

Environmental Association of Burning Agricultural Biomass in the Indus River Basin

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Key Points:

- The concentration of smog constituents is above threshold throughout the year
- Stubble burning acts as a catalyst to an already polluted environment
- The farming community perhaps should not be solely liable for smog events

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

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Abstract Intensification of smog episodes, following harvesting of paddy crops in agricultural plains of the Indus basin in the Indian subcontinent, are often attributed to farming practice of burning standing stubble during late autumn (October, November) months. Biomass burning (paddy stubble residual) is a preferred technique to clear farmlands for centuries by farmers in that basin. However, despite stable agricultural landholding and yield, smog is being increasingly associated with burning agricultural biomass, thus creating a paradox. Here, we show that the concentration of smog (NO_x, PM_{2.5}, SO₂) in the ambient air exceeds the safe threshold limits throughout the entire year in the region. This study argues that agricultural biomass burning is an ephemeral event in the basin that may act as a catalyst to a deteriorated air quality in the entire region. Results further demonstrate that simultaneous saturation of air pollutants along with high ambient moisture content and low wind speeds following the monsoon season are strongly related to aggravated smog events. Findings from this study should help make holistic mitigation and intervention policies to monitor air quality for sustainability of public health in agricultural regions where farming activities are a dominant economic driver for society.

Plain Language Summary Northern central Indus and northwestern Ganges basin experienced intense smog incidents post-monsoon-post harvesting season. Smog in this region is primarily characterized by premature mortality, low visibility, eye irritation, and damage to crops, but the recent intensification of these episodes had raised an overdue concern. Due to the specific temporal existence of these episodes, it has been associated with the practice of residual crop burning. Using in-situ and remote sensing data, we have shown that significantly high concentration of smog in the ambient air exists throughout the year. Simultaneously, stubble burning is a brief event that can only affect on a small spatial and temporal scales. Along with low wind speed in October and November (concerned months), we have found a considerable increase in dew point temperatures in last ten years, indicating a possible favorable condition for smog and entrapment of air pollutants. We expect that results from this work will provide a comprehensive discussion to manage air quality in the Indus basin.

1. Introduction

Smog, a mixture of atmospheric pollutants and fog, primarily consists of fine particulate matter (<2.5microns) and ground-level ozone (Haagen-Smit, 1964; Wang et al., 2014). Generally referred as urban air pollution, smog not only causes severe health disorders but also increases the risk of sustainability of an ambient environment through the deterioration of air quality, thus leading to respiratory illness (Dockery & Pope, 1994; Hemminki & Pershagen, 1994; Knox & Gilman, 1997; Nyberg et al., 2000; Pope et al., 1995; Schwartz, 1994). Typically, air pollutants do not have low thresholds implying that slight exposure of pollutants to humans may affect their long-term health and well-being (Brunekreef & Holgate, 2002; Mp & Sharma, 2013). Smog episodes are caused by various natural or anthropogenic activities such as volcanic eruptions, burning of coal, burning fuels, vehicular and industrial emission, forest and agricultural fires (Cheng et al., 1998; Gregg et al., 2004; Ma et al., 2012; Whittaker et al., 2004). Smog episodes can be enhanced through hydroclimatic or meteorological processes (Sati & Mohan, 2014). As an example, under prevailing low wind speed conditions, there is a possibility of stagnation of water vapors, which can entrap small particulate matter (Hanst et al., 1982). Smog generally occurs during months of low wind speed (Guttikunda & Gurjar, 2012), which acts as a catalyst to lengthen the duration of the episodes by

