO_2 emissions

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* Corresponding author. TRIP-Centre, Indian Institute of Technology, New Delhi, India.
E-mail addresses: sguttikunda@gmail.com, sguttikunda@urbanemissions.info (S.K. Guttikunda).

https://doi.org/10.1016/j.atmosenv.2024.120974
Received 2 June 2024; Received in revised form 8 November 2024; Accepted 3 December 2024

and a change in the residual aerosol index signifying an increase in particulate emissions from combustion sources. Moving forward, tracking NCAP progress will require at least a tenfold increase in monitoring capacity, establishment of multi-pollutant emissions baselines, and a shift in evaluation to regional airshed scales to provide a better spatial representation of emission activities extending beyond city limits.

1. Introduction

India's National Clean Air Programme (NCAP) was launched in 2019, to achieve clean air targets in 131 cities (CPCB, 2019). These cities were designated as "non-attainment" based on historical $PM_{2.5}$ and PM_{10} (particulate matter, PM, with aerodynamic diameter less than 2.5 μm and 10 μm, respectively) concentrations recorded under the national ambient monitoring programme (NAMP), operated by the Central Pollution Control Board (CPCB, New Delhi, India). The original target of the programme was for the cities to demonstrate a reduction of 20–30% of PM pollution by 2024 compared to the annual averages recorded in 2017 (Ganguly et al., 2020; Guttikunda et al., 2023a). This was revised to demonstrate a reduction of 40% of PM_{10} pollution by 2026 or reach the national annual standard of 60 $\mu g/m^3$ (India-PIB, 2023).

In this paper, we present an evaluation of the progress made (or not made) during the NCAP period between 2019 and 2023, using data from ambient monitoring network and satellite retrievals. The scope of the discussion is limited to the influence of change in the NCAP target to PM_{10} and how it limits the overall air quality picture in India, including $PM_{2.5}$, SO_2 (sulphur dioxide), NO_2 (nitrogen dioxide), CO (carbon monoxide) and ozone.

2. Methods and data

This evaluation process uses annual averages to focus on long-term changes during the NCAP period from 2019 to 2023, aiming to achieve the program's overarching goal of a 40% reduction in PM_{10} pollution by 2026 compared to 2017 annual averages. Despite year-to-year meteorological variations, progress in the NCAP program is measured solely through annual averages. With this in mind, for consistency, our analyses also used annual averages to assess changes over the study period. The statistical methods used to evaluate the year-on-year changes in the pollutant concentrations across Indian cities and an evaluation of the data to spot anomalies is presented independently (Dammalapati and Guttikunda, 2024b). For satellite observations, data at a 0.1° spatial resolution was used alongside annual averages to construct frequency distributions based on the number of spatial grids within specific pollutant concentration ranges. The trend analysis also accounted for the number of grids exceeding two and three standard deviations between years, serving as an indicator of increasing or decreasing columnar densities.

2.1. National clean air programme and the non-attainment cities

NCAP is an ambitious programme aimed at tackling the severe air pollution problem across India (https://prana.cpcb.gov.in). This national programme was launched on the heels of Environment Pollution (Prevention & Control) Authority (EPCA), which was replaced with the Commission for Air Quality Management (CAQM) tasked to undertake pollution prevention and control actions in Delhi and its surrounding areas (Dutta, 2018; India-PIB, 2021). Under NCAP, 24 states are represented with 41 cities on the Indo-Gangetic Plain (IGP), the most polluted belt of the Indian Subcontinent (Chatterjee et al., 2023; Ganguly et al., 2020; Guttikunda and Ka, 2022). This list includes Delhi (from IGP) followed by 36 cities from Central India covering Maharashtra, Madhya Pradesh, Chhattisgarh, and Odisha, 25 from South India, 20 from the Western and Eastern Himalayan regions, and remaining nine from the Northwest India covering Gujarat and Rajasthan. Maharashtra has the highest (19) number of non-attainment cities, followed by 17 in Uttar Pradesh, the most populous state in India. The list includes all state capital cities and the cities with at least one million population. States not represented on the list are Goa and Kerala on the West Coast and Manipur, Mizoram, and Tripura from the Northeast. Of the 24, Chandigarh and Delhi are the Union Territories.

Each of the non-attainment cities is required to formulate a city-specific clean air action plan to address local sources of air pollution. The sectors and the level of action necessary in these sectors is quantified and prioritized based on emission inventory and source apportionment studies.

2.2. Ambient monitoring network and air quality index bulletins

NAMP network of monitoring stations include manual and continuous ambient air quality monitoring stations (CAAQMS). The continuous data is reported on CPCB's real-time portal at 15-min intervals for all the criteria pollutants - $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, ozone, and ammonia (CPCB, 2024a). The manual monitoring stations report daily averages of select pollutants ($PM_{2.5}$, PM_{10}, SO_2, and NO_2) for at least 104 days in a year. As of December 2023, there are 540 continuous and 900 manual monitoring stations operational across India. The network capacity increased 3–4 times since 2019, with the availability of funds under NCAP and the XVth financial commission to support data collection and preparation of action plans (India-PIB, 2022). However, the overall numbers continue to be below par to mathematically represent the pollution levels in the cities with most of the cities operating only one or two stations (Brauer et al., 2019; Pant et al., 2018). Table 1 summarizes the change in the number of continuous stations by state as

Table 1
Number of all the continuous monitoring stations in the state and the number of stations in the state's National Clean Air Programme cities.

