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Stubble-burning activities in north-western India in 2021: Contribution to air pollution in Delhi

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ABSTRACT

Stubble-burning in northern India is an important source of atmospheric particulate matter (PM) and trace gases, which significantly impact local and regional climate, in addition to causing severe health risks. Scientific research on assessing the impact of these burnings on the air quality over Delhi is still relatively sparse. The present study analyzes the satellite-retrieved stubble-burning activities in the year 2021, using the MODIS active fire count data for Punjab and Haryana, and assesses the contribution of CO and $PM_{2.5}$ from such biomass-burning activities to the pollution load in Delhi. The analysis suggests that the satellite-retrieved fire counts in Punjab and Haryana were the highest among the last five years (2016–2021). Further, we note that the stubble-burning fires in the year 2021 are delayed by ~1 week compared to that in the year 2016. To quantify the contribution of the fires to the air pollution in Delhi, we use tagged tracers for CO and $PM_{2.5}$ emissions from fire emissions in the regional air quality forecasting system. The modeling framework suggests a maximum daily mean contribution of the stubble-burning fires to the air pollution in Delhi in the months of October–November 2021 to be around 30–35%. We find that the contribution from stubble burning activities to the air quality in Delhi is maximum (minimum) during the turbulent hours of late morning to afternoon (calmer hours of evening to early morning). The quantification of this contribution is critical from the crop-residue and air-quality management perspective for policymakers in the source and the receptors regions, respectively.

1. Introduction

Air pollution has been a growing concern for many developing cities across the globe. Delhi often tops the list of the most polluted cities globally [1]. The rapid increase in the air pollution episodes over Delhi and the National Capital Region (NCR), for the past several years, especially in the post-monsoon and the winter seasons, primarily due to steady growth in a broad range of local emission sources such as transportation, industrial power generation, and construction activities, in addition to the seasonal burning of the

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crop-residue (stubble) in the upwind regions of the national capital of India, has posed a greater health risk to a large residential population [2,3]. In the past few years, the increase in $PM_{2.5}$ concentrations observed more commonly in the post-monsoon period in the Delhi-NCR and further down-wind regions [4] has been connected with the open crop-residue burning in the north-western states of India apart from the local emission sources [5–12]. In India, fires are often used as a tool for agricultural management, such as removing residues from paddy cultivation. These fires mainly occur during the post-monsoon season (roughly October–November) due to widespread stubble-burning in preparation for planting the next round of crops [4,13]. A sharp rise in rice production and yields in India, the world's biggest exporter of grain, has exacerbated the problem of crop waste within the two northwestern states, Punjab and Haryana, generating more than 27 million tonnes of rice straw a year [13]· It is estimated that about 46 million tonnes/year of cereal crop residue is generated in Punjab alone, out of which ~21 million tonnes is burnt in a year (~7−8 million tonnes during winter) [14,15]. In Haryana, the total cereal crop residue generated is ~25.73 million tonnes/year, and 9.18 million tonnes are burnt in a year [15]. The coincidence of the fire activities with the unfavorable meteorological conditions such as a stable boundary layer with near-surface temperature inversion results in the cold and polluted air trapped close to the surface, promoting the hazy conditions [16,17]. Due to the greater residence time for pollutants and relatively poorer dispersion owing to the atmospheric inversion, the smoke accumulates in the lower atmosphere posing a greater risk of damage to the health of the residents [18]. Several studies have reported the average $PM_{2.5}$ mass concentration in Delhi during the post-monsoonal season to be crossing at least 120 μg m^{-3} [19–21]. With episodic peaks that can even cross 900 μg m^{-3} especially during the time of Diwali [19]. The non-local fire emissions play an important role in modulating these concentrations. Previous studies have shown that stubble-burning contributes to around 20% of the $PM_{2.5}$ mass concentration in Delhi during the burning season [12,22–24].