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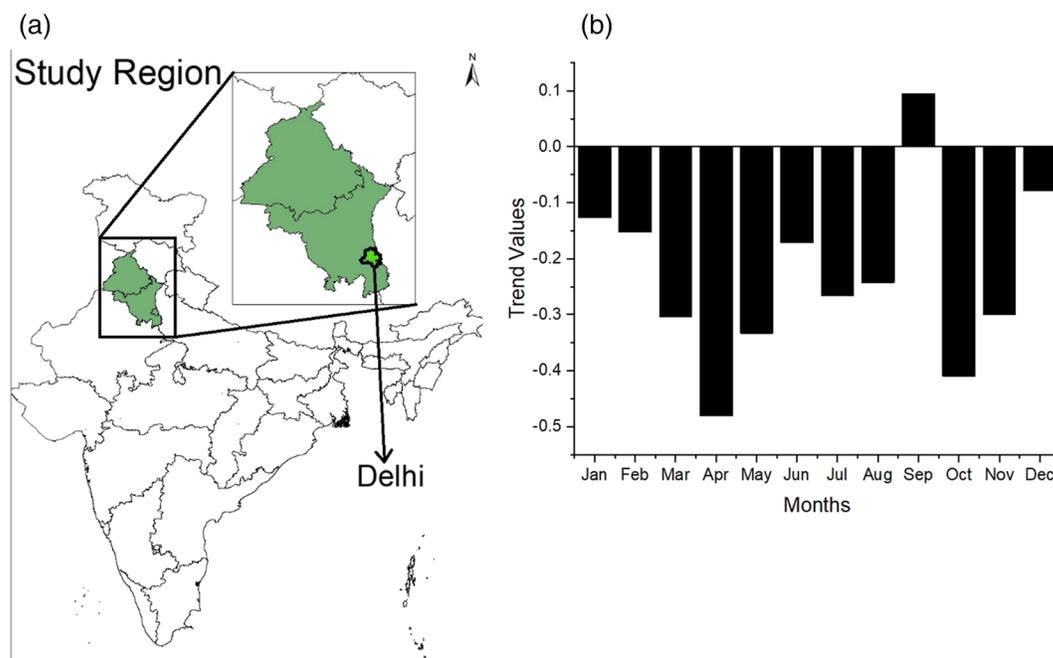


Figure 1. (a) study region (b) correlation values (trend) of outgoing longwave radiation (OLR) with time: Trend values represent 15 years (2002 to 2016) of analysis. Apart from September, all other months showed a negative trend in OLR, suggesting a reduction in OLR around the year.

minimizing the dispersion of particulates. Ambient air and dew point temperatures and air pollutants are amongst few other variables apart from wind speed that has recently been shown to be associated with the occurrence of smog incidence (Zhou et al., 2015).

Intense month specific smog episodes in the Indus and Ganges basin (Figure 1(a)) affects more than 90 million people (Marlow & Mazumdar, 2018; Mohan, 2017) every year. The severity and frequency of these incidences have intensified in the last few years (Guttikunda & Gurjar, 2012; Sati & Mohan, 2014). As a result, there is a continuous degradation of air quality in the entire region. Based on several media reports (Bera & Choudhary, 2018; Biswas, 2018; Pardikar, 2018; Slater, 2018; Web Desk, 2018), the primary source for smog is attributed to the conventional practice of biomass (crop stubble) burning after harvesting paddy crop in the northern states of Punjab and Haryana (Chauhan & Singh, 2017; Guttikunda & Calori, 2013; Singh & Kaskaoutis, 2014) in India. The debate on the exact source, which includes various factors such as vehicular traffic, industries, and firecrackers, is a subject of debate in the entire region. Punjab and Haryana are major rice producers in the Indus basin in India (14.84 million tonnes in 2014–2015 source: <https://data.gov.in/resources/state-wise-production-rice-2010-11-2014-15-ministry-agriculture-and-farmers-welfare>), and are considered the key smog originating areas.

Stubble (or biomass) burning is not unique to the region since this practice has been there for several centuries (Streets et al., 2003; Venkataraman et al., 2006). Biomass burning is instead a universal phenomenon, which includes clearing of land for agricultural use. Therefore, any burning on a massive scale may harm regional weather, climate, and human health, primarily due to the emission of atmospheric aerosols and air pollutants (Anu Rani Sharma et al., 2010; Jain et al., 2014). Major air pollutants emitted from biomass burning include particulate matters (PM), carbon dioxide (CO₂), carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH₃), the volatile organic compound (VOC) and non-methane hydrocarbons (NMHC) (Jain et al., 2014; Zhang et al., 2016). Within the agricultural region of India, paddy generates the most amount of dry residual (31%) of stubble followed by wheat (19%) and sugarcane (17%) (Jain et al., 2014). Out of these three major cash crops, rice is harvested in October, wheat in March, and sugarcane both in March and October.