	State name	No. Of. NCAP cities	2019	2020	2021	2022	2023
1	Andhra Pradesh	13	5–3	5–3	4–2	7–4	11–8
2	Assam	5	1–1	2–2	2–2	6–6	8–8
3	Bihar	3	6–6	12–11	32–12	35–12	34–12
4	Chandigarh	1	1–1	1–1	2–2	3–3	3–3
5	Chhattisgarh	3	0–0	0–0	2–1	10–9	14–9
6	Delhi	1	40–40	41–41	42–42	40–40	41–41
7	Gujarat	4	5–1	6–1	15–8	17–10	17–10
8	Haryana	1	24–2	30–5	30–5	30–5	30–5
9	Himachal Pradesh	7	0–0	0–0	0–0	1–1	1–1
10	Jammu & Kashmir	2	0–0	0–0	1–1	1–1	1–1
11	Jharkhand	3	1–0	1–0	1–0	1–0	4–2
12	Karnataka	4	16–12	23–12	30–13	37–17	40–19
13	Madhya Pradesh	7	13–5	16–8	16–8	20–12	28–20
14	Maharashtra	19	23–22	39–38	41–40	39–38	90–78
15	Meghalaya	1	1–0	1–0	1–1	3–1	3–1
16	Nagaland	2	0–0	1–1	1–1	1–1	1–1
17	Odisha	7	2–1	2–1	2–1	10–2	19–9
18	Punjab	9	8–6	8–6	8–6	8–6	8–6
19	Rajasthan	5	10–7	10–7	10–7	10–7	45–16
20	Tamil Nadu	4	8–6	13–11	14–11	24–11	27–12
21	Telangana	4	7–7	7–7	7–7	14–14	14–14
22	Uttar Pradesh	17	27–21	26–20	47–40	56–48	54–47
23	Uttarakhand	3	0–0	0–0	0–0	1–1	3–3
24	West Bengal	6	15–14	15–14	15–14	14–13	15–14

total and those operational in the NCAP cities. Only in 2023, there is at least one continuous station operational in each of the states represented on the NCAP list. Between 2019 and 2023, the number of CAAQMS in the NCAP cities doubled from 155 to 340. At the end of 2023, 30 cities are yet to start operating a CAAQMS. At the national level (including non-NCAP cities), the number of CAAQMS tripled from 220 to 530. Among the states, Bihar, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Uttar Pradesh had large jumps and Bihar expanded the network the most (from 6 to 34) to include all the districts with at least one station.

The monitoring data from continuous and manual stations is also used to calculate the air quality index (AQI) and release a daily bulletin for public awareness. For each city, these bulletins include information on (a) AQI of the day and the conditional pollutant and (b) number of stations used to calculate the AQI of the day. The bulletin doesn't include data on the absolute concentrations of the pollutant(s) defining the AQI of the day. Between 2015 and 2023, the number of unique cities listed in the bulletins increased 12-fold from 22 to 271 and the number of stations increased 14-fold from 37 to 514. However, 215 cities used only one monitoring station to calculate AQI, which while is a reference number to disseminate the pollution information for public awareness purposes, it is not a representative number for policy analysis (Dammalapati and Guttikunda, 2024a). A copy of the AQI and other supporting data from the daily bulletins is included in the supplementary.

2.3. Satellite retrievals

TROPOspheric Monitoring Instrument (TROPOMI), on board the Copernicus Sentinel-5 Precursor satellite, monitors trace gases relevant for air quality and climate research (Veefkind et al., 2012). The level-3 TROPOMI dataset is available on open access Google Earth Engine (GEE) platform for SO_2, NO_2, tropospheric ozone, and formaldehyde (HCHO). Applying a 10% cloud fraction, we extracted the images covering the Indian Subcontinent, to calculate monthly and annual averages for pre-defined urban and regional airsheds. The image collections accessed on GEE are COPERNICUS/S5P/OFFL/L3_NO2, L3_SO2, L3_O3, L3_HCHO, and L3_AER_AI.

Multi-Angle Implementation of Atmospheric Correct (MAIAC) product is derived from Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard NASA's Terra and Aqua satellites. This dataset also from open access GEE platform provides aerosol retrievals at 1 km spatial resolution at multiple bands - green band (0.55 µm) and blue band (0.47 µm). Green band is used in this study. The image-collection accessed on GEE is MODIS/061/MCD19A2_GRANULES. Links to algorithms, airshed shapefiles, and the extracted data is included in the supplementary.

3. Results and discussion

3.1. Ambient concentrations in NCAP cities

Number of NCAP cities in various concentration bins is presented in Fig. 1. The fraction of the cities with $PM_{2.5}$ concentrations above 120 µg/m^3 (very poor air quality category in India's AQI scales) dropped from 30% to 20%, but the fraction of the cities with concentrations between 60 and 120 µg/m^3 continue to be above 50%. The NCAP target pollutant PM_{10} showed no change in the fraction (at 50%) of cities with concentrations above 150 µg/m^3. The change in the number of cities showing an increase in NO_2 and ozone concentrations is a trend which should not be ignored. A gradual increase in the number of vehicles and their usage is a key indicator of on-ground NO_2 emissions. In the presence of sunlight and volatile organic compounds (VOCs), nitrogen species undergo a series of chemical reactions and produce ozone - which is also trending upwards with more cities exceeding the daytime standards. With $PM_{2.5}$, Ozone is also an important secondary pollutant with direct linkages to multiple health endpoints, including premature death (HEI-SoGA, 2024; Pozzer et al., 2023).