Given the aforementioned significance of agricultural burning practices in north-western India to the ambient pollution levels in Delhi-NCR and the northern part of India, we in this study analyze the fire events that occurred over Punjab and Haryana in the post-monsoon season of the year 2021. For that, we use active fire counts information retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the polar-orbiting satellites Aqua and Terra of NASA. Additionally, we analyze the results of the operational air quality forecasting system, the 'Air Quality Early Warning System (AQEWS)' of the Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, India, to understand the contribution of the stubble-burning fires to the air quality in Delhi-NCR in the post-monsoonal months of the year 2021. The AQEWS [25–29], which employs the regional chemistry transport model WRF-Chem, has employed tagged tracers for CO and $PM_{2.5}$ emissions from fires for the first time. With the help of these tracers, we quantify the contribution of stubble-burning to CO and $PM_{2.5}$ mass concentration in Delhi. Such quantification is very critical from the perspective of air-quality management in Delhi.

The details about the data used and the methodology employed can be found in section 2. The results are discussed in section 3. The main conclusions from the study are listed in section 4 of the paper.

2. Data and methodology

Multiple satellite systems play a crucial role in detecting, monitoring, and characterizing fires for location, timing, and burned area of active fires. The National Aeronautics and Space Administration, USA (NASA) provides active fire and burned area products [30] using the MODIS instrument. The MODIS functional fire product onboard the two polar-orbiting satellites, NASA's Terra and Aqua, detects active fires at the time of overpass with a spatial resolution of 1-km under relatively cloud-free conditions. We use the daily active fire counts data from MODIS for the period 15th September to 15^{th}December of 2021 to detect the fires over the states of Punjab and Haryana. Additionally, we also examine similar data for 2016 to 2020 to compare and contrast with the year 2021.

To quantify the contribution of stubble-burning to the air quality in the Delhi-NCR region, we use the AQEWS of IITM, Pune. The AQEWS employs the online regional chemistry transport model, Weather Research and Forecasting with Chemistry (WRF-Chem version 3.9.1). Several previous studies have already evaluated the ability of WRF-Chem model in simulating aerosol loading over the Indian region [31–40]· The model domain in our study covers the Northern part of India with a resolution of 10 km. The MOZART-4 gas-phase chemistry linked to the GOCART aerosol scheme (MOZCART) is used in the model to simulate aerosol and gas-phase chemistry. The anthropogenic aerosol and trace gas emissions are derived from version 2.2 of the Emission Database for Global Atmospheric Research-Hemispheric Transport of Air Pollutants (EDGAR-HTAP) [41]. However, specifically for Delhi and the 19 districts surrounding it, we employ the anthropogenic emissions inventory prepared by The Energy Research Institute (TERI) [42]. The Biogenic emissions are employed using the Gases and Aerosols from Nature (MEGAN) model. The static geographical fields such as soil properties, vegetation fraction, and land-use pattern are taken from MODIS datasets. The fire emissions are generated by making use of climatological data from the Fire Inventory from NCAR (FINN v1.5) [43] at 1×1 km^2 resolution and the active fire count information from MODIS and Visible Infrared Imaging Radiometer (VIIRS) fire products [28]. The methodology makes use of the near real-time fire count information to trigger climatological FINN fire emissions for the pixels with non-zero fire counts [28]. The use of near-real-time fire count information for generating fire emissions in AQEWS enhances its ability to capture severe air-quality episodes occurring in the northern states of India [4]. The AQEWS system is initialized with the Global Forecast System (GFS) forecast run at the Indian Institute of Tropical Meteorology, Pune, India. The system assimilates near-real-time aerosol optical depth retrieved by MODIS instrument and that measured by over 260 Central Pollution Control Board (CPCB) monitoring stations across India. The necessary quality control filters are applied to the data, as mentioned in the previous study [28]. The assimilation is carried out using the three-dimensional variational (3DVAR) scheme of the community Gridpoint Statistical Interpolation (GSI) system version 3.5, similar to above study [28]. The fire emissions of CO and $PM_{2.5}$ are traced in the domain using the tagged-tracer approach [44,54]. These tracers enable the identification of CO and $PM_{2.5}$ originating from fires and thus help quantify the contribution of fires to the total CO and $PM_{2.5}$.

