Bending Delhi's Air Pollution Curve

Learnings from 2020 to Improve 2021

L. S. Kurinji, Adeel Khan, and Tanushree Ganguly

Issue brief | June 2021

There was a lower PM 2.5 contribution from power plants in Delhi in October and November 2020 as energy generation from NCR coal-fired plants was 25 and 70% lower in these months, respectively, compared to the corresponding months in 2019.

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The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions. **The Council uses data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources.** The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public.

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The Council's current initiatives include: A go-to-market programme for decentralised renewable energy-powered livelihood appliances; examining country-wide residential energy consumption patterns; raising consumer engagement on power issues; piloting business models for solar rooftop adoption; developing a renewable energy project performance dashboard; green hydrogen for industry decarbonisation; state-level modelling for energy and climate policy; reallocating water for faster economic growth; creating a democratic demand for clean air; raising consumer awareness on sustainable cooling; and supporting India's electric vehicle and battery ambitions. It also analyses the energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka and Vietnam.

The Council has a footprint in 22 Indian states, working extensively with state governments and grassroots NGOs. It is supporting power sector reforms in Uttar Pradesh and Tamil Nadu, scaling up solar-powered irrigation in Chhattisgarh, supporting climate action plans in Gujarat and Madhya Pradesh, evaluating community-based natural farming in Andhra Pradesh, examining crop residue burning in Punjab, promoting and deploying solar rooftops in Delhi, Bihar and Meghalaya.

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We would like to thank Bloomberg Philanthropies and Shakti Sustainable Energy Foundation (SSEF) for their support to carry out this study.

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UrbanEmissions provided their modelled $PM_{2.5}$ source apportionment data and TomTom International BV the congestion data for Delhi, for which we duly acknowledge both the organisations. We appreciate the efforts of Danwant Narayanasamy, Research Analyst, CEEW and Vidur Mithal, Research Intern (CEEW) for helping us collecting the data set for this study.

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A policy researcher at The Council, Kurinji focuses on devising efficient methods to monitor and control various air polluting sources. She holds a bachelor's degree in energy and environmental engineering from Tamil Nadu Agricultural University, Coimbatore. She is an Indian Green Building Council (IGBC) accredited professional.

"Shuttered cities during the pandemic brought clearer skies and clean air. But did the pandemic's blue skies endure in the winter of 2020? This study sheds light on what was different in winter 2020 in Delhi and reinforces the significance of timely and deeper emission cuts. Going forward, enforcement agencies should strategically assimilate observations from air quality forecasts to plan emission control measures in advance to avert smog episodes."

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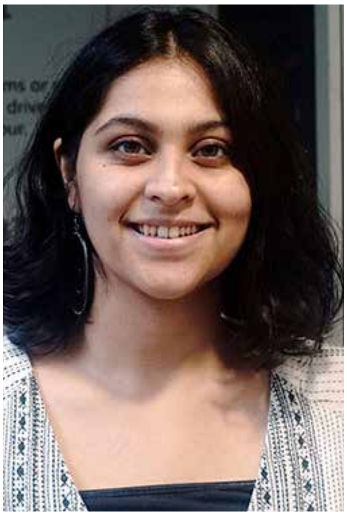
A research analyst at The Council, Adeel uses air quality data from monitoring stations, satellite retrievals, and model outputs to recommend policy making decisions. He holds a master's degree in environmental science and resource management from TERI School of Advanced Studies and bachelor's in physical sciences from St Stephen's college, Delhi.

"Curtailing emissions can significantly improve air quality and we have seen that during the lockdown. The impact of emissions can be more severe in unfavourable weather seasons. Therefore, we require source-wise and season-wise mitigation strategies for tackling air pollution. Further, pre-emptive measures towards source reduction needs to be incorporated through the use of model forecast."



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A programme associate at The Council, Tanushree assesses alternative methods for monitoring air quality to understand and address current regulatory challenges in effectively implementing clean air policies. She has a master's degree in environmental engineering from the Georgia Institute of Technology and is a certified engineer-in-training under California law.

"Delhi's Graded Response Emergency Plan (GRAP) should be based on the use of sophisticated weather and air quality forecasting models so that preventive measures are put in place to reduce pollutant emissions. Meteorological conditions cannot be controlled and can significantly worsen or improve air quality. Therefore, the government should be prepared to combat unfavourable meteorological conditions with measures to reduce emissions from transport and industrial and construction activities."

Delhi topped the chart of the world's most polluted capital cities for three straight years in 2020 (IQ Air 2021).

Image: iStock

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Acronyms

AQ	air quality
AQI	Air Quality Index
BAM	beta attenuation mass monitor
C3S	Copernicus Climate Change Service
CAAQMS	continuous ambient air quality monitoring stations
CAQM	Commission on Air Quality Management
CEA	Central Electricity Authority
CPCB	Central Pollution Control Board
CTM	chemical transport models
DUSIB	Delhi Urban Shelter Improvement Board
ECMWF	European Centre for Medium-Range Weather Forecasts
EPCA	Environmental Pollution Control Authority
ERA 5	ECMWF Reanalysis 5th Generation
FIRMS	Fire Information for Resource Management System
GRAP	Graded Response Action Plan
IDW	inverse distance weighted
IITM	Indian Institute of Tropical Meteorology
MoES	Ministry of Earth Sciences
NAAQS	National Ambient Air Quality Standard
NASA	National Aeronautics and Space Administration
NCR	the National Capital Region
NOAA	National Oceanic and Atmospheric Administration
RFID	radio frequency identification
SAFAR	System of Air Quality and Weather Forecasting And Research
Suomi-NPP	Suomi National Polar-orbiting Partnership
USD	US dollar
VIIRS	Visible Infrared Imaging Radiometer Suite
WRF	weather research and forecasting

Waste burning for space heating and disposal purposes contributes significantly to the pollution burden in the national capital region (Bhandari et al. 2020).

Image: iStock

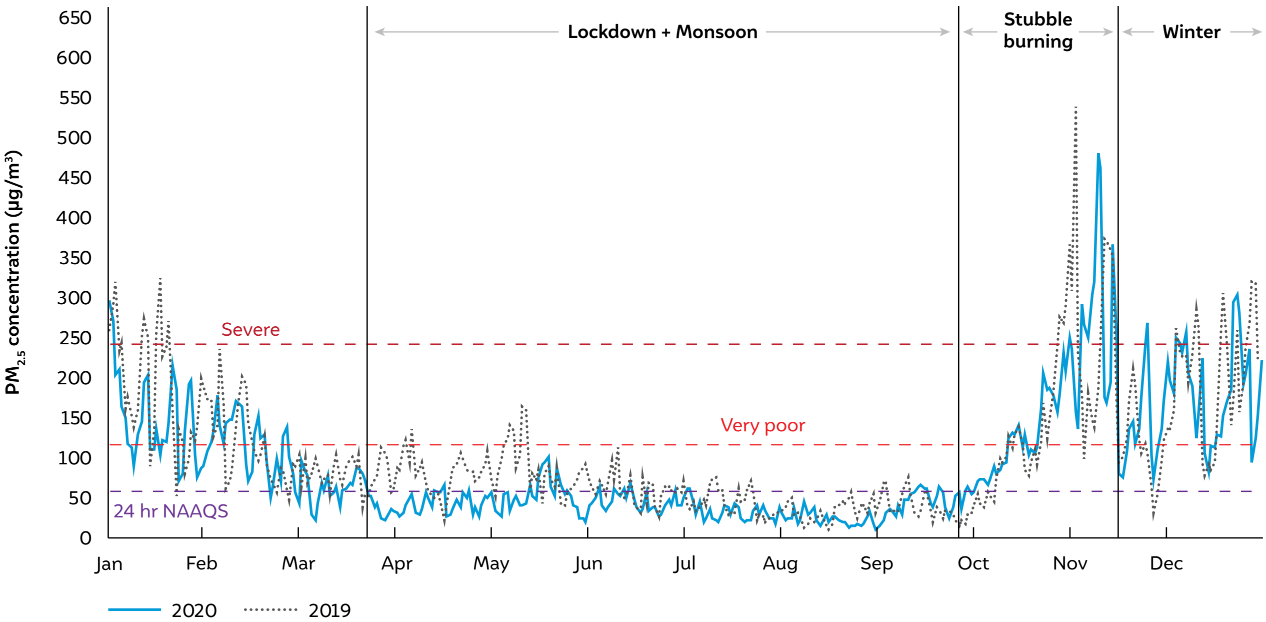
Executive summary

Delhi is among the most polluted cities in the world (IQ Air 2021). In 2019 alone, air pollution caused over 17,000 premature deaths and an economic loss of 1,207 million USD in the national capital (Pandey et al. 2021). With regards to air quality, 2020 was an aberration. The pandemic-induced lockdown measures provided temporary respite from the year-round poor air quality.

Despite the lockdown, Delhi's annual average $PM_{2.5}$ in 2020 was more than 2-times its permissible limit

Barring a few days in April and May, Delhi experienced National Ambient Air Quality Standard (NAAQS)[1] compliant air quality on most days during the lockdown. Yet, the annual average $PM_{2.5}$ concentration in 2020 was 93 µg/m³, which is more than twice the permissible limit for $PM_{2.5}$ in India. Despite low activity levels for close to eight months (March to November) in 2020, Delhi residents were exposed to NAAQS non-compliant air for more than half of the year (Figure ES1).

Figure ES1 Air quality gains made from lockdown were lost in winter with the unlock



Source: Authors' analysis

1 The Ministry of Environment, Forest, and Climate Change (MoEFCC) notified the National Ambient Air Quality Standards for 12 air pollutants, including particulate matter, in 2009. The 24-hour and annual National Ambient Air Quality Standards for $PM_{2.5}$ are 60 and 40 µg/m3 respectively (The Gazette of India 2009).

Winters saw poor quality despite proactive measures by the government

While the NAAQS non-compliant air quality in Delhi is not a new phenomenon, the winter of 2020 witnessed proactive measures from the State Government in the wake of COVID and evidence pointing at the association between high air pollution and COVID mortality (Petroni et al. 2020; Cole, Ozgen, and Strobl 2020; Wu et al. 2020). This includes the Y*uddh Pradushan Ke Virudh* (war against pollution) campaign and a seven-point action plan to combat air pollution in Delhi which listed measures ranging from combating dust and mitigating hotspots to a mobile application called Green Delhi for complaints and a 'war room' for monitoring air pollution control activities (PTI 2020a). Similar to 2019, the Graded Response Action Plan (GRAP), also came into force on 15th October 2020 and the Environmental Pollution Control Authority (EPCA)[2] oversaw its implementation until the announcement of its dissolution on 28th October 2020 (Koshy 2020; EPCA 2020). However, despite these measures, the $PM_{2.5}$ levels remained almost three times higher than the NAAQS on an average between October 2020 and January 2021.

We also observe that $PM_{2.5}$ levels in winter 2020 were higher than those in 2019. To explain this end, we analyse meteorological parameters, source activity levels, and contributions to establish primary drivers of pollution during different phases of the winter season. Through this brief, we intend to help the Delhi government, the Central Pollution Control Board (CPCB) and the Delhi Pollution Control Committee (DPCC) to identify priority areas of intervention for the year 2021. We summarise key highlights as follows.

Air quality in winter 2020 was worse than winter 2019

Delhi observed 92 severe and very poor air quality days in the winter of 2020 compared to 80 such days in 2019. Compared to an average $PM_{2.5}$ concentration of 161 µg/m^3 in 2019, between October and November 2020, this value was 172 µg/m^3. It further shot up to an average level of 192 µg/m^3 in the period between December 2020 to January 2021 compared to 178 µg/m^3 during the same period previous year.

Contributions from stubble burning and household emissions from cooking and space heating were significant fractions of the pollution pie

Modelled source contribution estimates of particulate matter ($PM_{2.5}$) by UrbanEmissions suggest that relative contribution from farm fires was the highest (~30 per cent) in the period between 15 October and 15 November 2020 (Figure ES2). We find that compared to the stubble burning period in 2019, a longer harvesting season in 2020 led to a significant increase in the number of fires. In the following months, contribution from household emissions (including domestic cooking, space heating, water heating, and lighting) primarily drove poor air quality in Delhi. It is worth highlighting that these values are modelled estimates and are subject to the sector-specific assumptions used in the model.

Delhi observed 92 severe and very poor air quality days in the winter of 2020 compared to 80 such days in 2019

2 The EPCA was replaced by the Commission on Air Quality Management (CAQM) in the National Capital Region (NCR) and adjoining areas. It is important to note that the CAQM ceased to operate only five months after it was formed as the ordinance that set it up had lapsed on 12 March 2021 .