A summary of annual average concentrations from CAAQMS is included in the supplementary material for the years 2019 and 2023. The NCAP authorities use data from both the manual and CAAQMS to evaluate changes in the ambient pollution levels. Delhi, the most monitored and studied city in India, recorded no significant change in $PM_{2.5}$ annual averages between 2019 and 2023, with observed averages of 105.1 and 103.3 µg/m^3, respectively. Although interventions targeted emissions reductions across various sectors, these benefits were largely

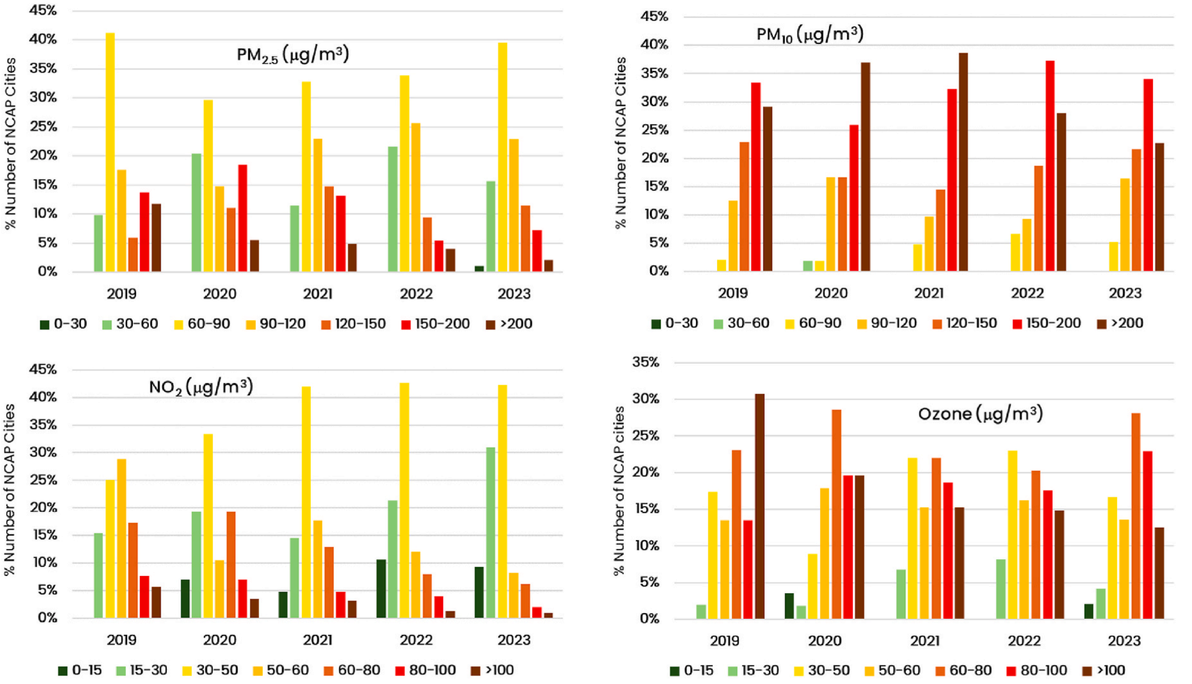

Fig. 1. Percent NCAP cities in various bins for maximum seasonal concentrations of $PM_{2.5}$, PM_{10}, NO_2, and (daytime) Ozone between 2019 and 2023.

offset by increases in vehicle usage, industrial activity, and waste burning (Supplementary Table S3) (Guttikunda et al., 2023b). The largest drops are observed in the cities of Uttar Pradesh, with little in the way to explain these reductions, especially for $PM_{2.5}$ concentrations originating from fossil fuel combustion activities at business as usual. These concentration reports carry significant uncertainty due to differences in sample sizes—most cities operate only one station—and the varied characteristics of monitoring locations. Without detailed metadata and a clear representative baseline, improvements from small networks should be interpreted with caution.

SO_2 is the only pollutant under the national ambient standard in all the cities and the overall average is also low (~10 $\mu g/m^3$ – a quarter of the WHO guideline). Two interventions that made this change possible in all Indian cities are (a) the promotion of use of clean fuels like liquified petroleum gas and electricity for cooking and (b) low-sulphur fuels for on-road vehicles (Chatterjee et al., 2023; Guttikunda and Ka, 2022). As of March 2024, sulphur content of petrol and diesel sold in India for passenger and freight vehicles is 10 ppm. Some cities continue to record high numbers, like Pune, Talcher, and Varanasi with annual average above 20 $\mu g/m^3$), linked to coal combustion activities in the region.

While there are some improvements in data from official monitoring networks, we remain cautious about drawing definitive conclusions from the observed changes. Although the number of cities reporting AQI has increased 12-fold from 2015 to 2023, most cities lack the minimum recommended number of monitoring stations. In 2023, for the data presented in Figs. 1 and 215 out of 271 unique cities (80%) reported AQI data from only one station, which is not a statistically representative sample for studying long-term trends within a city. Only 15 cities reported data from more than five stations, which is considered an ideal sample size to capture a range of locations, such as residential, industrial, traffic, commercial, and background areas. Delhi, with the largest network of 40 monitoring stations, still exhibits significant variability across stations due to strong heterogeneity. This suggests that even with 40 stations, substantial data variability remains, underscoring the need for further expansion of monitoring networks to improve representativeness (Dammalapati and Guttikunda, 2024a).