3. Results and discussion

3.1. Stubble-burning fires in the north-western states of India in the year 2021

The spatial locations of the fires from the MODIS active fire count data for the period September 15, 2021 to December 15, 2021, over the north Indian region, are shown in Fig. 1a. The colours indicate the number of fire counts observed at each pixel over the entire season. It can be seen that over the two north-western Indian states, namely Punjab and Haryana, the fire counts at individual pixels exceed the count 250 over many locations. In fact over Punjab, the count 250 is crossed at every fire location. There is a gradient in fire count in the north-west to south-east direction. The peak is observed in Punjab and north-western parts of Haryana, beyond which the counts reduces as one approaches Delhi and Uttar Pradesh. The count is very low in the state of Uttar Pradesh possibly linked with lesser harvest of Wheat in the state [45]. The neighboring states of Rajasthan, Himachal Pradesh, and Uttaranchal show scattered locations of high number of fire counts. Fig. 1b shows the total number of active fire counts in Punjab and Haryana on a daily basis for the study period. The daily active fire counts depict episodic behavior, with several incidents of a sudden rise in fire counts encapsulated by relatively calmer days. The fire counts reached their peak in the first week of November 2021. Though the fires increased relatively gradually from mid-September to reach the peak in November, they dropped down hurriedly after reaching the peak, with a substantially reduced number of fires after the November 22, 2021. Similar analyses has been carried out by a few previous studies for fire counts in Haryana in the year 2019 [9] and for the four states of Punjab, Haryana, Uttar Pradesh and Delhi from 2016 to 2020 [7]. Compared to the last five years (2016–2020), the fires in Punjab and Haryana in 2021 depict a distinct behavioral pattern. The cumulative MODIS active fire counts from Punjab and Haryana for 15th September to 15th December for the last six years are shown in Fig. 1c. It may be noted that the fire counts gradually increase in the first month before rising rapidly at the start of the second month. The year 2021 shows a relatively subdued first half of the fire season from 15th September to 15th October, with the fire count being the lowest in the last six years. The cumulative fire count on October 15, 2021 is ~2500, while those for the last five years range between 3500 and 8000. However, in the next 30 days, the fire counts in 2021 have increased rapidly to surpass the cumulative count for the last five years on 15th November. Additionally, we also notice a consistent temporal shift in the fire counts over the last six years, e.g., for 2016, a cumulative count of 4000 is achieved by 9th-10th of October, but for the year 2021 by 17th-18th of October. Thus, there is a clear shift of a week or so in the occurrence of the stubble-burning fires from 2016 to 2021. Our results are consistent with the previous studies[[3,46,47]] which report such shift in the burning activities in Punjab and Haryana. The studies attribute the shift to the implementation of a groundwater preservation act in Punjab Haryana post 2010. This act ensures that the farmers make use of monsoonal rains for the cultivation of the crops instead of the already depleting ground water. This delays the harvesting of the