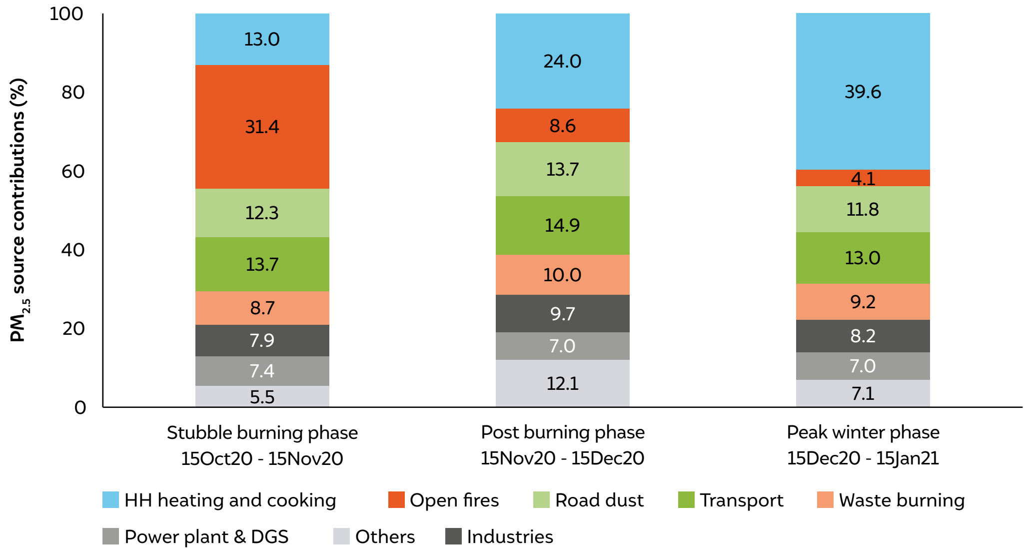


Figure ES2
The primary contributor to pollution changes as the season progresses

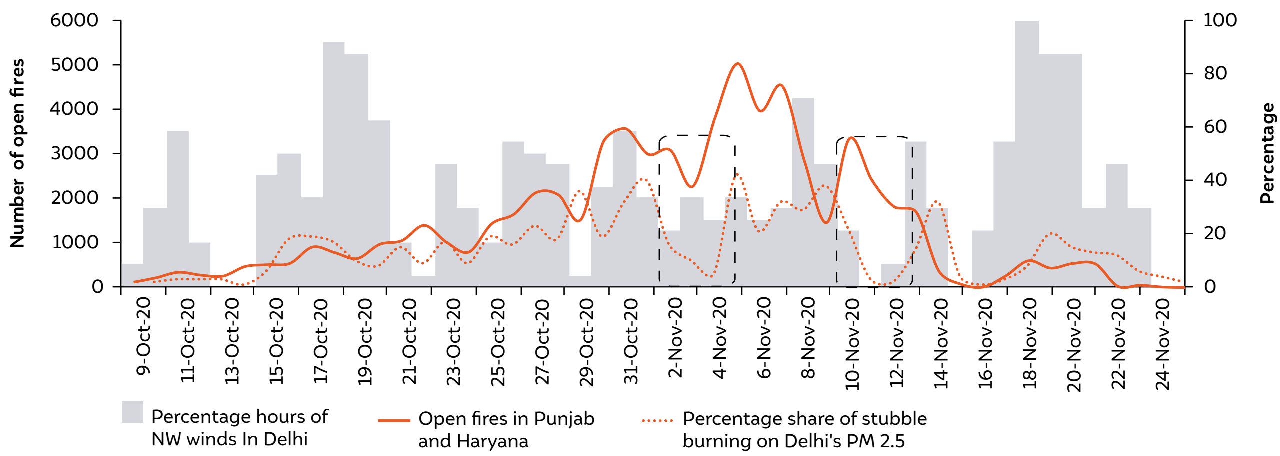
Source: Authors' analysis

Note: Modelled estimates of daily particulate matter ($PM_{2.5}$) concentration and relative source contributions retrieved from UrbanEmissions. As per the estimates, the average $PM_{2.5}$ concentration was 240 µg/m³ in phase 1 (15 October to 15 November 2020), 160 µg/m³ in phase 2 (15 November to 15 December 2020) and 200 µg/m³ in phase 3 (15 December 2020 to 15 January 2021).

Calmer winds in October and November amplified the impact of farm fires on Delhi's air quality

The stubble burning phase (15 October to 15 November) in 2020 experienced 172 hours (70 per cent higher) of calm and light winds (<5 km/h) compared to 101 hours in 2019. Winds predominantly from the north-west direction facilitated the transport of smoke emanating from farm fires and calm winds in Delhi further intensified its adverse impact on air quality. Interestingly, for brief periods in the season, even when high fire counts were reported in Punjab and Haryana, Delhi's air quality was not affected due to favourable meteorological conditions (Easterly and southerly winds) (Figure ES3). Unfavourable meteorological conditions include low wind speeds and shallow mixing height height[3].

Figure ES3 Higher share of stubble burning on Delhi's $PM_{2.5}$ levels on days when north-western winds were blowing



Note: Black box indicates the days (3–4 and 11–12 November 2020) when the contribution of farm fires was lower (<5%), despite the higher number of daily open fires in Punjab and Haryana, due to favourable meteorological conditions in Delhi

Source: Authors' analysis; ECMWF Reanalysis 5th Generation (ERA 5) meteorological data and System of Air Quality and Weather Forecasting And Research (SAFAR) data on the contribution from farm fires in Punjab and Haryana on Delhi's $PM_{2.5}$ levels.

3 Mixing height represents the height of the vertical mixing of air and suspended particles above the ground and is influenced by the atmospheric temperature profile.

Lowered activity levels at the start of winter due to lockdown bounced back to the previous year's levels as the winter progressed

While Delhi's average $PM_{2.5}$ concentration during the stubble burning period (October'20 and November'20) was 172 µg/m³, it increased to 192 µg/m³ during peak winter (December'20 and January'21). The higher $PM_{2.5}$ levels in December 2020 and January 2021 were primarily caused by locally emitted pollutants and added burden of household emissions from space heating. Activity levels were low at the start of the season, but most activities, including vehicular traffic and power generation, bounced back to the previous year's levels (proxied by indicators such as congestion and electricity generation levels in Figures ES4 and ES5) as the season progressed.

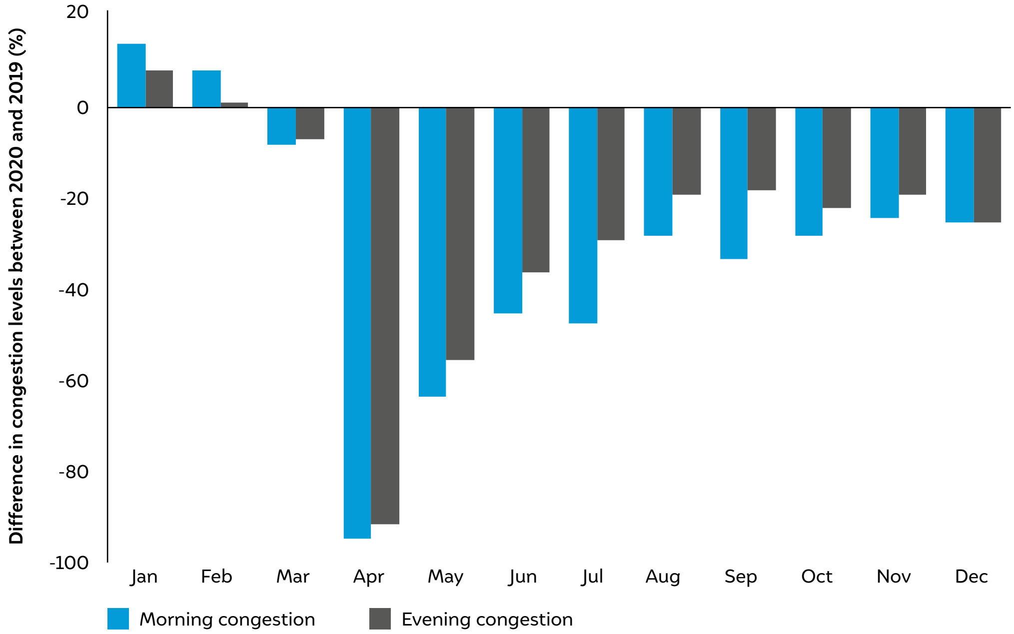
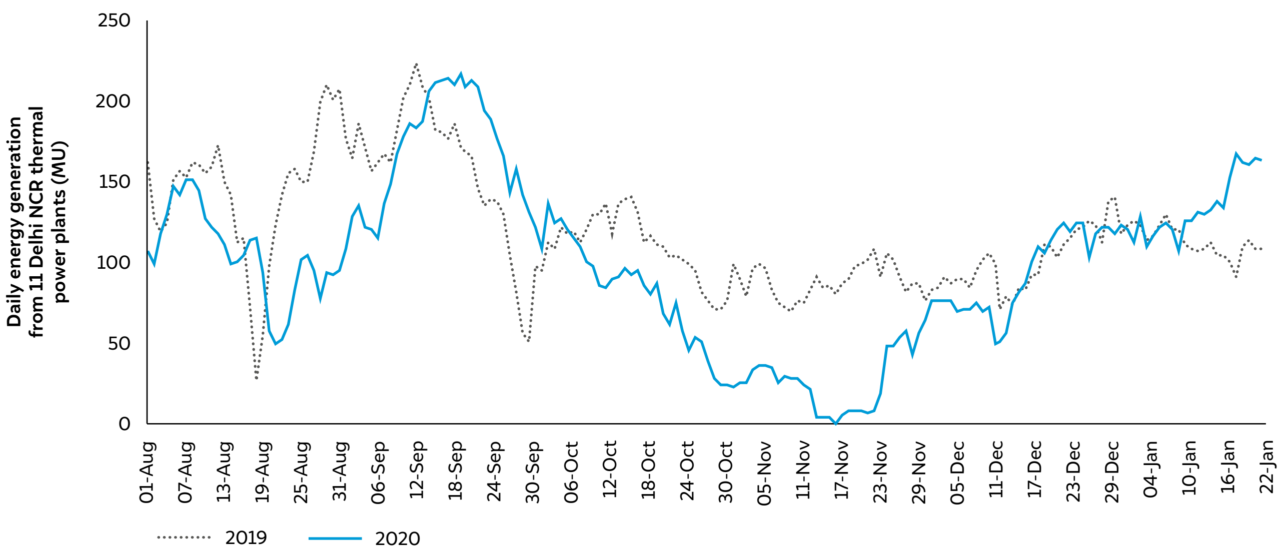


Figure ES4
Congestion level bounced back to 80% of the 2019 level during the winter of 2020

Source: TomTom. 2020. "New Delhi Traffic Report." TomTom Traffic Index. https://www.tomtom.com/en_gb/traffic-index/new-delhi-traffic/.

Note: Congestion level refers to the expected percentage increase in travel time compared to free-flow conditions. Free-flow conditions generally occur at night but can happen any time of day.

Figure ES5 Power plants operated at a lower capacity in October and November 2020



Source: Authors' compilation; Daily energy generation data as reported by Central Electricity Authority

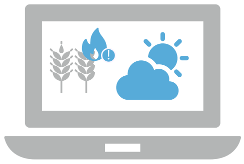
Delhi needs a dedicated air quality forecasting cell to facilitate roll out of preventive measures

We attribute the brief periods of moderate air quality during winter 2020 largely to favourable meteorological conditions. It is evident that adverse meteorological conditions in Delhi intensified the impact of local and regional emissions on Delhi's air quality. While meteorological conditions cannot be controlled, sustained air quality gains can be realised only by steeper emission cuts across sectors.

Delhi has in place a publicly available air quality forecast system provided by UrbanEmissions for over five years. The Indian Institute of Tropical Meteorology (IITM), under the aegis of Ministry of Earth Sciences (MoES), has also built an official air quality warning system for Delhi (PIB 2018). However, none of these forecasts were actively used to take pre-emptive measures to reduce emission loads from anthropogenic activities. Some countries roll out emergency measures in response to air quality (AQ) forecasts and not after air quality actually dips to dangerous levels. For instance, Beijing's Ministry of Ecology and Environment issues a red alert if the daily mean citywide air quality index (AQI) is forecasted to be greater than 200 for four days (96 hours) or more; greater than 300 for two days (48 hours) or more; or greater than 500. In contrast, the Delhi government issues orders to execute emergency measures under GRAP ex-post, that is, after air quality concentrations reach a certain threatening level. Responsive measures cannot prevent the occurrence of high pollution episodes.

Further, adding relative source contributions to air quality forecasts, similar to the way UrbanEmissions issues forecasts, can help identify the primary contributors during a particular episode. Integrating such forecasts with a decision support system would enable the local regulatory agencies to implement on-demand emission control interventions targeting prominent sources during forecasted high-pollution episodes.