3.2. Change in conditional/target pollutant to PM_{10}

A marked increase was observed in the number of times PM_{10} is listed as the conditional pollutant in the daily AQI bulletins between 2015 and 2023 (Table 2). This stands in contrast to the official reports that claim a reduction in average PM_{10} pollution levels in 95 NCAP cities (India-PIB, 2024). This increase in the presence of PM_{10} as the conditional pollutant on more days is an indicator of two possibilities: (1) An increase in the urban dust emissions from construction and vehicle movement activities, which forms a large fraction of the PM_{10} composition, along with a wider representation of PM_{10} data from the monitoring networks. A review of source apportionment studies (Yadav et al., 2022) concluded that a major source of PM_{10} pollution is all-forms of dust, including tyre wear and tear. (2) When PM_{10} was lobbied to be the primary target pollutant, NCAP goals were updated from 2024 to 2026 and a change in the target to an overall reduction of 40% by 2026 (India-PIB, 2023). This change has led cities to report PM_{10} values more frequently to the AQI system, even when other pollutants were also being monitored. Consequently, the doubling of PM_{10}'s share as a conditional pollutant contrasts with cities' claims of reducing PM_{10} pollution. In addition to PM_{10}, $PM_{2.5}$ is also frequently listed as a conditional pollutant in the bulletins. Annually, one of the PM fractions (PM_{10} or $PM_{2.5}$) was a conditional pollutant 80% of the time, followed by gaseous pollutants such as NO_2, CO, SO_2, and ozone.

Change in the target pollutant also resulted in the use of intermediate emission control actions in the NCAP cities to specifically address PM_{10} and dust concentrations. Under NCAP, 60 dust control and management cells were established (mostly in the national capital region - 11 in Delhi, 18 in Uttar Pradesh, 17 in Haryana, and 14 in Rajasthan) to promote use of sweeping machines and sprinklers of water and dust suppressants on roads, maintenance of roads for potholes, conversion of non-paved roadsides to paved and covered with vegetation, and laying of roads to support mechanised sweeping in the industrial areas. Similar programs are being replicated in the other state capitals and NCAP cities. Often these reductions are temporary, as they are not addressing the emission sources. These dust management actions focus solely on reducing the target pollutant PM_{10}, tied to performance funding from central and state environmental programs, but do not address the more harmful $PM_{2.5}$ pollution or other gaseous pollutants.

A net result of focus on ambient PM_{10} concentrations and dust management is also evident in the drop of overall AQI in the cities. A summary of monthly average AQI values from the daily bulletins between 2019 and 2023 for the NCAP cities is presented in Table 3. AQI is a unitless calculated value using an approved methodology based on India's air quality standards (CPCB, 2024b). Since the final value does not distinguish between the pollutants nor the measurement techniques, these comparisons are only subjective in nature to represent an average public awareness metric. As an annual average, there is an improvement of 13% between 2019 and 2023 (from an AQI of 132 to 113), with the winter months continuing to experience pollution levels in the very poor and severe categories of AQI.

3.3. Changes in pollution trends at regional airsheds

Monitoring stations represent emission activities in their vicinity of approximately 2-km radius. To truly represent all the emission activities, Indian city's need to operate more than the current monitoring capacity (Brauer et al., 2019; Guttikunda et al., 2023a). Across India, using CPCB's thumb rules for minimum monitoring to capture PM pollution trends, there should be at least 4094 operational CAAQMS. The monitoring data from the stations will always have some inherent bias because of handpicked location, instrument used, operating procedures, and sampling time periods. While monitoring data is necessary for ground truthing, the data gaps in the spatial and temporal trends doesn't provide a complete picture for regional and national assessments, because areas with no stations (like outside the city administrative boundaries) and rural areas farther away from the cities, have no representation in the current progress report. In other words, any modelling

Table 2
Percent number of reporting days with PM_{10} as the conditional pollutant in the daily AQI bulletins released by the Central Pollution Control Board, New Delhi, India.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2015					24%	11%	13%	24%	22%	17%	16%	18%
2016	16%	25%	36%	31%	24%	27%	19%	23%	25%	23%	17%	24%
2017	20%	29%	34%	36%	39%	33%	34%	35%	30%	30%	24%	26%
2018	26%	42%	47%	58%	53%	54%	52%	49%	55%	49%	34%	32%
2019	32%	41%	54%	61%	63%	61%	55%	52%	55%	42%	33%	30%
2020	34%	41%	48%	46%	50%	47%	46%	46%	53%	44%	32%	35%
2021	31%	46%	57%	58%	52%	53%	48%	53%	48%	46%	30%	31%
2022	36%	46%	54%	59%	60%	56%	48%	49%	50%	46%	37%	34%
2023	33%	49%	50%	59%	57%	61%	52%	66%	56%	54%	35%	36%

Table 3
Monthly average air quality index value (unitless) of all NCAP cities in the daily bulletins released by the Central Pollution Control Board, New Delhi, India.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
2019	207	160	136	132	130	107	78	67	65	129	184	182	132
2020	166	148	102	83	90	73	57	52	76	135	179	194	114
2021	192	170	150	128	91	83	67	67	58	109	187	176	123
2022	155	138	143	137	123	103	61	65	71	112	163	176	121
2023	176	144	113	111	98	85	60	73	69	116	164	153	113

work using the monitoring data with limited representation will result in a biased assessment of progress and any impacts associated with it.