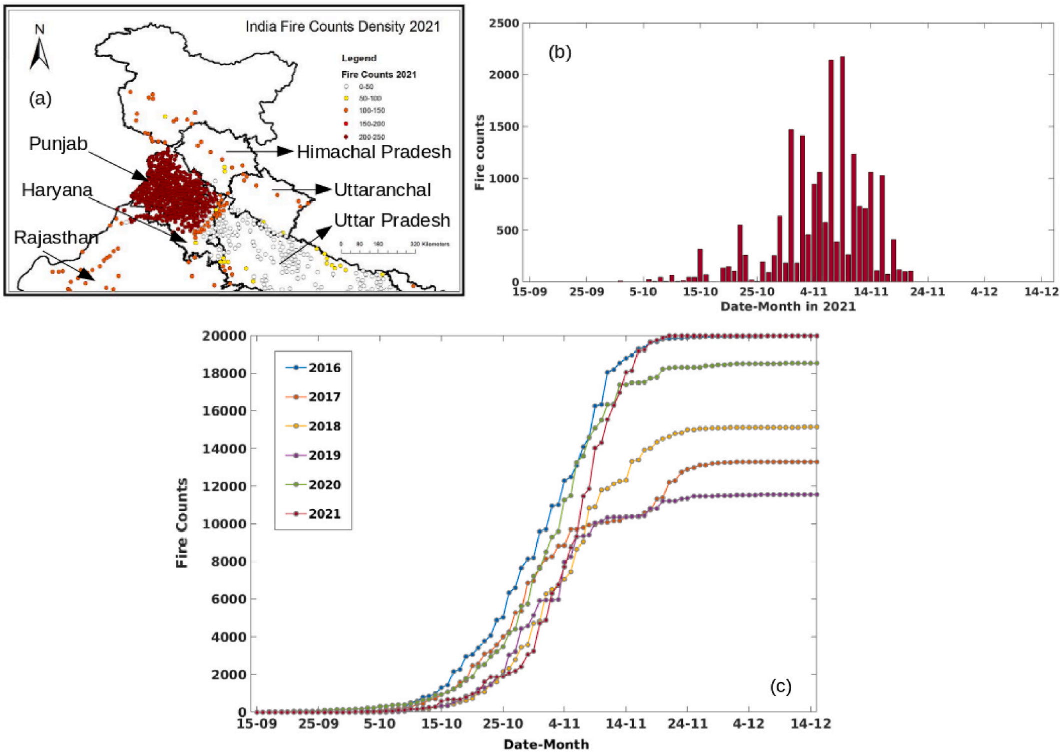

Fig. 1. (a) Spatial distribution of MODIS active fire counts' density in northern India during 15th September 2021–December 15, 2021. b). Daily active fire counts in Punjab and Haryana during 15th September 2021–December 15, 2021. c). Accumulation of MODIS active fire counts over Punjab and Haryana during 15th September - 15th December of the years 2016 to 2021. The states are identified with their names in Fig. 1a.

Kharif crops into November instead of October as in the pre-2010 era. As a result, the burning of the stubble also gets delayed by 10–12 days [3,46,47].

3.2. Contribution of the stubble-burning fires to the air quality in Delhi

We use the AQEWS to understand the contribution of stubble-burning to the air quality in Delhi during the study period of the year 2021. Before examining the contribution of fires to the air quality in Delhi, we briefly evaluated the performance of AQEWS for the study duration. Much formal evaluation of AQEWS has already been carried out in recent studies [27,28,38]. The hourly and daily variation of $PM_{2.5}$ mass concentration (μg m^{-3}) is shown in Fig. 2a and b respectively. The time series is generated by averaging the data obtained from Delhi. The blue line in the panels indicates the data obtained from the 38 CPCB observational stations whereas the red line shows the AQEWS forecasted $PM_{2.5}$. The simulated results are in good agreement with the observations.

It can be observed that there is a shooting of $PM_{2.5}$ mass concentration on 17th October and again on 21st October. Also, during the late hours of 4th and November 5, 2021, a sharp peak (900 μg m^{-3}) can be observed in $PM_{2.5}$ concentration, this huge rise in $PM_{2.5}$ could be contributed from the burning of crackers and fireworks during Diwali night and the day after, however in the next section we would explore the contribution of stubble-burning fires to this severe air pollution episode. The air quality thereafter remains poor till 11th November and starts improving henceforth. From Fig. 2b, it can be seen that after 14th November the simulation results slightly overestimated the observed values by an average of approximately 60 μg m^{-3}. This reduction in the observed $PM_{2.5}$ is specifically associated with the improvement in the air-quality due to the imposed restrictions by the Government of Delhi and the Commission for Air Quality Management in Delhi and the adjoining areas (CAQM) (https://www.dpcc.delhigovt.nic.in//uploads/pdf/Directions16-11-2021pdf-30033b0c97ed9df8044c3f1a0eb16961.pdf). The AQEWS system on the other hand did not employ such a reduction emission in its formulation. Nevertheless, apart from such episodic disparities the AQEWS simulated $PM_{2.5}$ in Delhi confirms well with the observations.