The Graded Response Action Plan (GRAP) presents the state government with an opportunity to constitute an air quality forecasting cell that can advise the government to take necessary measures to prevent severe air quality episodes in the capital city. We recommend that going forward, the Delhi government, the CPCB, and the DPCC **use the air quality forecasts not only to issue public health warnings but also for taking pre-emptive actions in the national capital**. We must move from a system that enforces the Graded Response Action Plan as an ex-post measure to one that prevents the occurrence of high pollution episodes through pre-emptive emission control measures.



Move from a system that enforces the Graded Response Action Plan as an ex-post measure to one that prevents the occurrence of high pollution episodes through pre-emptive emission control measures

Despite complete and partial lockdown measures in place for close to eight months, Delhiites inhaled National Ambient Air Quality Standard (NAAQS) non-compliant air for half of the year in 2020.

Image: iStock

1. Background and motivation

The pandemic-induced lockdown measures brought life in Indian cities to a complete standstill in 2020 (Chaudhary, Sodani, and Das 2020). Delhi reeled under the impact of COVID-19, with about 1.05 million people infected, out of which 14,628 died, as of 25 April 2021 (Covid19 India 2021). The life-threatening nature of COVID-19 made the central, state, and local governments take aggressive measures to contain the spread of the disease (*The Lancet* 2020). Unfortunately, air pollution that resulted in 17,000 deaths and an economic loss of 1,207 million USD in 2019 in Delhi has not been addressed with the same urgency (Pandey et al. 2021) despite evidence from international studies demonstrating a link between exposure to air pollution and the likelihood of getting infected by COVID-19 (Petroni et al. 2020; Cole, Ozgen, and Strobl 2020; Wu et al. 2020).

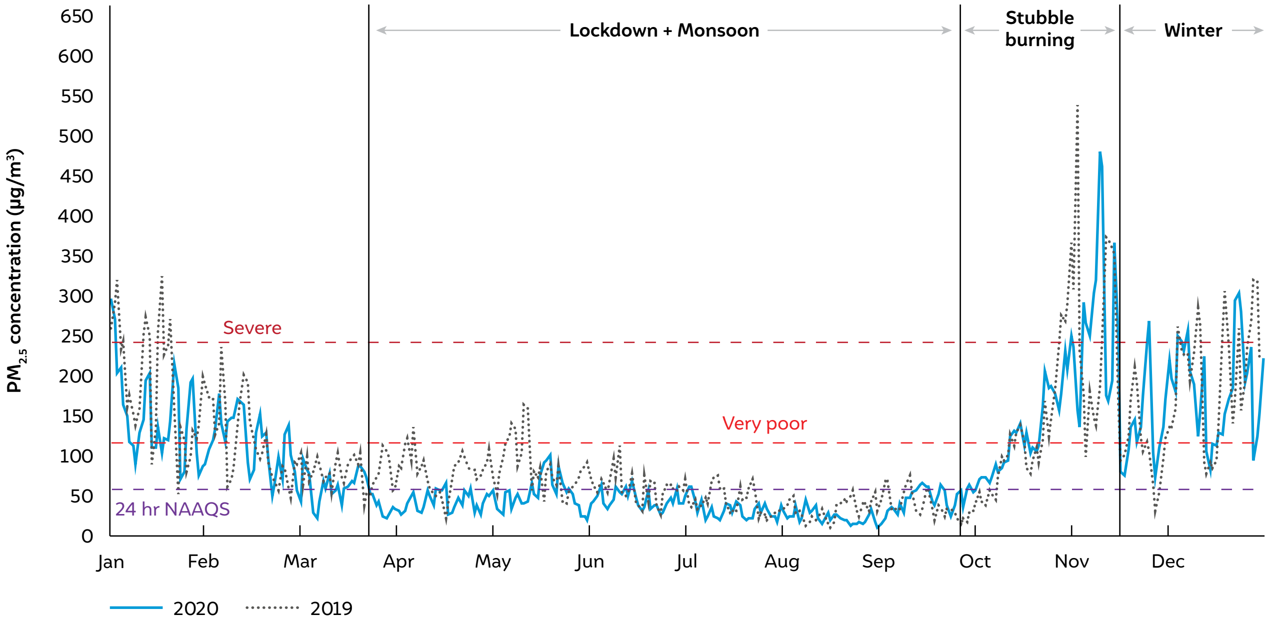
Air quality gains experienced during the months under lockdown followed by the monsoon period were lost with the unlock of economic activities coinciding with the onset of winter

In the first phase of the pandemic-induced lockdown (25 March to 25 April), cities across the country reported a 20–50 per cent reduction in $PM_{2.5}$ levels (Garg, Kumar, and Gupta 2021; Pandey et al. 2021). The Central Pollution Control Board (CPCB), India's pollution regulating agency, confirmed a reduction of over 50 per cent in $PM_{2.5}$ concentration during the lockdown[1] compared to 2019 levels in the national capital (CPCB 2020a).

However, air quality gains experienced during the months under lockdown followed by the monsoon period were lost with the unlock of economic activities coinciding with the onset of winter (Figure 1). In fact, despite complete and partial lockdown measures in place for close to eight months, Delhiites inhaled National Ambient Air Quality Standard (NAAQS) non-compliant air for half of the year in 2020. On an average, the $PM_{2.5}$ levels were almost three times higher than the NAAQS between October 2020 and January 2021. The year's maximum level was reached on 9 November 2020 when the daily average $PM_{2.5}$ levels touched 500 µg/m^3.

1 Lockdown phase I (25 March to 19 April 2020) and lockdown phase II (20 April to 3 May 2020).

Figure 1 Delhi experienced NAAQS non-compliant air for half of the year in 2020 despite the lowered activities during the lockdown



Source: Authors' analysis

While winter-time severe air quality levels in Delhi are not a new phenomenon, the winter of 2020 witnessed proactive measures from the State Government in the form of the *Yuddh Pradushan Ke Virudh* (war against pollution) campaign, a seven-point action plan to combat air pollution in Delhi. The plan listed measures ranging from combating dust and mitigating hotspots to a mobile application called Green Delhi for complaints and a 'war room' for monitoring air pollution control activities (PTI 2020a). Similar to 2019, the Graded Response Action Plan (GRAP), came into force on 15th October 2020 and the Environmental Pollution Control Authority (EPCA) oversaw its implementation until the announcement of its dissolution on 28th October 2020 (Koshy 2020; EPCA 2020). The EPCA was replaced by the Commission on Air Quality Management (CAQM) in the National Capital Region (NCR) and adjoining areas which aimed at better coordination, research, identification, and resolution of problems pertaining the air quality index (Ministry of Law and Justice 2020). The CAQM now stands disbanded as the ordinance that led to its formation lapsed on 12 March 2021.

In this brief, we analyse and compare winter particulate matter concentrations in 2020 with 2019 levels to understand how this winter was, if at all, different in the circumstances and polluting activity in so far as the NCR region is concerned. To this end, we analyse meteorological parameters, source activity levels, and contributions to establish primary drivers of pollution during different phases of the winter season. Through this brief, we aim to help the Delhi government, the Central Pollution Control Board, and the Delhi Pollution Control Committee identify priority areas of intervention for the year 2021.

2. Data and approach


Image: Milan Jacob/CEEW

We employed trend analysis for inter-year comparison of particulate matter levels and also assess variations in the meteorological parameters. We used several data sets, including data on power generation, congestion, satellite-derived fire events, and modelled source contributions by UrbanEmissions to examine the impact of different anthropogenic activities on Delhi's air quality (Table 1). We also accessed ECMWF Reanalysis 5th Generation data by the European Centre for Medium-Range Weather Forecasts (ECMWF) to capture the relationship between air quality and meteorological parameters. Given that stubble burning is estimated to contribute to 20 per cent of Delhi post-monsoon particulate concentration (Kulkarni et al. 2020), we used linear regression to assess the relative importance of factors like distance-weighted fire counts and local and regional meteorological conditions on the contribution of fires in Punjab to Delhi's air quality.

Table 1
Data sets used

Data set	Description	Period	Source
$PM_{2.5}$ data	Hourly $PM_{2.5}$ data from 37 regulatory grade continuous ambient air quality monitoring stations (CAAQMS) in Delhi were accessed via Openaq platform (OpenAQ 2021) and CPCB dashboard (CCR 2021). Spatial averaging was done to compute the city-level mean $PM_{2.5}$ concentration.	1 January 2019 to 31 January 2021	Central Pollution Control Board (CPCB)
Meteorological data (10 m wind speed, 10 m wind direction, temperature at 2 m, planetary boundary layer height)	Hourly ERA 5 climate reanalysis data from ECMWF was retrieved via Copernicus Climate Change Service (C3S) (Copernicus 2021) The data is available at a spatial resolution of 0.25° x 0.25° (~25 km x 25 km). Spatial averaging across Delhi and Punjab was done to compute the mean values.	1 January 2019 to 15 January 2021	European Centre for Medium-Range Weather Forecasts (ECMWF)
Active fire product (open fires)	Active fire product was detected by Visible Infrared Imaging Radiometer Suite (VIIRS) sensor aboard the joint National Aeronautics and Space Administration (NASA)–National Oceanic and Atmospheric Administration (NOAA) Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite. Data were accessed from the Fire Information for Resource Management System (FIRMS) of NASA (NASA 2021). This study uses fire pixel data with confidence levels of 'nominal' and 'high' to ensure fewer false detections of fire pixels (Kurinji 2019).	1 September to 30 November for 2019 and 2020	FIRMS
Percentage share of stubble burning on Delhi's $PM_{2.5}$ levels	The System of Air quality and Weather Forecasting and Research (SAFAR) runs weather research and forecasting (WRF)-Chem to model daily contribution of farm fires from Punjab and Haryana to Delhi's $PM_{2.5}$ levels (Beig et al. 2021). The modelled stubble share data is accessed from SAFAR website (SAFAR 2020).	15 October to 25 November for 2019 and 2020	SAFAR
Congestion data	Historical monthly congestion level for Delhi was accessed from TomTom International BV (TomTom 2020). Congestion level refers to the expected percentage increase in travel time compared to free-flow conditions. Free-flow conditions generally occur at night but can happen any time of day.	2019 and 2020	TomTom International BV
Power generation data	Daily power generation data from 11 coal-fired thermal power plants (Annexure A1) in the Delhi National Capital Region (NCR) published by the Central Electricity Authority (CEA) was used (Ministry of Power 2021).	1 January 2019 to 31 December 2020	CEA

Source: Authors' compilation

Data set	Description	Period	Source
Source apportionment data	Using the WRF-CAMx modelling system, urbanemission.info conducts a series of simulations every day to model source contributions to hourly average $PM_{2.5}$ levels, based on a detailed spatially and temporally resolved emissions inventory. Hourly modelled data is then averaged to monthly source apportionment data. The modelled average is for all the 0.25° x 0.25° grids (~25 km x 25 km) overlapping in each of the districts in Delhi (UrbanEmissions 2021). More details are provided in Annexure A2. It is important to note that these values are modelled estimates and are subject to the sector-specific assumptions used in the model.	15 October 2020 to 15 January 2021	UrbanEmissions

Source: Authors' compilation

The maximum number of farm fires (nearly 70,000) in the last three years in Punjab were recorded in 2020.

Image: iStock

3. Results and discussion

In this chapter, we present and discuss the observed air quality trends and determine the influence of meteorological conditions and activity levels on Delhi's air quality in 2020 and compare them with 2019. We also explain how air quality forecasts should ideally be used for managing Delhi's air quality.

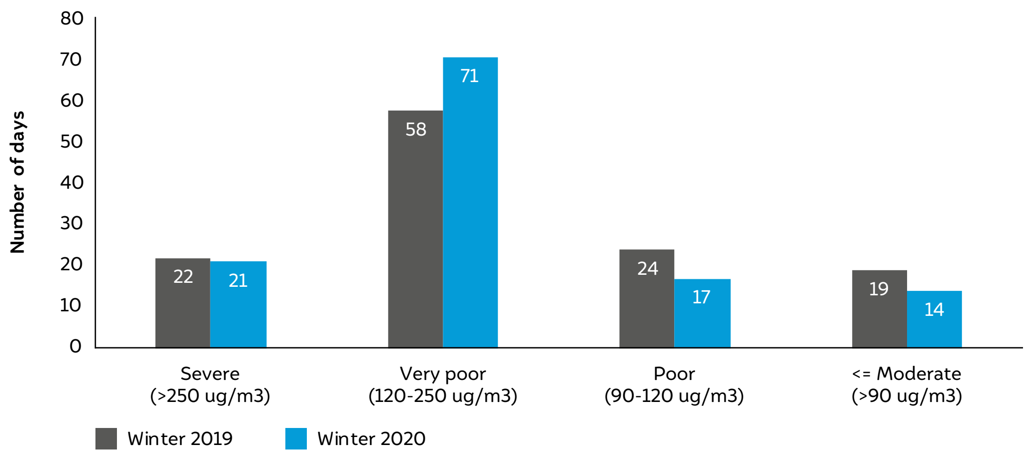
Though very poor and severe air quality extends till January in the winter, attention to the problem peaks only in October and November coinciding with the stubble burning season and dies out with the season

3.1 Winter 2020 was more polluted than winter 2019

We observed 92 severe and very poor air quality days in the winter of 2020 compared to 80 such days in 2019 (Figure 2). Compared to an average $PM_{2.5}$ concentration of 161 µg/m³ in 2019, between October and November 2020, this value was 172 µg/m³. It further shot up to an average level of 192 µg/m³ in December 2020 and January 2021 compared to 178 µg/m³ in December 2019 and January 2020 (Figure 3).