In addition to urban scale assessments which used only the ambient monitoring data, pollution levels were investigated for 15 regional airsheds across India using satellite retrievals. These airsheds were delineated as agro-climatic zones which possess similar geographical, demographic, environmental, and meteorological characteristics, which are also relevant for pollution and emissions movement in the region (Fig. 2) (Guttikunda, 2024). The 15 airsheds were further clubbed into six geographical blocks – four in IGP, four covering the Plateau between the Western and the Eastern Ghats, three coastal zones, two Himalayan zones, one arid/desert plain, and the islands.

The ambient monitoring capacity and ambient monitoring data is based on all the operational stations in India (Table 4). The largest increase in the monitoring capacity is over the Plateau region and the overall capacity increased 3–4 times. We also investigated satellite retrievals averaged at the airshed level (Tables 4 and 5). While these values are columnar in nature, these numbers represent a regional average of not only the local emissions but also account for the long-range transport and chemical evolution of the pollutants. This applies to both aerosol and gaseous species. For convenience, only the annual averages are presented in this study.

Summary of TROPOMI satellite retrievals for the gaseous species for 2019 and 2023 is presented in Table 5. Unlike the aerosol observations, gaseous species showed an increase in columnar loadings across all the airsheds. A major conclusion of this observation is that the cities (and regions) are focused on reducing $PM_{2.5}$ and PM_{10} emissions (especially the later) from non-combustion sources like dust and not focusing on the combustion sources responsible for other pollutants like black carbon (soot) and other gaseous species. A similar conclusion can be made from TROPOMI's UVAI observations in Fig. 2 and Table 4. Unlike AOD, UVAI is a residual index, with the positive values indicating the presence of UV-absorbing aerosols (like dust, smoke, and soot) and the strongly negative values indicating the presence of non-absorbing aerosols

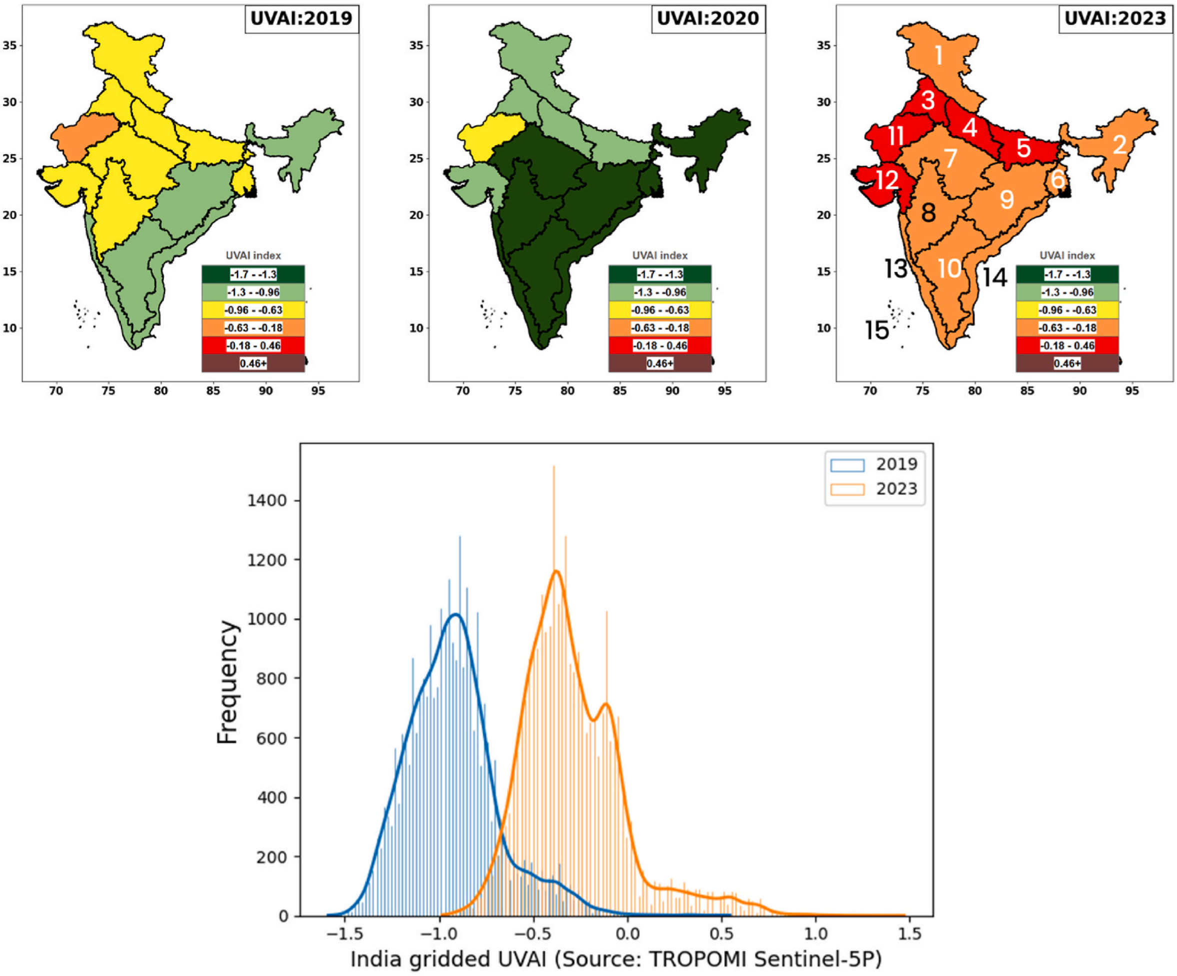

Fig. 2. (a) Agro-climatic airsheds used in this study for regional assessments (marked 1 to 15) and annual average ultraviolet aerosol index (UVAI) from Sentinel-5P TROPOMI satellite observations (b) Frequency distribution of gridded UVAI data for 2019 and 2023. Grid resolution covering India is 0.1° (excluding islands).