We used tagged tracers employed in the AQEWS to understand the contribution of stubble-burning fires to $PM_{2.5}$ over Delhi. We first analyze the carbon monoxide emitted from fires (CO_{fire}). The temporal variation of the CO_{fire} concentration (Parts Per Billion by Volume, ppbv) during the post-monsoon season of the 2021 over Delhi is shown in Fig. 3a. The figure indicates the rise in atmospheric CO concentration associated with fires as the burning season progresses. Fig. 3a is in agreement with Fig. 2 in terms of deterioration of air quality over Delhi. Every year major crop residue burning activities occur during this season in Punjab and Haryana which continues for almost a month or two, as shown in Fig. 1. Such a biomass burning activity has a significant connection with the degradation of air quality even during the pre-monsoon season over NCR and IGP [48–50]. The peaks in Fig. 3a coincide with the crop residue burning events over Haryana and Punjab (Fig. 1). The high peak events occurring during 6th-11th Nov, contribute an average of ~400 ppb of CO to the local atmosphere of Delhi. The highest contribution of 550 ppb of CO is observed on November 9, 2021 which accounts for 30% of the total CO over the Delhi region (Fig. 3b). The western disturbances start prevailing during the post-monsoon season which carries the smoke over NCR from the Haryana, Punjab, and other north western regions of the adjoining areas where the biomass burning amplifies. One such example of the intrusion of a plume of pollutants from Punjab and Haryana into the atmosphere of Delhi is shown in Fig. 3c. The shaded quantity is CO_{fire} while the vectors denote the magnitude and direction of 10-m winds during one particular hour (03 UTC) of November 7, 2021. It can be very clearly seen that the CO emitted from the fires in Punjab-Haryana finds its way not only up to Delhi but also downwind into the central Indo-Gangetic Plains. The CO generated from

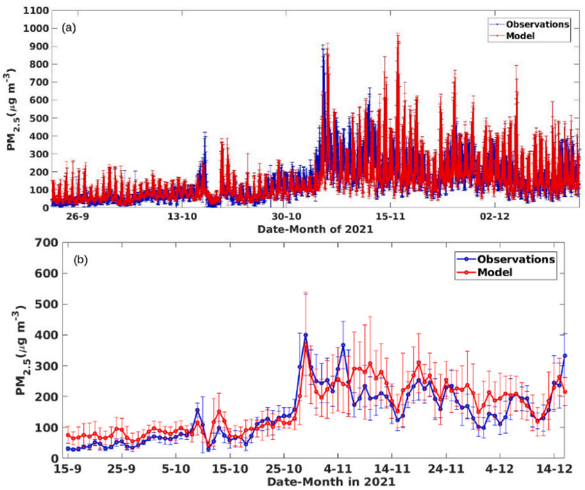

Fig. 2. Time series of (a) hourly and (b) daily variation of observed (blue line) and simulated (red line) $PM_{2.5}$ (μg m^{-3}) averaged over 43 stations covering NCR and adjoining areas. The dataset covers the period from September 15, 2021 to December 15, 2021. The location and names of the 43 stations can be found in Fig. 1 of Sengupta et al., 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