Though very poor and severe air quality extends till January in the winter season, attention to the problem peaks among the public and media only during late October and early November coinciding with the stubble burning phase and dies out once stubble burning decreases (S. Guttikunda 2017; Adhikary et al. 2020). For instance, over 14,000 complaints regarding pollution in the neighbourhood was registered from 29 October to 4 December 2020 on the Green Delhi mobile app launched by the Delhi government. However, in the next two months, only 5,000 complaints were registered, indicating a drop in the active use of the app (supporting data can be viewed in Annexure A4).

Figure 2
Higher number of severe + very poor air quality days in Delhi in winter 2020 compared to winter 2019



Notes: Winter 2020—1 October 2020 to 31 January 2021; Winter 2019—1 October 2019 to 31 January 2020; air quality index (AQI) based on $PM_{2.5}$ concentration

Source: Authors' analysis

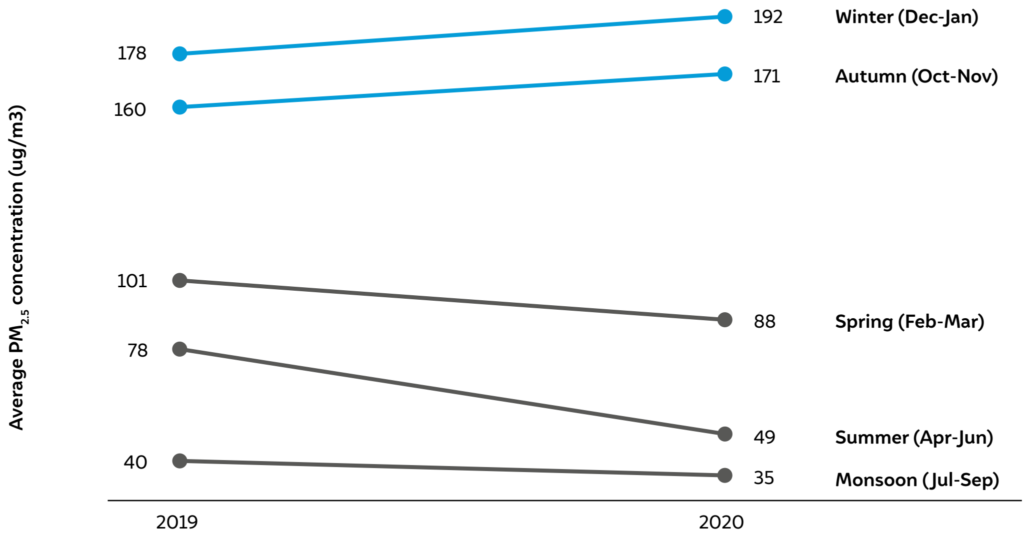


Figure 3
Air quality gains made from lockdown were lost in winter and autumn with the unlock

Source: Authors' analysis

3.1.1 Reduction in incidences of emergency air quality conditions

The Graded Response Action Plan (GRAP) for Delhi defines emergency or severe+ as a condition when $PM_{2.5}$ values of ≥300 μg/m³ persist for 48 hours or more (CPCB 2017). Delhi experienced one emergency episode (8–10 November) in 2020, coinciding with the peak burning phase against two emergency episodes in 2019. Diwali triggered the first emergency condition in 2019, which was further amplified by emissions from farm fire (29 October–2 November). Similarly, in 2020, the smoke from firecrackers along with emissions from local and regional sources built up the $PM_{2.5}$ levels to a severe category on the Diwali (14 November) night. But speedy winds and rain on the next day cleared the sky and prevented the second emergency condition (PTI 2020b).

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3.2 Adverse meteorological conditions in October and November 2020

Meteorological parameters determine the severity of atmospheric emissions to a large extent. While fast winds facilitate dispersion of pollutants, calm winds (wind speed <5 km/h) (IMD 2005) slow down dispersion, leading to a build-up of their concentration. Rains flush out the particulates and dissolve gaseous pollutants, exerting a 'scavenging effect' (Queensland Government 2017). Temperature and particulates are negatively correlated during winter, with low-temperature periods corresponding to periods of high particulate matter concentration (Hernandez et al. 2017). Incoming solar radiation (insolation) heats up the surface, leading to variations in the mixing height (Pleim and Mckeen 2012). Mixing height represents the height of the vertical mixing of air and suspended particles above the ground and is influenced by the atmospheric temperature profile. A low mixing height (typically observed during winter mornings) results in trapping of emissions near the surface (Murthy et al. 2020).

The meteorological conditions observed during winter in Delhi are often described as unfavourable for the dispersion of pollutants. S. K. Guttikunda and Gurjar (2012) observe that even though emissions are of a similar magnitude across the months of a year, the observed pollutant concentrations are 40–80 per cent higher than average in the winter months (November, December, and January) and 10–60 per cent lower in the summer months (May, June, and July). However, some emission sources such as agricultural residue burning, biomass burning for space heating, and emissions from brick kilns are seasonal in nature. The variation in pollutant concentration across winter and summer months is primarily determined by the shift in weather patterns across seasons. As shown in Figure 4, calmer winds, colder temperatures, and low mixing layer height are typical in winter months. These factors result in stagnant weather conditions that hamper pollution dispersion during winter. Further, north-western winds in the months of October and November bring in additional load from stubble burning from adjoining states of Punjab, Haryana, and western Uttar Pradesh.

Figure 4 A snapshot of meteorological conditions in Delhi (2020)

Temperature (°C)

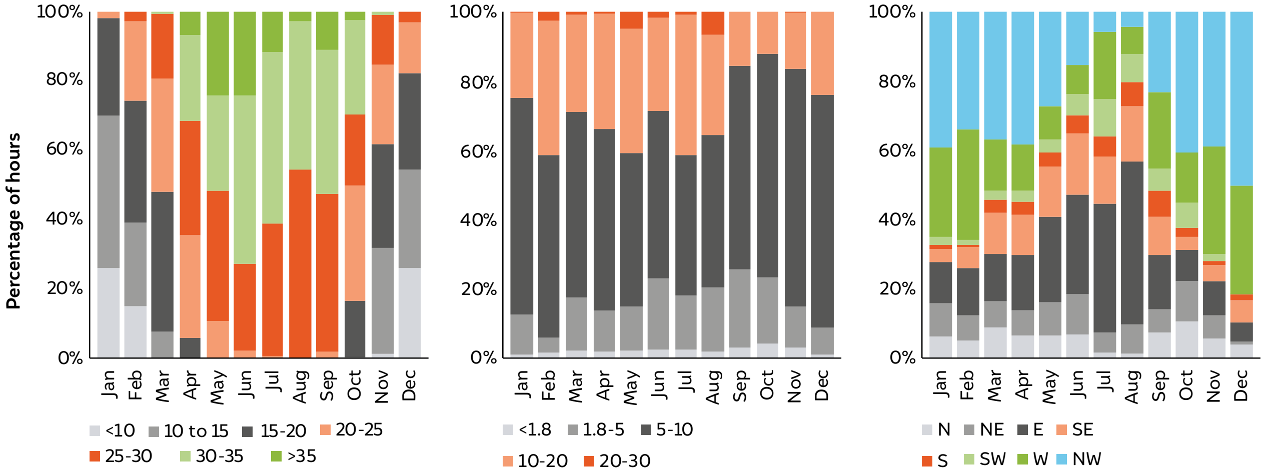
Temperature and particulates are negatively correlated during winter, with low-temperature periods corresponding to periods of high particulate matter concentration

Wind speed (km/h)

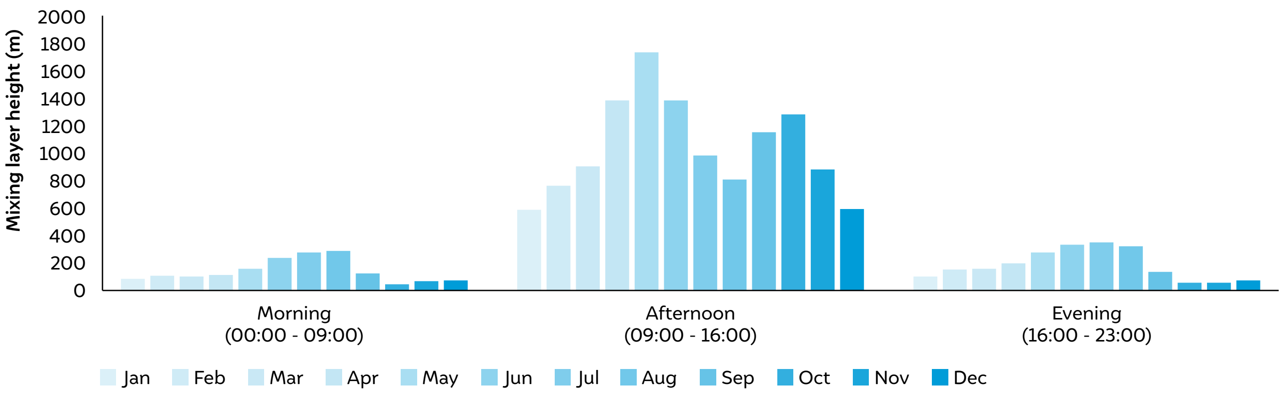
Wind speed and particulates are negatively correlated with fast winds facilitating dispersion of pollutants, and vice versa by calm winds.

Wind direction

Wind direction contribute to temporal variation in air pollutant concentration. For instance, during stubble burning season (October and November), north western winds facilitate the transport of smoke from north western states towards Delhi and beyond.



A low mixing height (typically observed during winter mornings) results in the trapping of emissions near the surface



Source: Authors' analysis; ERA 5 data from the European Centre for Medium-Range Weather Forecasts

A comparison of meteorological variations in Delhi in 2020 with those in 2019 is presented below:

- The stubble burning phase (15 October to 15 November) in 2020 experienced 172 hours (70 per cent higher) of calm and light winds (<5 km/h) compared to 101 hours in 2019 (Figure 5).

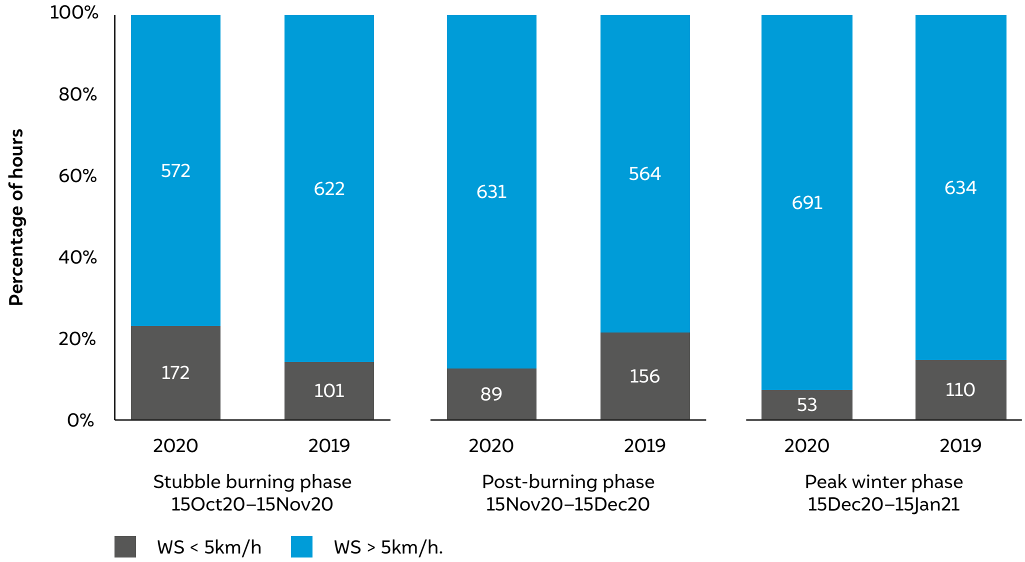


Figure 5
More hours of calm winds were observed in 2020 during the stubble burning phase

Source: Authors' analysis; ERA 5 data from the European Centre for Medium-Range Weather Forecasts

- In the winter of 2020, Delhi recorded only six rainy days (rainfall >2.5 mm) as against 10 in the winter of 2019. Further, the national capital experienced trace and very light rain (0.01–2.4 mm) only for 11 days (65 per cent lower) in the winter of 2020 compared to 32 days in the winter of 2019.
- The months of October and November in 2020 were cooler, with the air temperatures being 1–1.5°C lower than the corresponding months in 2019.