Table 4

Regional airshed level summary of ambient monitoring capacity, regional airshed level annual average aerosol optical depth (AOD) from MODIS-MAIAC and ultraviolet aerosol index (UVAI) from Sentinel-5P TROPOMI satellite observations.

	Airshed Name	%Land	%Pop	CAAQMS		AOD (*10^{-1})			UVAI		
		Mass	**2021**	**2019**	**2023**	**2019**	**2023**	**%**	**2019**	**2020**	**2023**
1	Western Himalayas	11.0%	6.1	1	5	1.2	1.1	−9%	−0.8	−1.0	−0.4
2	Eastern Himalayas	9.1%	6.1	3	20	2.7	2.9	6%	−1.1	−1.4	−0.5
3	Trans Gangetic Plain	4.0%	9.3	72	83	6.8	5.9	−17%	−0.8	−1.1	0.0
4	Upper Gangetic Plain	4.1%	9.0	26	49	7.2	6.5	−10%	−0.8	−1.2	−0.1
5	Middle Gangetic Plain	5.5%	8.4	7	39	8.5	7.4	−15%	−0.9	−1.3	−0.1
6	Lower Gangetic Plain	2.4%	9.4	14	14	8.6	8.1	−6%	−1.0	−1.4	−0.3
7	Central Plateau	11.3%	7.4	16	48	6.3	5.9	−8%	−0.9	−1.3	−0.2
8	Western Plateau	9.1%	7.1	10	50	6.4	5.8	−10%	−0.9	−1.4	−0.3
9	Eastern Plateau	11.3%	8.1	6	35	7.0	7.1	1%	−1.1	−1.5	−0.4
10	Southern Plateau	10.0%	6.7	26	64	6.4	5.7	−13%	−1.1	−1.5	−0.5
11	Arid Desert	5.2%	7.1	1	13	6.4	5.7	−11%	−0.5	−0.8	0.4
12	Gujarat Coast & Plains	5.6%	7.4	5	17	5.9	5.6	−5%	−0.7	−1.2	0.0
13	West Coast	3.8%	6.2	18	62	5.2	5.1	−1%	−1.1	−1.5	−0.5
14	East Coast	6.8%	6.7	10	28	7.2	6.6	−10%	−1.1	−1.5	−0.5
15	Islands	0.7%	4.4			3.1	2.3	−36%	−1.4	−1.7	−0.6

Table 5

Regional airshed level annual average columnar density (mol/m^2) extracted from Sentinel-5P TROPOMI satellite observations of gaseous species - NO_2, SO_2, and HCHO.

	Airshed Name	NO_2 (*10^{-5})			SO_2 (*10^{-5})			HCHO (*10^{-4})		
		2019	2023	%	2019	2023	%	2019	2023	%
1	Western Himalayas	5.9	6.1	3%	1.9	2.7	30%	0.7	0.8	11%
2	Eastern Himalayas	5.6	6.1	9%	0.3	4.3	92%	1.3	1.4	11%
3	Trans Gangetic Plain	8.5	9.3	8%	8.0	9.2	13%	1.9	1.9	0%
4	Upper Gangetic Plain	8.2	9.0	9%	6.9	8.4	18%	2.0	2.0	2%
5	Middle Gangetic Plain	7.7	8.4	9%	5.8	8.1	28%	2.0	2.1	5%
6	Lower Gangetic Plain	8.2	9.4	13%	9.7	15.5	37%	1.9	2.1	10%
7	Central Plateau	7.0	7.4	6%	5.7	6.4	12%	1.5	1.5	−2%
8	Western Plateau	6.6	7.1	8%	6.2	9.4	34%	1.5	1.6	5%
9	Eastern Plateau	7.4	8.1	10%	14.1	18.6	24%	1.8	1.8	4%
10	Southern Plateau	6.1	6.7	9%	3.8	6.6	41%	1.5	1.6	8%
11	Arid Desert	6.6	7.1	7%	3.8	4.6	18%	1.4	1.4	−3%
12	Gujarat Coast & Plains	6.8	7.4	7%	6.0	8.3	28%	1.4	1.5	1%
13	West Coast	5.8	6.2	8%	1.8	3.4	48%	1.7	1.8	5%
14	East Coast	6.1	6.7	9%	6.1	9.5	36%	1.6	1.7	9%
15	Islands	4.2	4.4	5%				0.9	0.9	1%