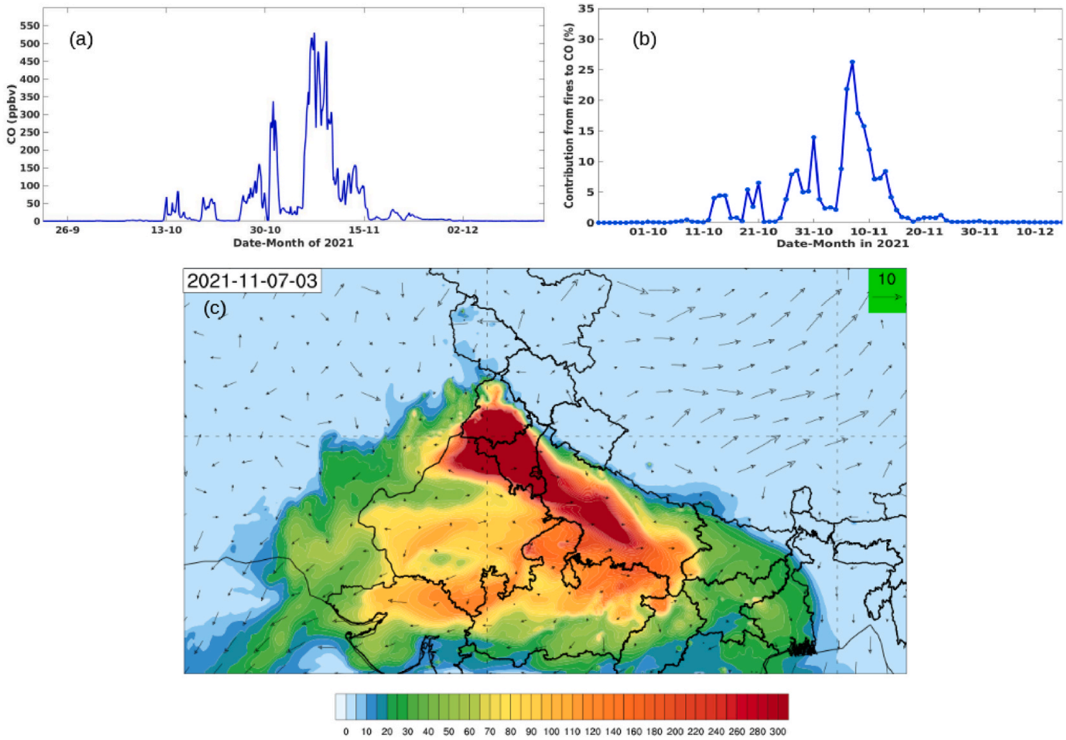

Fig. 3. Temporal variation of (a) the hourly magnitude (b) the daily percentage contribution of CO from fire emissions in the total simulated CO in Delhi from September 22, 2021 to December 15, 2021. (c) Spatial distribution of CO_{fire} on during 03 UTC hours of November 7, 2021. The contours indicate CO magnitudes in ppbv while the vectors denote wind speed and direction at 10 m height above the surface.

such fires in north-central India is even seen to affect the air quality in the far-eastern states of West Bengal and Odisha before heading into the Bay of Bengal (Fig. 3c). While the non-local fires affect the air quality of entire north-central India, the effect is the maximum over Delhi and the nearby locations.

In addition to CO, we analyze the contribution of fires to PM2.5 in Delhi by using the tagged-tracer within AQEWS for $PM_{2.5}$ associated with fire activities. The percentage of fractional contribution of biomass burning to $PM_{2.5}$ mass concentration over Delhi for the period 6th October-17th November 2021, as obtained from AQEWS can be seen in Fig. 4. The contribution of fires to $PM_{2.5}$ in Delhi (Fig. 4) confirms the trend the CO_{fire} shows (Fig. 3b). It also maximizes during the periods of the peak in the fire activity (1st week of November 2021) (Fig. 1b). The highest daily mean contribution from fires to the $PM_{2.5}$ in Delhi is ~35–40%, which occurs during the peak of the fire activities. If Figs. 2 and 3 are examined together, we can see that most of the peaks in fire CO contribution & $PM_{2.5}$ are in phase with Fig. 4 peaks. In contrast, the $PM_{2.5}$ peak during the 4–5 November (Diwali night) is not present in Fig. 4, which indicates the separation and filtering of $PM_{2.5}$ contribution from stubble-burning to other sources. Our results show consistency with the previous estimates of the contribution of stubble-burning to the air quality in Delhi [11]· Such quantification of the contribution of fires to the air quality in Delhi-NCR is very critical from the perspective of air quality management. Based on such information, several policy-level

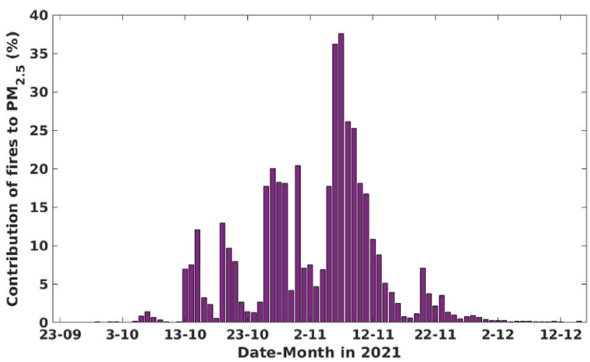

Fig. 4. Fractional contribution of stubble-burning fire to the $PM_{2.5}$ mass concentration in Delhi for the period 23rd September-15th December 2021, as obtained from AQEWS.

decisions could be taken regarding the stubble-burning activities in Punjab and Haryana. Moreover, the authorities could also understand the quantitative significance of local and non-local emissions to $PM_{2.5}$mass concentrations in Delhi through such quantifications.