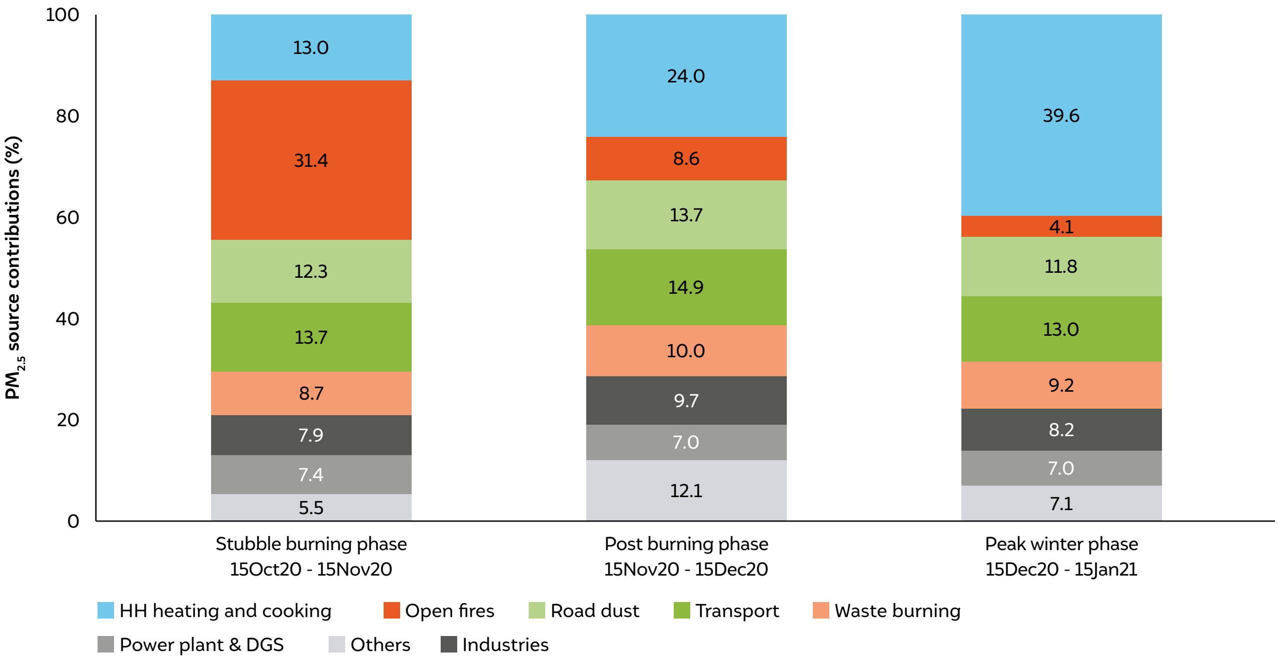
Thus Delhi had unfavourable meteorological conditions in the winter of 2020 such as lesser rainfall, more calm conditions, and colder temperature compared to the winter of 2019. These conditions led to exacerbating the impact of emissions on Delhi's air quality. While models can only be used to predict meteorological conditions, the conditions themselves cannot be altered. In order to reduce pollution, policymakers and state and city administration should pay attention to the meteorological forecasts and ensure that mechanisms for ex-ante and early roll-out of emission control measures are in place.

3.3 Stubble burning and emissions from burning of waste for space heating needs contributed significantly to pollution

To assess the contribution of different polluting sources as the season progresses, we analysed UrbanEmissions' modelled estimates of $PM_{2.5}$ source contribution. UrbanEmissions runs a series of simulations every day using the WRF-CAMx modelling system to model source contributions to hourly average $PM_{2.5}$ levels. The modelled average is available in 0.25° x 0.25° grids (~25 km x 25 km) covering India and is open to public use since 2016. It is important to note that the values described in this sub-section are modelled estimates and are subject to the sector-specific assumptions used in the model.

In the stubble burning phase, the average relative contribution of emissions from farm fires is the highest, at ~30 per cent (Figure 6). In the subsequent periods, local sources dominate with emissions from household solid fuel usage for cooking and space heating being the primary contributor, followed by road dust and transport emissions.

Figure 6 The primary contributor to pollution changes as the season progresses



Source: Authors' analysis

Note: Modelled estimates of daily particulate matter ($PM_{2.5}$) concentration and relative source contributions retrieved from UrbanEmissions. As per the estimates, the average $PM_{2.5}$ concentration was 240 µg/m³ in phase 1 (15 October to 15 November 2020), 160 µg/m³ in phase 2 (15 November to 15 December 2020) and 200 µg/m³ in phase 3 (15 December 2020 to 15 January 2021).

3.3.1 The maximum number of farm fires (nearly 70,000) in the last three years in Punjab were recorded in 2020

We find that the contribution of stubble burning to Delhi's $PM_{2.5}$ levels exceeded 30 per cent for seven days in 2020 as against three days in 2019 using the System of Air quality and Weather Forecasting and Research (SAFAR) data on the share of the contribution of stubble burning in Punjab and Haryana to Delhi's $PM_{2.5}$ between 10 October and 25 November 2020 (Figures 7). This season was longer compared to 2019 or 2018 as fires started early in late-September and a significant increase in the number of fires was observed (Figure 8).

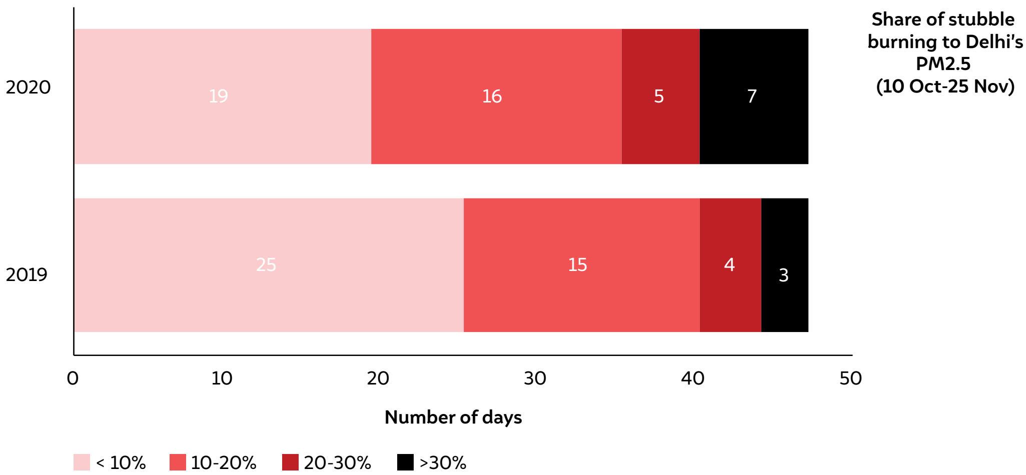
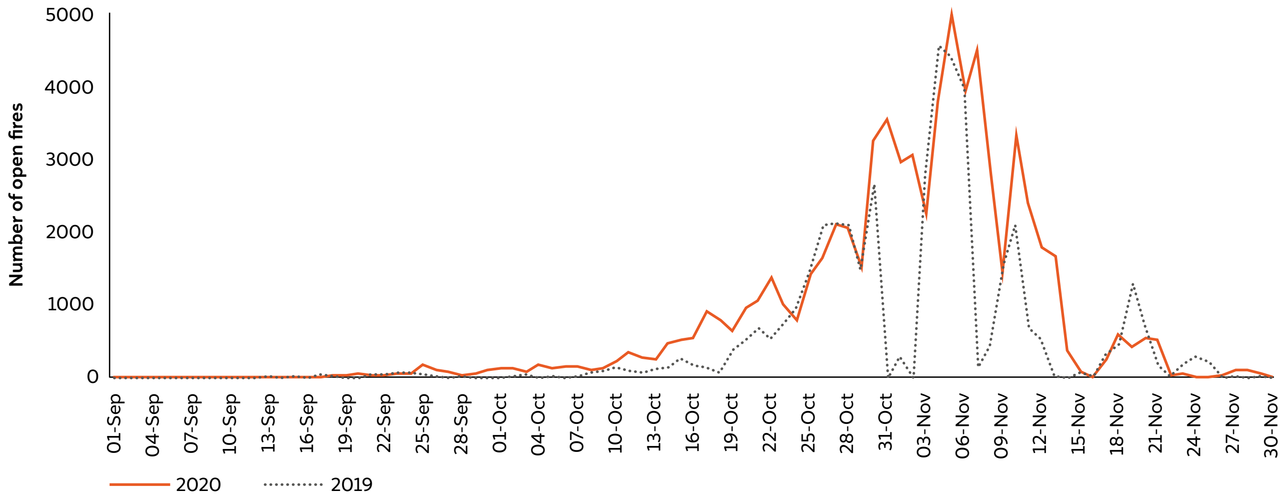


Figure 7 Number of days with higher stubble burning share (> 30%) doubled in 2020 compared to 2019

Source: Authors' compilation; System of Air quality and Weather Forecasting and Research (SAFAR) data on the share of stubble burning in Punjab and Haryana on Delhi's $PM_{2.5}$ for 10h October to 25 November in 2019 and 2020.

Figure 8 Extended stubble burning season in 2020



Source: Authors' analysis; Open fires with high and nominal confidence values are considered.

- **Fire counts along with wind speed in Punjab and wind direction in Delhi determine the impact of fires on Delhi's air quality**

The impact of farm fires in the neighbouring states on Delhi's air quality is determined by the number of fires and the prevailing local and regional meteorological conditions (CPCB 2016; Jethva et al. 2018). We carried out a multivariate regression analysis to explore the relative importance of these factors. To account for fires, we used inverse distance weighted (IDW) fire counts in Haryana and Punjab. IDW fire count is a composite variable that takes into account both the fire counts and their distance from Delhi. The weight is given based on the distance of the fire to Delhi (Parks 2014). Based on a simple regression analysis, we find that fire counts with a 24-hour lag, along with wind speed and direction in Punjab and wind direction in Delhi (Figure 9), are statistically significant predictors of the impact of crop fires on Delhi's air quality. The results agree with previous studies (Jethva et al. 2018), which show that smoke from Punjab and Haryana would take nearly 14–22 hours to reach Delhi under favourable meteorological conditions. The data supporting the conclusion are provided in Annexure Table A3.