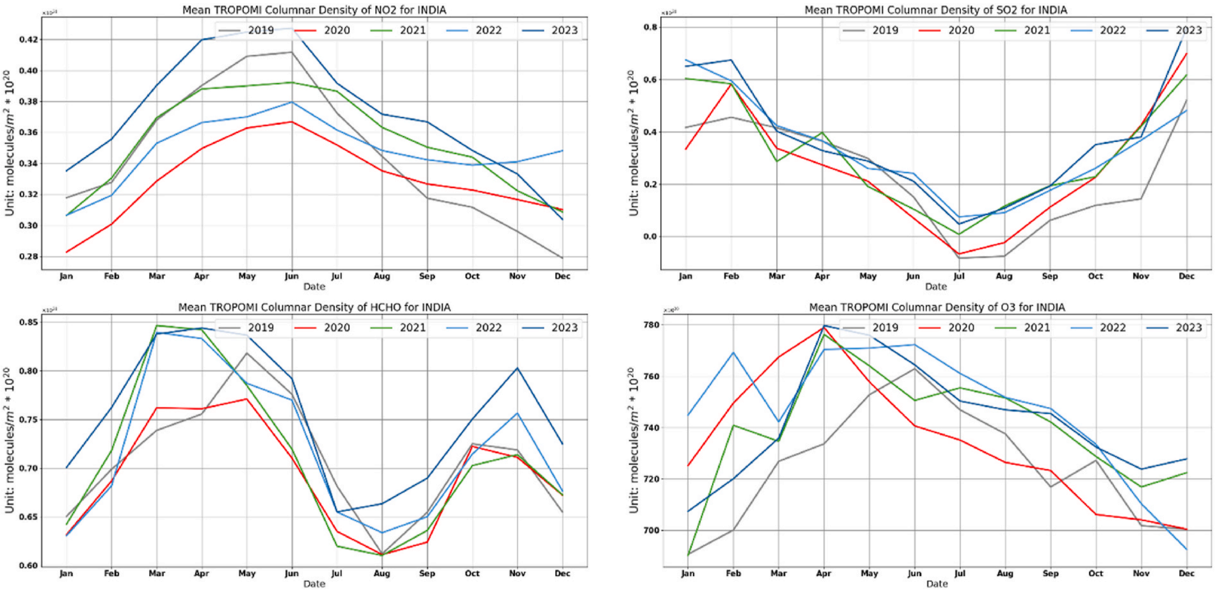

Fig. 3. Monthly average columnar density values for India for NO_2, SO_2, HCHO and ozone from Sentinel-5P TROPOMI satellite observations for years 2019–2023.

including sulphate aerosols. Comparing between 2019 and 2020, the UVAI values turned more negative, meaning absence of dust, smoke and soot, which was an observation across India due to COVID19 restrictions on movement of vehicles, most of the industrial activities, and construction works. The drops observed in 2020 cannot be attributed to initiation of NCAP but can only be used as a natural experiment to demonstrate the impact of reducing emissions at sources at large scale. Comparison between 2019 and 2023, the UVAI values turned more positive, meaning presence of more smoke and soot from the combustion activities, assuming that the dust control activities are resulting in some reductions locally. This is a relative metric, which should be studied in combination with trends in emissions of other pollutants. A major conclusion from Table 4 is that if there is a reduction in PM_{10} values across the cities, then the relative UVAI metric suggests that there is a parallel increase in the combustion sourced pollutants like smoke and soot. The drop in the absolute AOD values can be a result of the dust management, since the columnar aerosol metric doesn't differentiate between particle sizes and partly due to meteorology (Xie et al., 2024). Xie et al. suggest that detrending meteorology in the chemical transport model explains up to 10% drop in the AOD values observed in 2022–23.

NO_2 and SO_2 are primary pollutants, and both show an increase in their columnar densities between 2019 and 2023–10% and 30% across India, respectively (Table 5 and Fig. 3). HCHO is partly emitted and partly a product of chemical reactions with nitrogen species and ozone, also show an overall increase. The increasing trend remains consistent across all months from 2019 to 2023. Frequency distribution plots for these gases are provided in the supplementary materials. Additionally, we examined the frequency of hotspot grids within airsheds, identified as grids exceeding two and three standard deviations in 2019 and 2023, using 2019 data as the baseline. For NO_2, the number of hotspot grids increased by 67% and 57%, respectively; for SO_2, by 71% and 86%; and for HCHO, by 11% and 400%. Frequency distribution plots for the individual airsheds in Table 5 are provided in the supplementary materials for NO_2, SO_2, HCHO and UVAI.

In case of NO_2, the increase in the regional signature is directly linked to an increase in fuel consumption in road, rail, and aviation sectors and coal combustion at the heavy industries. In India, total number of registered vehicles increased from 300 million in March 2019 to 370 million on May 2024 (https://vahan.parivahan.gov.in/vahan4dashboard). In case of SO_2, this increase (compared to a decrease in the ground monitoring data) can be explained using the difference in the energy consumption patterns at the urban and the regional scale. In the cities, most of the sulphur emissions originate from transportation using the lowest sulphur content fuel, while the regional signatures are marked with coal combustion at heavy industries (including power plants, brick manufacturing, iron and steel, etc), often located outside the city limits. At the regional scale, use of coal and petcoke has increased at the same scales (Guttikunda and Ka, 2022). According to an open archive of energy consumption trends in India (https://robbieandrew.github.io/india), in 2024 as monthly totals, total coal consumption at all the power plants peaked at 100 million tons; total diesel consumption peaked at 8.5 million tons; total petrol consumption peaked at 3.5 million tons; and total natural gas consumption peaked at 6000 mmscm. All the numbers are the highest since 2000. With limited controls in place, an increasing fossil fuel combustion trend means more emissions, more ambient pollution levels, and more columnar loadings across the airsheds.

