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Seasonal impact of regional outdoor biomass burning on air pollution in three Indian cities: Delhi, Bengaluru, and Pune

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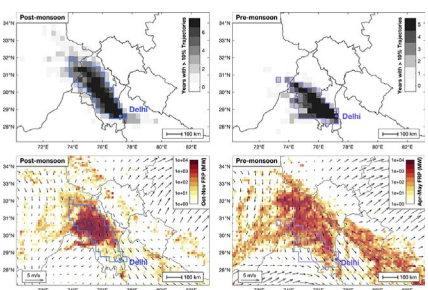
GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution in many of India's cities exceeds national and international standards, and effective pollution control strategies require knowledge of the sources that contribute to air pollution and their spatiotemporal variability. In this study, we examine the influence of a single pollution source, outdoor biomass burning, on particulate matter (PM) concentrations, surface visibility, and aerosol optical depth (AOD) from 2007 to 2013 in three of the most populous Indian cities. We define the upwind regions, or "airsheds," for the cities by using atmospheric back trajectories from the HYSPLIT model. Using satellite fire radiative power (FRP) observations as a measure of fire activity, we target pre-monsoon and post-monsoon fires upwind of the Delhi National Capital Region and pre-monsoon fires surrounding Bengaluru and Pune. We find varying contributions of outdoor fires to different air quality metrics. For the post-monsoon burning season, we find that a subset of local meteorological variables (air temperature, humidity, sea level pressure, wind speed and direction) and FRP as the only pollution source explained 39% of variance in Delhi station PM_{10} anomalies, 77% in visibility, and 30% in satellite AOD; additionally, per unit increase in FRP within the daily airshed (1000 MW), PM_{10} increases by 16.34 μg m^{-3}, visibility decreases by 0.097 km, and satellite AOD increases by 0.07. In contrast, for the pre-monsoon burning season, we find less significant contributions from FRP to air quality in all three cities. Further, we attribute 99% of FRP from post-monsoon outdoor fires within Delhi's average airshed to agricultural burning. Our work suggests that although outdoor fires are not the dominant air pollution source in India throughout the year, post-monsoon fires contribute substantially to regional air pollution and high levels of population exposure

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around Delhi. During 3-day blocks of extreme $PM_{2.5}$ in the 2013 post-monsoon burning season, which coincided with statistically significant high fire activity, concentrations in Delhi averaged 304 μg m^{-3}, or more than 1000% above the 24-h $PM_{2.5}$ guideline (25 μg m^{-3}) of the World Health Organization. These results suggest that providing viable alternatives to agricultural residue burning could help improve post-monsoon air quality for a growing population of 63 million (39% in urban areas) within Delhi's airshed.

1. Introduction

More than half of the Indian Subcontinent's population is exposed to average annual fine particulate matter (diameter less than 2.5 μm; $PM_{2.5}$) concentrations that surpass the least stringent annual $PM_{2.5}$ guideline (35 μg m^{-3}) of the World Health Organization (WHO); mean annual $PM_{2.5}$ in 49% of the subcontinent's inhabited area exceeds the most stringent 10 μg m^{-3} guideline (Dey et al., 2012; WHO, 2006). Recent global air pollution studies highlight the public health importance of improving air quality in India, where approximately 600,000 annual premature deaths are attributable to outdoor air pollution, ranking second only to China (Lelieveld et al., 2015; Ghude et al., 2016; WHO, 2016). $PM_{2.5}$ exposure is associated with an average lost life expectancy of 3.4 years across the country and up to 6.4 years in Delhi (Ghude et al., 2016). Air pollution in India is a growing threat to public health, especially in high-density population centers exposed to high concentrations of particulate matter.

Controlling air pollution in India is challenging because of complex interactions between local and regional sources (Kumar et al., 2015a). Due to atmospheric transport, areas with higher aerosol emissions do not always correspond to higher aerosol concentrations (Kishcha et al., 2014). Across the country, the most common anthropogenic emissions sources are from vehicles, manufacturing, electricity generation, construction and road dust, waste burning, and household energy use (Guttikunda et al., 2014; CPCB, 2011, Gargava and Rajagopalan, 2015a; 2015b; Sharma and Dikshit, 2016). Even single sources can have large health impacts. For example, emissions from coal-fired power plants have increased by 70% since the mid-1990s (Lu and Streets, 2012), and 111 coal-fired power plants across the country were linked to an estimated 80,000–115,000 premature deaths due to $PM_{2.5}$ exposure in 2010–2011 (Guttikunda and Jawahar, 2014). Despite implementation of different air quality policies, population growth, increasing living standards, and the concomitant demand for transportation, energy, and industry have contributed to increasing PM pollution levels over the past decade (Gurjar et al., 2016; CPCB, 2012). Rising emissions, especially when coupled with population growth, are expected to increase the future burden of population exposure to air pollution (Lelieveld et al., 2015; Guttikunda and Jawahar, 2014), underscoring the need to better understand how different sources impact air pollution.