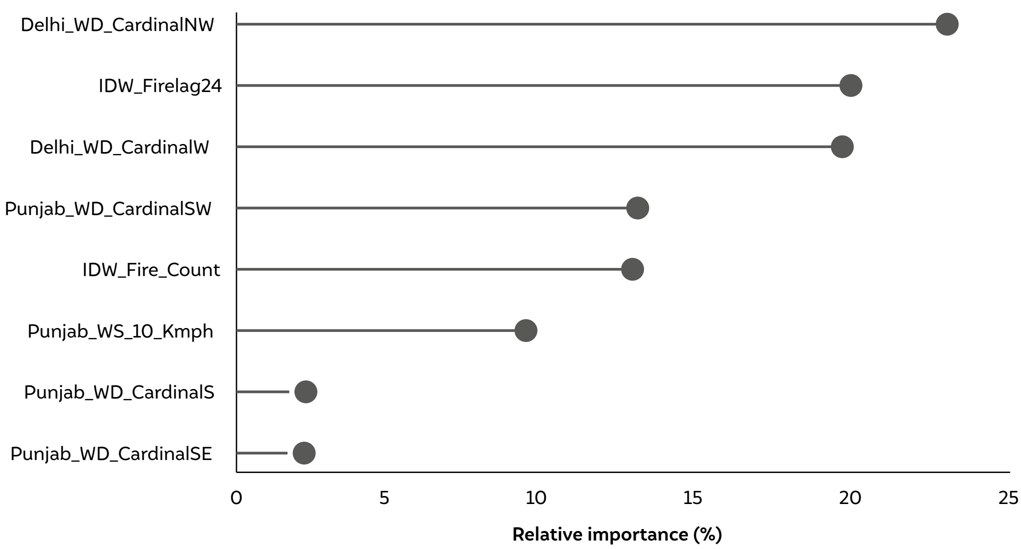


Figure 9 North-western and western winds and farm fires with a 24-hour lag are the key drivers of smoke contribution in Delhi

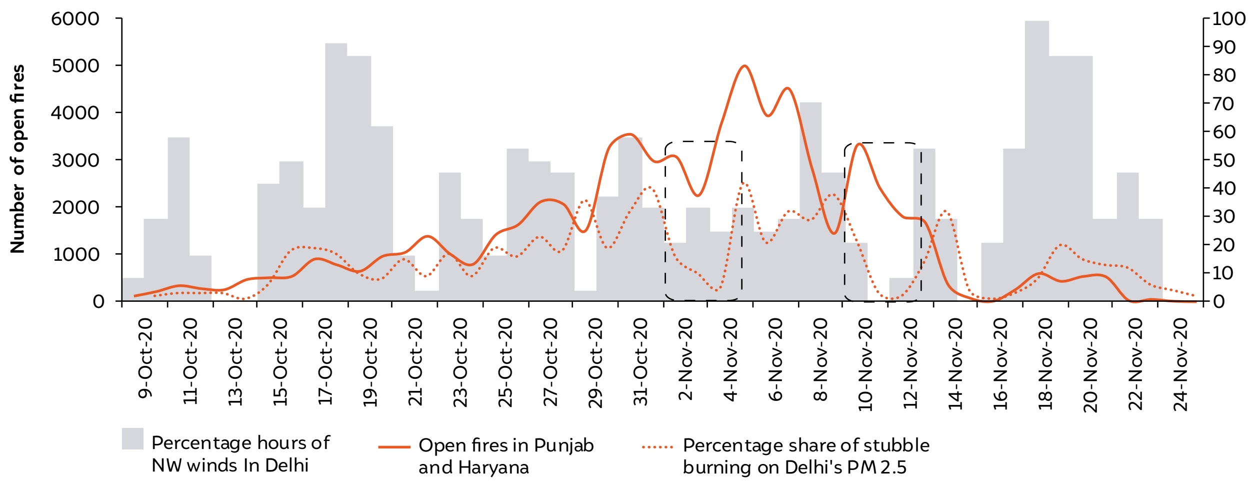
Source: Authors' analysis

Note: Relative importance signifies the contribution of each independent variable on the overall R^2 value (We only show significant variables that have a p-value of less than 0.05 in the above graph)

Anecdotally, we also observe two instances (3–4 and 11–12 November 2020) this season when high fire counts were reported in Punjab and Haryana, but favourable meteorological conditions (shift away from north-westerly winds) ensured that they did not have an impact on $PM_{2.5}$ levels in Delhi (Figure 10).

Studies show that alternatives for stubble burning such as in-situ and ex-situ options to manage stubble are lagging behind the demand (Gupta 2019; Kurinji and Kumar 2021). For districts such as Sangrur, Tarn Taran, and Patiala, which reported over 70 per cent its area burnt during stubble burning in 2020 (ICAR 2020), the state and central governments could introduce permitted burning under prescribed meteorological conditions as an interim measure. This is a widely adopted practice in California (California Air Resources Board 2019; Legal Information Institute 2021). In prescribed burning, regulating agencies issue burn directives and permit controlled burning only under specific forecasted meteorological criteria such that the impact of smoke can be minimised. We recommend trying prescribed burning on a pilot basis in a high-stubble-burning village with limited to no access to alternatives. To institute such a setup and manage air quality effectively, having access to accurate and reliable meteorological forecast models holds key (Pleim and Mckeen 2012).

Figure 10 Higher contribution from stubble burning on days of north-western winds



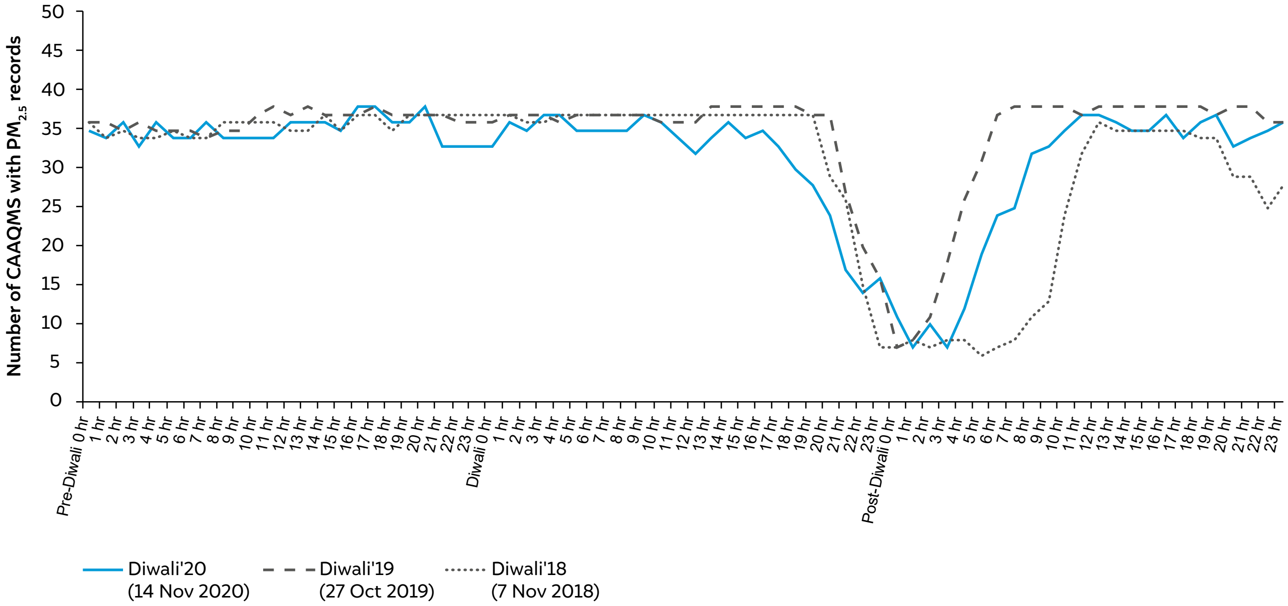
Source: Authors' analysis; Meteorological data from ERA 5 and contribution from farm fires on Delhi's $PM_{2.5}$ levels from SAFAR.Black box indicates the days (3–4 and 11–12 November) when the contribution of farm fires was lower (< 5 per cent), despite the higher number of daily open fires due to favourable meteorology.

3.3.2 Impact of Diwali fireworks was short-lived but significant

Despite a National Green Tribunal (NGT) ban on the sale of all kinds of firecrackers in Delhi NCR, pollution levels during Diwali 2020 reached the maximum values in the last four years (CPCB 2020b; NGT 2020). On the night of 14 November 2020 (Diwali), several continuous monitoring stations in Delhi reported a sharp jump in $PM_{2.5}$ levels from 250 µg/m³ to 500+ µg/m³ at 10 p.m., indicating a significant share of emissions from firecrackers. In less than an hour, most stations stopped reporting. This typically happens when the concentration exceeds the standard range (0–1,000 µg/m³) of a beta attenuation mass monitor[2] (BAM) (Ecotech 2012). As observed in 2018 and 2019, less than 10 out of 37 continuous monitoring stations in Delhi reported values between midnight and 3 a.m. on the Diwali night in 2020 (Figure 11).

6 Beta attenuation mass monitor (BAM) uses industry-proven principle of beta ray attenuation to record airborne particulates.

Figure 11 Majority of air quality monitoring stations did not report data during the Diwali night in 2020



Source: Authors' analysis

3.3.3 Modelled estimates attribute 40% of $PM_{2.5}$ in December 2020 and January 2021 to household emissions

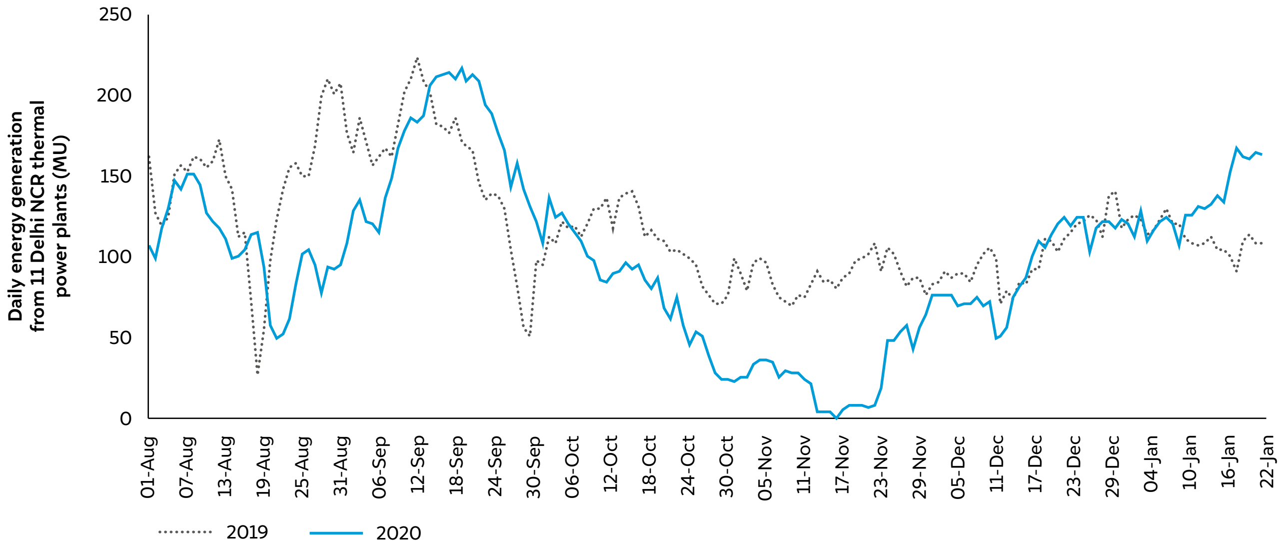
Typically, the period between December and January marks the second episodic 'peaking' of pollution levels in Delhi, following the first episodic peak experienced during the stubble burning phase (Chowdhury et al. 2019). Modelled estimates by UrbanEmissions suggest that the contribution to $PM_{2.5}$ from the residential sector (including domestic cooking, space heating, water heating, and lighting) was as high as 40 per cent in December 2020 and January 2021 (Figure 6). But recent assessments on the use of biomass in Delhi are not available. However, Delhi has seen a significant increase in the penetration of liquefied petroleum gas (LPG) for cooking and water heating purposes and exhibits a 30 per cent higher consumption per household compared to the national average (PPAC 2021).

In addition, Delhi is estimated to have 150,000–200,000 homeless people (IGSSS 2018). The Census of India 2011 refers to 'houseless household' as people in a family who do not live in buildings or census houses but live in the open on roadside, pavements, inhume pipes, under flyovers and staircases, or in places of worship, mandaps, or railway platforms (HRLN 2021). According to the Delhi Urban Shelter Improvement Board (DUSIB), as of January 2021, 319 shelter homes have been created with a boarding capacity of 19,116 people (DUSIB 2021). However, these shelter homes can accommodate only around 10 per cent of the homeless population (approximately 180,000) in Delhi, which leaves a sizeable portion of the city's homeless population exposed to the elements. This population therefore is forced to use firewood/biomass fires to keep themselves warm during winters. Waste is also burnt to provide warmth and for disposal purposes, which also contributes significantly to the pollution burden in the national capital (Bhandari et al. 2020).

3.3.4 Average contribution of emissions from the 11 power plants in Delhi NCR was 7% between October 2020 and January 2021

In Delhi, all coal-fired power plants within the 300 km radius except two units at Dadri Power Plant were shut during the lockdown (first week of April) due to overall reduction in power demand (Aruga, Islam, and Jannat 2020; Myllyvirta and Dahiya 2020). However, with the slow opening up of the regional economy, many plants resumed operations. To gauge the contribution from power plants during winter months, we use power generation data reported by the Central Electricity Authority (CEA) from 11 NCR thermal plants as an indicator. Given the EPCA directives on account of GRAP implementation and presumably low demand due to lockdown, the power plants also operated at much lower levels in October and November 2020 (PTI 2020c; EPCA 2020). We observe that energy generation from NCR coal-fired plants was 25 and 70 per cent lower in October and November, respectively, compared to the corresponding months in 2019 (Figure 12), implying a lower contribution on these months. However, once the 'fuss' about air quality dissipated and demand picked up, the daily energy generation levels scaled up to 2019 levels in December 2020 and January 2021.