Ozone is a secondary pollutant, dependent on the presence of nitrogen oxides (NO_x) and VOCs (HCHO can be used a regional proxy for VOCs). The chemistry between these pollutants is complicated and varies with the ratio of NO_x and VOC emissions and concentrations (Yang and Zhao, 2023). On average, change in the ozone concentrations is positive (increasing), but the detection levels are small at the annual scale. These changes are more pronounced during the summer months and at the urban scale, where sharper shifts in the NO_x to VOC ratios occur, warranting further investigation.

4. Way forward

Cities are implementing various emission control measures to improve air quality, but growing consumption patterns are offsetting these technical gains. For instance, while new vehicle fuel standards improve fleet-average emission factors, these benefits are negated by rising vehicle numbers and usage. Similarly, advancements in waste management are counteracted by increasing waste generation rates, and enhancements in industrial standards are offset by heightened electricity use for air conditioning due to intensified urban heat island effects. Given these ongoing changes, this paper evaluated long-term air quality trends in Indian cities since the inception of the NCAP program in 2019–2023, utilizing a combination of ground monitoring data from the official network and satellite observations to provide a regional perspective. A key conclusion of our assessment is the disproportionate emphasis on reducing PM_{10} pollution, particularly from road dust sources in cities. While there is some improvement in AQI values linked to PM_{10} and road dust management, this does not translate to overall air quality improvement in cities or regional airsheds. Observed trends in regional gaseous pollutant concentrations and national fuel consumption patterns indicate that fossil fuel combustion emissions continue to rise at business-as-usual rates, largely unaffected by these targeted efforts.

The major limitation of the NCAP assessment criteria is the quality of the monitoring data. In the NCAP announcement, the key action items included promoting alternative methods for expanding the monitoring network to meet the representative minimums in all the cities, expanding the monitoring network to rural areas with at least one station, revising the guidelines for ambient monitoring (last updated in 2003) (CPCB, 2003) to allow for validation and inclusion of the emerging technologies like low-cost sensors, establishing at least ten supersite stations to promote research facilities including certification system for new monitoring instruments, and establishing a central air information centre. Between 2019 and 2023, the monitoring capacity in the NCAP cities and across India has increased substantially, especially expanding also to Tier 3 and smaller cities, however the spatial representativeness of the monitors continues to be a major limitation. The combined 104 designated urban airsheds for the 131 cities, continues to operate lower than the recommended number of stations, approximately 20–40% (Guttikunda et al., 2023a). The way forward to bridge this monitoring gap is the use of a combination of regulatory grade stations, regularly calibrated low-cost sensors, and model outputs nudged with satellite retrievals (Ajnoti et al., 2024; Brauer et al., 2019; Holloway et al., 2021; Morawska et al., 2018). An increase in the overall number of stations in each of the NCAP cities will further increase the confidence levels in documenting the progress made for better air quality during the NCAP period.

A holistic, multi-pollutant approach is essential to bring all criteria pollutants, not just PM_{10} or road dust, within ambient standards. The approach is crucial for India's air quality management where $PM_{2.5}$ is a key pollutant that often exceeds the standards, resulting in premature mortality and morbidity, and carries at least 20–40% of secondary contributions from chemical conversion of gaseous species (Yadav et al., 2022). A summary of the approved action plans is presented in (Ganguly et al., 2020), listing measures ranging from controlling on-road vehicular emissions via promotion of public transportation, non-motorized walking and cycling, and alternate fuels like compressed natural gas and electricity; controlling industrial pollution by strengthening the emission norms, improving the inspection and audit programs; promotion of clean fuel for cooking and heating; programs for waste generation reduction, collection, and management; maintenance of roads to suppress dust emissions; stricter norms for construction sites; and increasing green cover. Regardless of the source apportionment results, over 50% of the proposed actions in these plans focus on reducing on-road vehicle exhaust emissions. This approach needs to shift toward a multi-sector, multi-stakeholder strategy to address the issue more comprehensively.

This multi-pronged approach under the NCAP program emphasizes collaboration, with urban local bodies leading the implementation of approved action plans, supported by central and state government agencies, non-governmental organizations, academic institutions within the national knowledge network (India-PIB, 2011), and all the line departments from transportation, industry, agriculture, and urban development.

While focusing on the cities is a start, the programme must also evolve to include areas beyond the urban settlements. There is a growing need to propose a regional airshed approach exampled in this paper not only to evaluate the impacts of interventions across India, but also to bring together stakeholders at all the levels – urban local bodies, districts, states, and central ministries.

CRediT authorship contribution statement

Sarath K. Guttikunda: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Sai Krishna Dammalapati:** Writing – review & editing, Visualization, Software, Investigation, Data curation. **Gautam Pradhan:** Writing – review & editing, Software, Resources, Investigation, Data curation.

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.

Acknowledgments

The analysis and conclusions presented herein are exclusively those of the authors and do not represent the supporting organizations or the educational departments. As this was a desk-based study, no ethical approval was required. No external funding was received towards this research. The authors declare no conflict of interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2024.120974.

Data availability

All the data is open access. Data links are shared in the manuscript and in the supplementary files

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