Several previous studies have examined air quality in Delhi National Capital Region (NCR; hereafter referred to as Delhi). During 2007–2008, more than two-thirds of $PM_{2.5}$ samples exceeded the national ambient air quality 24-h standard of 60 μg m^{-3} (Tiwari et al., 2013; CPCB, 2009), with the highest exposure in the winter when atmospheric conditions are typically more stable and surface ventilation is weak (Tiwari et al., 2013, 2014a). In Delhi, previous efforts to control pollution in the early 2000s, such as converting all commercial vehicles to compressed natural gas and closing polluting industries, helped to improve respiratory health (Foster and Kumar, 2011), but these gains may be now overshadowed by the increased vehicle population (Gurjar et al., 2016). Air pollution studies in other Indian cities are more limited, but also consistently show significant exceedances of air pollutant concentrations over national and international standards. In 2010, annual average PM_{10} concentrations in six Indian cities (Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot) ranged from 73 to 119 μg m^{-3}, all above the national standard and corresponding to 15,200 premature deaths per year, with contributions from industrial activities, transportation, and road dust (Guttikunda and Jawahar, 2012).

In addition to the contributions of urban sources to air quality degradation, outdoor fires are a regional air pollution source dominated by fires in agricultural regions (Vadrevu et al., 2008). Particularly in northern India, fires are mostly from residue burning, which peaks in April to May (pre-monsoon) and October to November (post-monsoon), corresponding to burning after the wheat and rice harvests, respectively (Vadrevu et al., 2011; Venkataraman et al., 2006). In the region of Punjab, mechanized harvesting has reduced the need for manual labor in the past two to three decades. However, the scattered, root-bound crop residue left behind by combine harvesters is difficult to remove, and burning is usually the fastest and cheapest method to clear fields for the next planting (Gadde et al., 2009; Kumar et al., 2015b). An estimated 7–8 million tonnes of rice residue associated with post-monsoon agricultural burning are burned each year in Punjab, India (Kumar et al., 2015b).

Wheat and rice residue burning releases accumulation mode aerosols that mostly contribute to the $PM_{2.5}$ fraction (Hays et al., 2005). Post-monsoon burning lasts for several weeks and is associated with increased AOD across the Indo-Gangetic Plains (IGP); in contrast, pre-monsoon fires are not the dominant contributor to air quality degradation (Vadrevu et al., 2011; Singh and Kaskaoutis, 2014). Atmospheric trajectory analysis shows aerosol plumes traveling eastward from northwestern India across the IGP (Kaskaoutis et al., 2014; Vijayakumar et al., 2016; Mishra et al, 2012). Satellite-based studies of post-monsoon burning in the Indo-Gangetic Basin (IGB) have shown elevated layers of aerosols from the surface to 4–4.5 km altitude, with peak concentrations below 1 km (Mishra and Shibata, 2012). Ground measurements in northwestern India also show increases in aerosol, SO_2, and NO_2 concentrations during rice and wheat burning periods (Mittal et al., 2009).

In this study, we investigate the contribution of a single pollution source, outdoor biomass burning, to PM concentrations (as well as surface visibility and AOD) from 2007 to 2013 in three of India's populous cities (Delhi, Bengaluru, and Pune) by combining satellite fire observations, atmospheric trajectory modeling, and ground and satellite-based air quality observations. We focus on these three cities because they consistently had the highest fire activity in their surroundings relative to other major cities. We specifically address the following questions: 1) In which of the three Indian cities considered in this study are PM concentrations most affected by outdoor fires in their surroundings; 2) In which seasons do outdoor fires upwind of the three Indian cities most strongly affect PM concentrations through transport of emissions to cities; 3) To what extent are PM concentrations from outdoor burning in airsheds of India cities attributable to agricultural burning versus other fire types; and 4) How many people are exposed to degraded air quality from outdoor fires in the airsheds in these Indian cities?

2. Data and methods

2.1. Fire activity

We quantify fire activity with MODIS daily maximum fire radiative power (FRP) observations over India from January 2007 to December 2013. MODIS FRP estimates the amount of energy released by a fire (Wooster et al., 2005) and has been previously used to estimate variability in fire activity over time and by land cover type in India