Figure 12 Power plants operated at a lower capacity in October and November 2020



Source: Authors' compilation; Daily energy generation data as reported by CEA

3.3.5 Average contribution of emissions from vehicles was 14% between October 2020 and January 2021

Vehicular emissions contribute 17–28 per cent to Delhi's $PM_{2.5}$ levels (TERI and ARAI 2018). The initial phases of the lockdown brought about a significant decline in traffic volume. We use a metric that captures 'congestion level' from TomTom International BV (TomTom 2020) and is indirectly an indicator for on-road traffic volumes. We observe that congestion levels were almost 92 per cent lower in April 2020 compared to the same period last year. As lockdown began to be relaxed and as economic activity resumed in the later half of the year, congestion levels were only 20–25 per cent lower between August and December 2020 than the corresponding congestion levels in 2019 (Figure 13). The lower congestion levels are representative of the reduced traffic volumes and vehicular emissions this 2020.

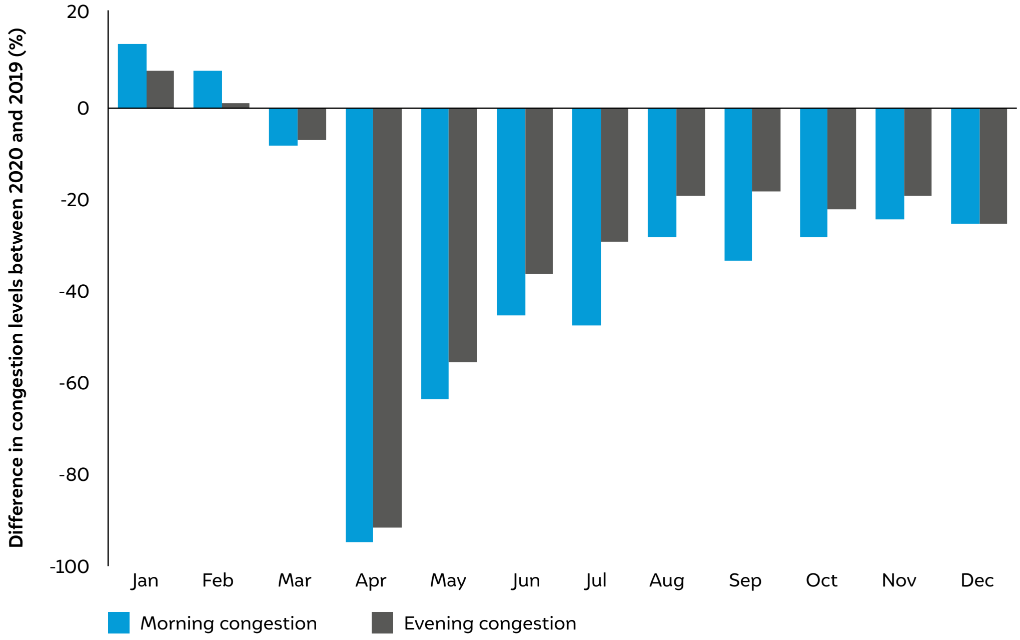


Figure 13
Congestion level bounced back to 80% of the 2019 level during winter 2020

Source: TomTom. 2020. "New Delhi Traffic Report." TomTom Traffic Index. https://www.tomtom.com/en_gb/traffic-index/new-delhi-traffic/.

Note: Congestion level refers to the expected percentage increase in travel time compared to free-flow conditions. Free-flow conditions generally happen during night time but can happen any time of the day

3.4 Meteorological conditions cannot be controlled but emissions can be managed

It is clear now that adverse meteorological conditions in Delhi intensified the impact of local and regional emissions on Delhi's air quality. While meteorological conditions cannot be controlled, emissions can certainly be managed to optimum levels. Chemical transport models (CTM), similar to the one used by UrbanEmissions, are used by atmospheric scientists to simulate meteorological and chemical processes in the atmosphere to provide estimates of pollutant concentrations for a given emission load.

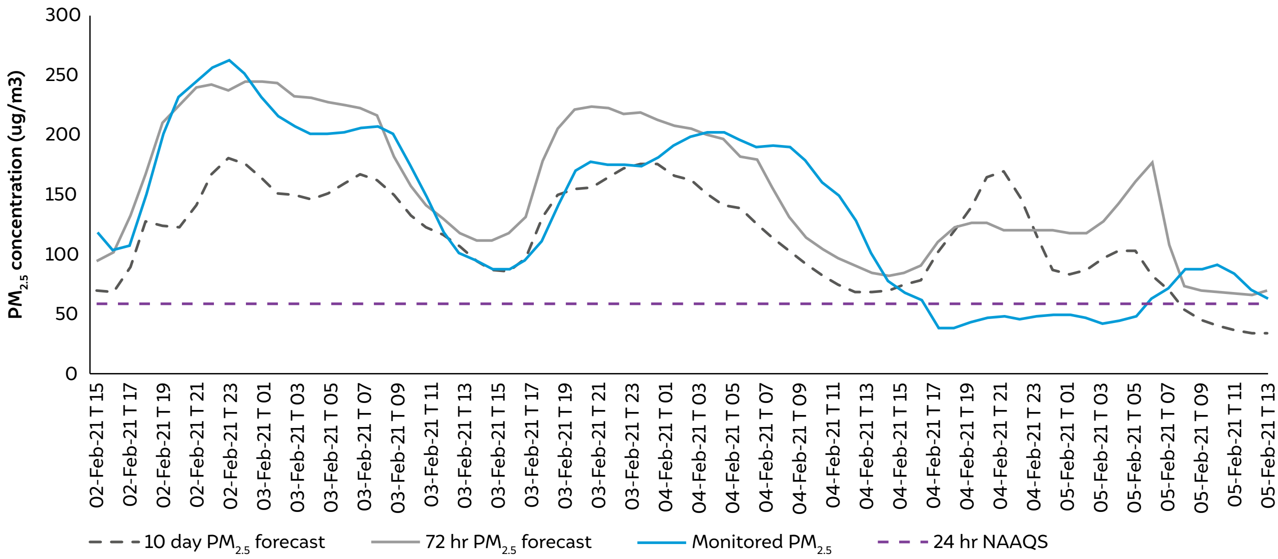
In some countries, emergency measures are rolled out in response to such air quality (AQ) forecasts and not after air quality actually dips to dangerous levels. For instance, Beijing's Ministry of Ecology and Environment issues a red alert if the daily mean citywide air quality index (AQI) is forecasted to be greater than 200 for four days (96 hours) or more; greater than 300 for two days (48 hours) or more; or greater than 500. Alerts are issued 24 hours in advance, and they are withdrawn only if the air quality, as forecasted or monitored, falls below the threshold of that alert level. But alerts are retained if the forecasted levels remain for more than 36 hours (Beijing Municipal Government 2020). In contrast, the Delhi government issues orders to execute emergency measures ex-post, that is, after air quality concentrations reach a certain threatening level. This type of response measures does not prevent the incidence of high pollution. Delhi is the only Indian city for which an 'air pollution emergency plan' was notified by the Ministry of Environment, Forest, and Climate Change (CPCB 2017).

The Indian Institute of Tropical Meteorology (IITM), under the Ministry of Earth Sciences (MoES), issues two air quality forecasts: a 72-hour forecast and a 10-day forecast. The 72-hour forecast is currently being used by MoES to notify health advisories and caution citizens in advance. UrbanEmissions runs a chemical transport model to forecast pollutant concentrations and relative source contribution (UrbanEmissions 2021a). Adding source contributions to air quality forecast can help identify the primary contributors during a particular episode. Integrating air quality forecast with a decision support system would enable the local regulatory agencies to implement emission control interventions 'on-demand' targeting prominent sources during forecasted high-pollution episodes. For example, the government can offer free access to public transit on days when high pollution is predicted levels to reduce vehicular emissions, a practice widely followed in countries like Germany (Biswas Atanu 2019). With radio frequency identification (RFID) tags made mandatory for all vehicles to pay toll fee, the Delhi administration could use this technology also to deploy on-demand congestion and pollution pricing gantries to deter the use of private vehicles during periods when air quality is forecasted to be poor.

Other measures such as travel restrictions, closure of commercial activities, and encouraging work from home on days when forecasted pollution levels would be high certainly can bring down anthropogenic emissions. The accuracy and reliability of these forecasts are therefore critical due to the high cost associated with such emission control interventions (NOAA 2001). While comparing the IITM forecasts, we observe a higher correlation between the monitored $PM_{2.5}$ levels and 72-hour air quality forecast than the 10-day forecast (Figure 14). The lower accuracy of 10-day forecast could be due to the relatively lower reliability of input feeds from 10-day weather forecasts (Cappucci 2019; Voosen 2019; SciJinks 2021; Zhang et al. 2019). Despite its lower reliability, the 10-day air quality forecast could be used to provide air quality outlook for eight to ten days advance, which would improve the preparedness of regulating agencies in executing control measures. Therefore, we recommend that in addition to supporting source identification studies, the government should also encourage air quality modelling and forecasting efforts. Support can be provided in the form of augmenting the existing monitoring infrastructure, which would help air quality modellers validate their forecasts. The state government and the city administration could also work collaboratively with the modellers in developing necessary databases to track emissions from local anthropogenic sources.

Integrating and air quality forecast with a decision support system would enable the local regulatory agencies to implement emission control interventions 'on-demand' targeting prominent sources during forecasted high-pollution episodes

Figure 14 Monitored $PM_{2.5}$ values correlate better with 72-hour forecast than the 10-day air quality forecast



Source: Authors' compilation.

Note: Monitored $PM_{2.5}$—Average $PM_{2.5}$ recorded across 37 continuous ambient air quality monitoring stations in Delhi; 72-hour $PM_{2.5}$ forecast—Hourly AQ forecast from the IITM WRF-Chem model; 10-day forecasted $PM_{2.5}$ values from IITM

Delhi has to move from a system that enforces the Graded Response Action Plan as an ex-post measure to one that prevents the occurrence of high pollution episodes through pre-emptive emission control measures.

Image: iStock

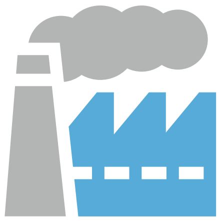
4. Conclusion

"I see skies so blue and clouds so white ... What a wonderful world," wrote Bob Thiele and George David Weiss in 1967.

It took a pandemic and complete shutdown of activities for blue skies and white clouds to appear in Delhi. This respite from year-round air pollution was short-lived and the gains from cessation of activities were lost with the unlock of economic activities and the arrival of winter in Delhi. Despite the reduced activity levels for close to eight months (March to November) in 2020, Delhi residents were exposed to NAAQS non-compliant air for more than half of the year.

Our analysis compared the anthropogenic activity levels and meteorological conditions in 2020 with those in 2019. We also explain how these factors influenced air quality in the winter of 2020. We find that air quality in the winter of 2020 was worse than in the winter of 2019. Lower vehicular congestion and power generation levels in October and November 2020 are indicative of reduced emissions from these two activities. A relatively longer stubble burning period, colder and drier winter conditions, and calmer winds in October and November 2020 were primarily responsible for the worsening Delhi's air quality that year. As the winter season progressed, most anthropogenic activities such as power generation and vehicular levels bounced back to previous year's levels. Household heating and cooking contributed to a significant share (40 per cent) to the pollution burden in December 2020 and January 2021.

We stress that the interplay of meteorological conditions on Delhi's air quality cannot be discounted, but there is need for steeper cuts in emissions across sectors. The GRAP presents the state government with an opportunity to constitute an air quality forecasting cell that can advise the government to take necessary measures to prevent severe air quality episodes in the capital city. We recommend that in addition to supporting source identification studies, the government should also encourage air quality modelling and forecasting efforts. Augmenting the existing monitoring infrastructure would help air quality modellers validate their forecasts. The state government and the city administration could also work collaboratively with the modellers in developing necessary databases to track emissions from local anthropogenic sources.