3.3. Diurnal variation in contribution of stubble burning to the air quality in Delhi

The stubble burning occurring in the states of Punjab and Haryana is a relatively distant source of pollutants as far as Delhi is concerned. In Fig. 5, we show the model-simulated mean diurnal variation in the contribution of stubble burning activities to the $PM_{2.5}$ load in Delhi, for the period of October 1, 2021 to November 30, 2021 (blue line, Fig. 5). To clearly understand this contribution, we compare and contrast it with the diurnal variation in the contribution of local emission sources (such as vehicles, industries, power plants, residential sources etc.) to the $PM_{2.5}$ burden in Delhi (orange line, Fig. 5). The contribution of local sources has been computed using the similar tagged tracer approach discussed in section 2. The stubble burning contribution maximizes in the afternoon hours around 15:30 local time. It is comparatively low during evening to early morning hours. It systematically increases from 8.30 local time to reach its maxima in the afternoon. On the contrary, the contribution from the local sources to the $PM_{2.5}$ in Delhi is seen to be the highest during the evening to early morning hours. It smoothly decreases down from 8:30 local time to reach its minima around 14:30 local time. Beyond that, it once again starts increasing and attains its daily maxima in the late evening hours.

This peculiar behavior of the distant (e.g. stubble burning) and the local sources in relation to the air quality in Delhi mainly appears to be driven by the evolution of boundary layer dynamics and winds within the atmospheric boundary layer during day and night time. During the hours of evening to early morning the winds are calm and boundary layer is shallow, which together limit the horizontal and vertical transport of pollutants. As a result they remain more in the vicinity of the sources. Hence, we see more dominance of the local sources to the $PM_{2.5}$ mass in Delhi during those hours. On the other hand, during the turbulent hours of day time, the winds are relatively stronger and boundary layers are relatively deep allowing enhanced three dimensional advection of pollutants away from the sources. This results in increased contribution from the distant sources like stubble burning and reduced contribution from the local sources to the pollution load in Delhi. The pollutants getting emitted from the local sources within Delhi would travel in the downwind region during such turbulent day time hours allowing the distant sources to dominate the PM budget. In this manner the boundary layer dynamics and winds decide which sources would dominate the air quality in Delhi. Unraveling this behavior of the local and distant sources in association with the air quality in the city is critical from the perspective of air quality management. The decision makers could take important policy level decisions about the distant stubble burning activities as well as the local anthropogenic activities based such results. Based on this analysis, we find that discouraging stubble burning activities in Punjab and Haryana occurring especially in the afternoon hours would be an effective policy as far as the air quality in Delhi is concerned.

Through this study, we shed light on the contribution of stubble burning activities to the air quality in Delhi. We also show that the contribution is the highest during the afternoon hours. However, revealing such information through numerical models with realistic fire emissions has been and continues to be a very challenging task. The satellite retrieval of fire counts, which is used to generate fire emissions in the model, could be posed with multiple shortcomings. A previous study has reported some dips or gaps in the regional total Fire Radiative Power (FRP) due to large parts of clouds, haze, and smoke [51]. The persistent, dense haze decreases brightness temperature over a broad region, thereby interfering with the detection of thermal signatures of small fires by the thermal infrared bands of MODIS and VIIRS. One other major issue is that the farmers are getting better at avoiding fire detections. Fires are often set in the late hours of the day or on cloudy days to avoid detection by the satellites. High PM concentration levels and low fire counts on the preceding days of rains indicate that high burning activity takes place on those days under cloud cover. Additionally, sometimes the stubble is collected over a small region of the field, and it is then burnt to avoid detection by the footprint of the satellites. Another critical issue is related to the temporal frequency of the pass of the polar-orbiting satellites. The satellites pass over the Indian region once a day in the morning to afternoon hours. So, fires occurring over all other times of the day are likely to be missed by the satellites. Additionally, an underestimation of crop residue burning emissions from Haryana and UP has been reported due to missing out on detecting partially burnt areas in these regions [52]. Many studies estimate the emissions from stubble-burning relying on the

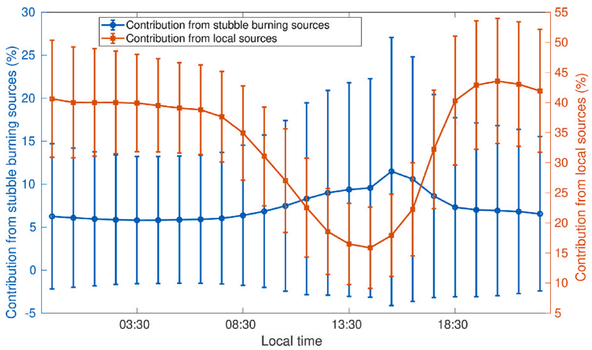

Fig. 5. Diurnal variation of contribution of stubble burning and local sources to the $PM_{2.5}$ mass concentration in Delhi, for the period of October 1, 2021 to November 30, 2021.

residue-to-product ratios. The rice stubble that is actually burnt on the field is mostly unaccounted for and leads to an underestimation of emissions by a factor of about 2–3 [53]. Thus, all the aforementioned limitations hamper satellites' detection of stubble-burning over Punjab and Haryana. These uncertainties will translate into the uncertainties in the model-estimated contribution of fires to the air quality in northern India. Nevertheless, our study possibly gives a lower bound to the contribution of stubble-burning fires to the air quality in Delhi, albeit with the uncertainties mentioned above.

4. Conclusions

To understand the evolution of the stubble-burning season in north-western India in the year 2021, we examined the satellite retrieved fire count data. We examined the data in light of the fire count data for the last 5 years over the same region. We further used the air quality forecasting system of IITM Pune (AQEWS) to understand the contribution of such stubble-burning fires to the air quality in Delhi in the year 2021. The salient conclusions from the study are as follows:

1. The active fire count data from the MODIS instrument in 2021 depicts the highest stubble-burning activity in Punjab and Haryana compared to the last five years.
2. While the count was the lowest in the first month of the burning season compared to the previous five years, it rose rapidly, reaching around ~20000 towards the end of the season.
3. A temporal shift (delay) of around one week is noticed in the stubble-burning activity in the year 2021 compared to the year 2016.
4. The tagged tracers for CO and $PM_{2.5}$ from fires in the AQWES air quality forecasting system indicate that the mean daily contribution of stubble-burning to the air quality in Delhi reached around 30–35% in the burning season of 2021, with its maxima occurring in the first week of November 2021.
5. The results of the study are valuable to policymakers in order to understand the evolution of the stubble-burning activities in the year 2021 and to get a quantitative idea about their contribution to the air quality in Delhi.
6. We find that the contribution from stubble burning activities to the air quality in Delhi is maximum (minimum) during the turbulent hours of late morning to afternoon (calmer hours of evening to early morning). This behavior is largely controlled by atmospheric boundary layer dynamics and lower tropospheric winds.

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Data availability statement

The MODIS data is available online on https://firms.modaps.eosdis.nasa.gov/ (last accessed on 31st May 2022). The data for model simulations can be made available upon a reasonable request to the corresponding authors.

Author contribution statement

Sachin D. Ghude; Gaurav Govardhan; Santosh Kulkarni: Conceived and designed the experiments.
Gaurav Govardhan; Rupal Ambulkar: Performed the experiments.
Sachin D. Ghude; Gaurav Govardhan; Rupal Ambulkar analysed and interpreted the data. All authors wrote the paper.

Ethics declarations

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

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.

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