Interplay of meteorological conditions on Delhi's air quality cannot be discounted, but there is need for steeper cuts in emissions across sectors

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Annexures

Annexure 1: Coal-fired thermal power plants in Delhi NCR

S. No.	Name	State	Capacity (MW)
1	National Capital Power Station (NTPC Dadri)	Uttar Pradesh	1820
2	Guru Hargobind Thermal Power Station (GHTP) Lehra Mohabbat	Punjab	920
3	Harduaganj TPS	Uttar Pradesh	500
4	Aravali Thermal Power Plant (Indira Gandhi STPS) Jhajjar	Haryana	1000
5	Mahatma Gandhi Thermal Power Station (CLP), Jhajjar	Haryana	1320
6	Panipat Thermal Power Station	Haryana	710
7	Rajiv Gandhi Thermal Power Station (RGTPP), Hisar	Haryana	1200
8	Rajpura Thermal Power Plant (Nabha Power)	Punjab	1400
9	Guru Gobind Singh Super Thermal Power Station (GGSSTP), Ropar	Punjab	1260
10	Talwandi Sabo Thermal Power Plant	Punjab	1980
11	Deenbandhu Chhotu Ram Thermal Power Plant (DCRTPP), Yamunanagar	Haryana	600

Source: Authors' compilation

Annexure 2: Details of sources in UrbanEmissions' modelled source apportionment data

Sector	Description
Household	Contribution of domestic cooking, space heating, water heating, and lighting
Road dust	Contribution of re-suspended dust on the roads and construction activities
PP and DGS	Contribution of power plants and in-situ diesel generator sets
Open fires	Contribution of open biomass burning (both agricultural lands and forest areas), a seasonal affair linked to dry conditions and agricultural clearing patterns (supported via satellite feeds)
Waste burning	Contribution of open waste burning
Industries	Contribution of industrial activities
Transport	Contribution of passenger transport (two, three and four wheelers, buses, and aviation) and freight transport (heavy and light trucks, non-road vehicles, and shipping)
Dust erosion	Contribution of wind-blown dust from dry and arid regions, dependent of hourly meteorological conditions
Natural	Contribution of biogenic and sea salt emissions, dependent of hourly meteorological conditions
Others	Contribution of anthropogenic emissions from outside India (and within the modelling domain)

Source: Urban Emissions. 2021. "India Air Quality Forecasts—District Average PM Source Contributions." Accessed 4 February 2021. https://urbanemissions.info/india-air-quality-forecasts/iaqi-pmsa-hourly/.

Annexure 3: Regression results

We run an ordinary least squares (OLS) regression with hourly fire contribution on $PM_{2.5}$ as the dependent variable and meteorological conditions in Delhi and Punjab along with inverse distance weighted (IDW) fires as the independent variables.

IDW Fire Count: Each fire count is weighted to the distance of fire to Delhi and the weight is given by:

$$w_i = \left(\frac{1}{d_i}\right) / \sum_{i=1}^{n} 1/d_i$$

$$IDW_{fires} = \frac{F_1 * \frac{1}{d_1} + F_2 * \frac{1}{d_2} + \ldots\ldots F_i * \frac{1}{d_i}}{\frac{1}{d_1} + \frac{1}{d_2} + \ldots\ldots \frac{1}{d_i}}$$

where d is the distance of fire from Delhi.

We consider the time frame between 28 October and 30 November 2020 for this regression. The R^2 value of the linear regression is 0.48 with F-statistic of 32.83 (p =0.00) and the detailed results of regressors are as follows:

Variable	Description	Coefficient	Std.error	p-value
Punjab_WS_10_Kmph	Wind speed at 10 m in kmph (Delhi)	0.685	0.268	0.011
Delhi_WD_CardinalW	Winds blowing from west direction (Delhi)	10.775	1.951	0.000
Delhi_WD_CardinalNW	Winds blowing from north west direction (Delhi)	11.045	1.696	0.000
IDW_Fire_Count	Distance weighted fire count	0.300	0.084	0.000
IDW_Firelag24	Distance weighted fire count with 24-hour lag	0.552	0.098	0.000
Punjab_WD_CardinalSE	Wind blowing from south-east (Punjab)	-7.618	2.808	0.007
Punjab_WD_CardinalS	Wind blowing from south (Punjab)	-15.353	4.387	0.000
Punjab_WD_CardinalSW	Winds blowing from south-west (Punjab)	-13.379	3.715	0.000
(Intercept)	Intercept	-48.085	55.100	0.383
Delhi_T2m	Air temperature at 2 m height (Delhi)	0.195	0.190	0.307
Delhi_BLH	Boundary layer height (Delhi)	0.001	0.001	0.669
Delhi_Rain	Total precipitation (Delhi)	0.155	3.292	0.962
Delhi_WS_10_Kmph	Wind speed at 10 m (Delhi)	−0.371	0.225	0.100

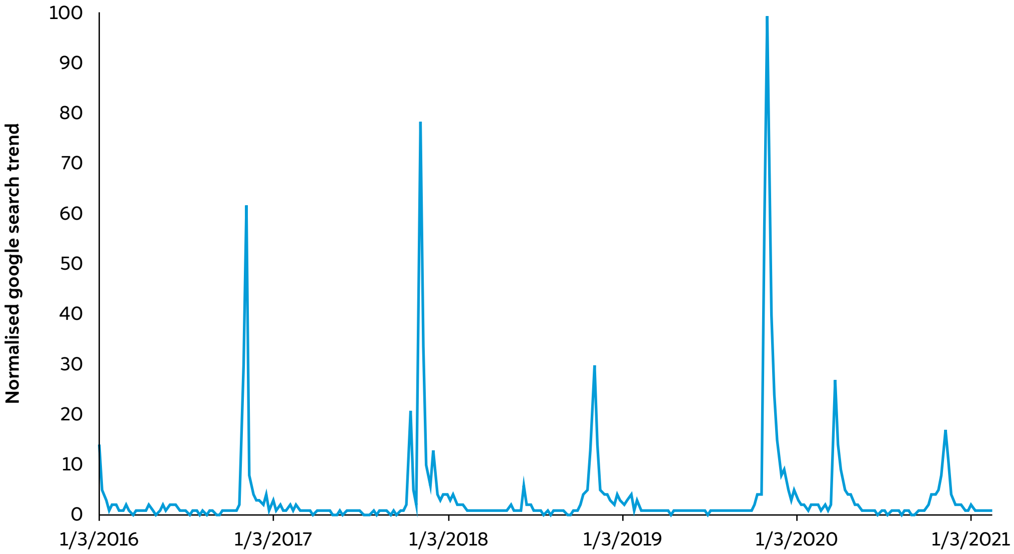
Variable	Description	Coefficient	Std.error	p-value
Delhi_WD_CardinalNE	Winds blowing from north-east (Delhi)	−1.711	2.306	0.458
Delhi_WD_CardinalSE	Winds blowing from south-east (Delhi)	1.239	2.621	0.637
Delhi_WD_CardinalS	Winds blowing from south (Delhi)	−2.140	4.444	0.630
Delhi_WD_CardinalSW	Winds blowing from south-west(Delhi)	7.718	4.020	0.055
IDW_Firelag48	Distance weighted fire with 48-hour lag	−0.152	0.081	0.059
Punjab_WD_CardinalNE	Winds blowing from north-east (Punjab)	1.174	1.816	0.518
Punjab_WD_CardinalE	Winds blowing from east (Punjab)	−3.205	2.260	0.157
Punjab_WD_CardinalW	Winds blowing from west (Punjab)	−1.159	1.901	0.542
Punjab_WD_CardinalNW	Winds blowing from north-west (Punjab)	−1.542	1.403	0.272
Delhi_WD_CardinalE	Winds blowing from east (Punjab)	−1.572	2.271	0.489

Source: Authors' analysis

Note: Green colour-coded variables are significant ($p<0.05$) while the orange colour-coded variable are not

Annexure 4: Interest in the topic 'Air pollution in Delhi' over time

Interest in the topic among public and media peaks only during late October and early November coinciding with stubble burning phase and dies out with the season.

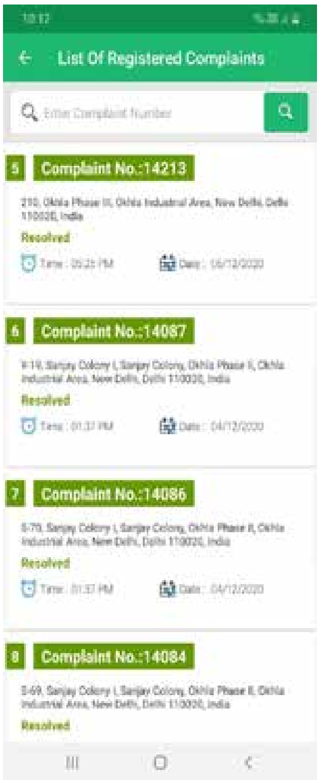


Source: Authors' compilation

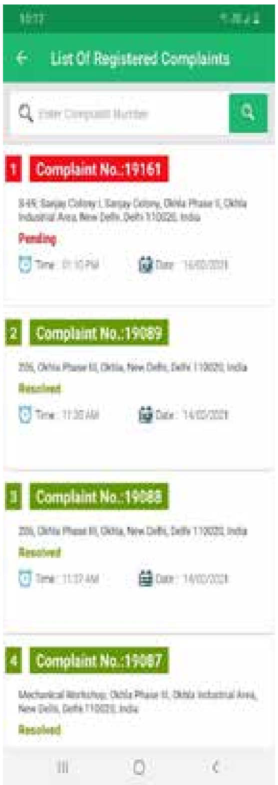
Complaints registered through Green Delhi mobile app publicised by the Delhi government

7,000 complaints as of 17 November 2020

14,000 complaints as of 6 December 2020



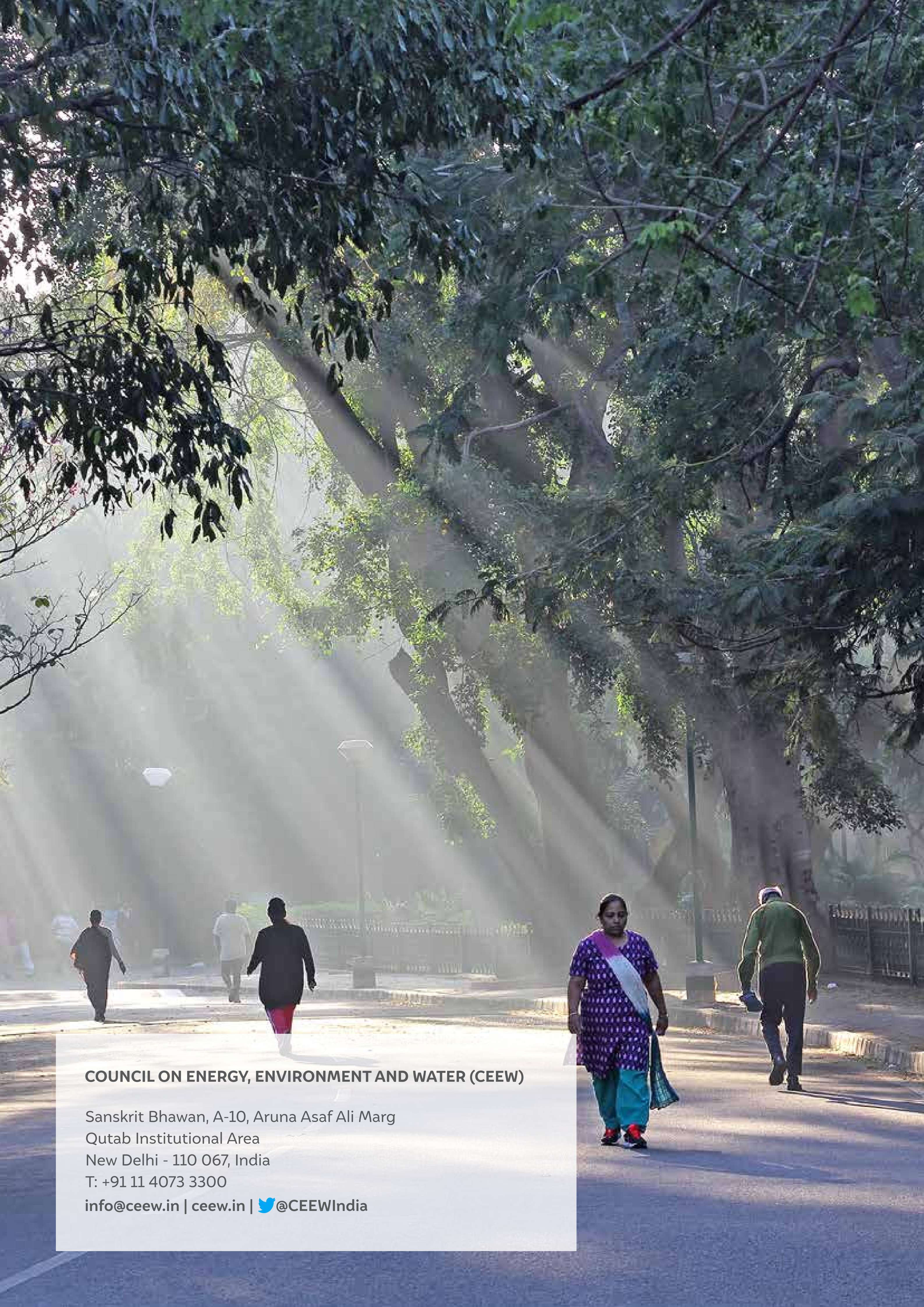
19,000 complaints as of 14 February 2020



Source: Authors' compilation; Screenshots taken from Green Delhi mobile app

Delhi had extremely unfavourable meteorological conditions in the winter of 2020, such as lesser rainfall, more calm conditions, and colder temperatures compared to the winter of 2019.

Image: iStock



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