Several popular media articles and political agendas are being promoted in the basin to curb the menace of smog. However, the target of intervention to reduce smog episode remains on innovation in farming

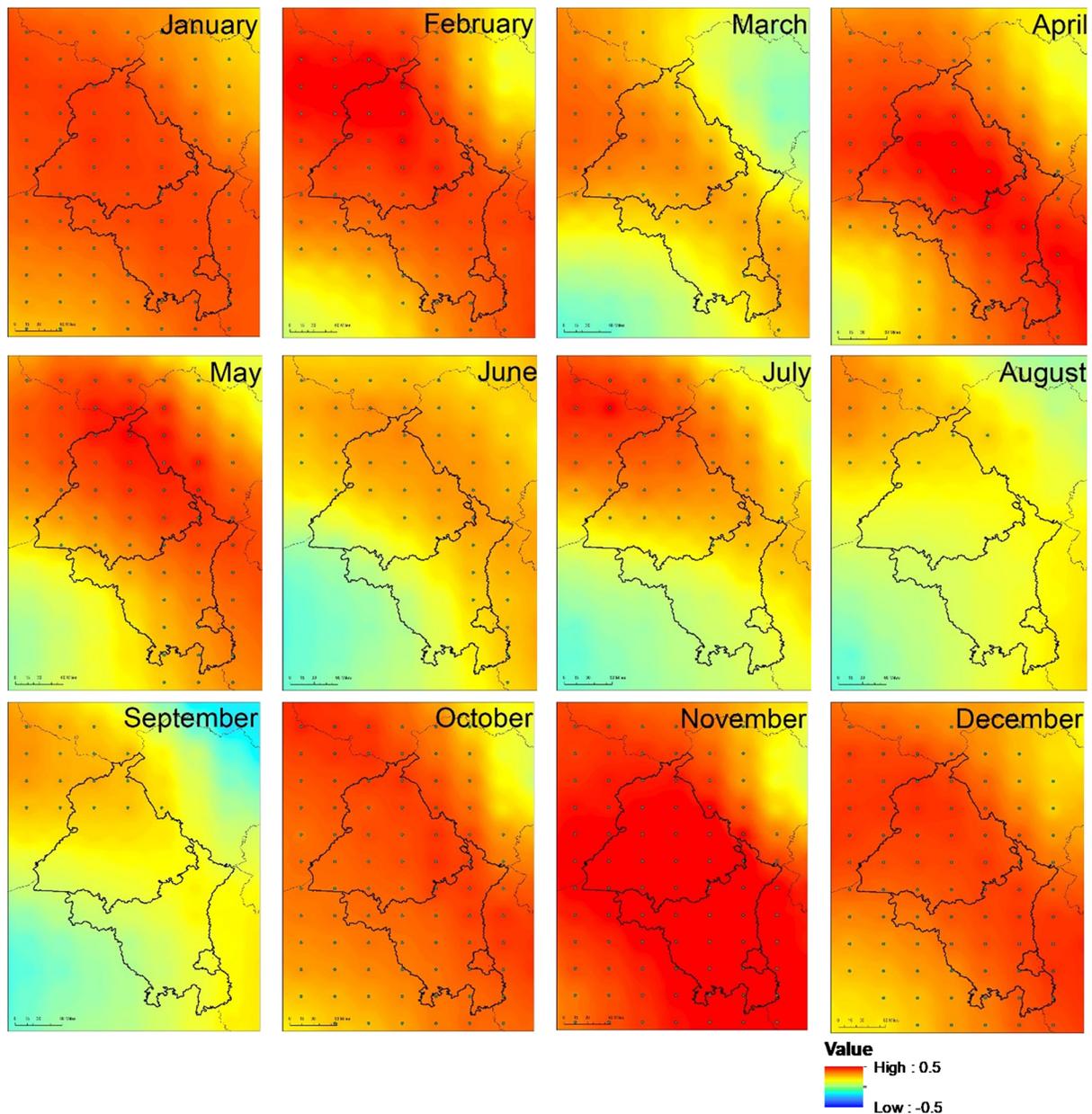


Figure 2. Significant PM_{2.5} trend points over the region with concentration greater than permissible threshold: Trend values vary between -0.5 and 0.5 and are represented with blue and red colors respectively. The dots on the figure represent statistically significant ($p < 0.05$) gridded points.

practices (such as no-tillage) and education of farmers (timing of harvesting). This forms the key motivation for this study as we examine if farming practices need to change or adapt to new rule sets. Hence, the goal of this study is to evaluate the causal environmental association of the smog episodes in the Indus basin. We argue that that the smog, particularly during concerned autumn months (October and November), is attributable to several confounding stakeholders and that it needs a holistic assessment of air quality in the region. We have investigated if region-wide environmental processes are associated with emergence and persistence of the smog in the entire basin during autumn months.

2. Data and Methodology

Outgoing Longwave Radiation (OLR) and wind speed dataset from NOAA-National Center for Environmental Prediction (NOAA-NCEP) at a resolution of $2.5^{\circ} \times 2.5^{\circ}$ were used in this study. Dew Point

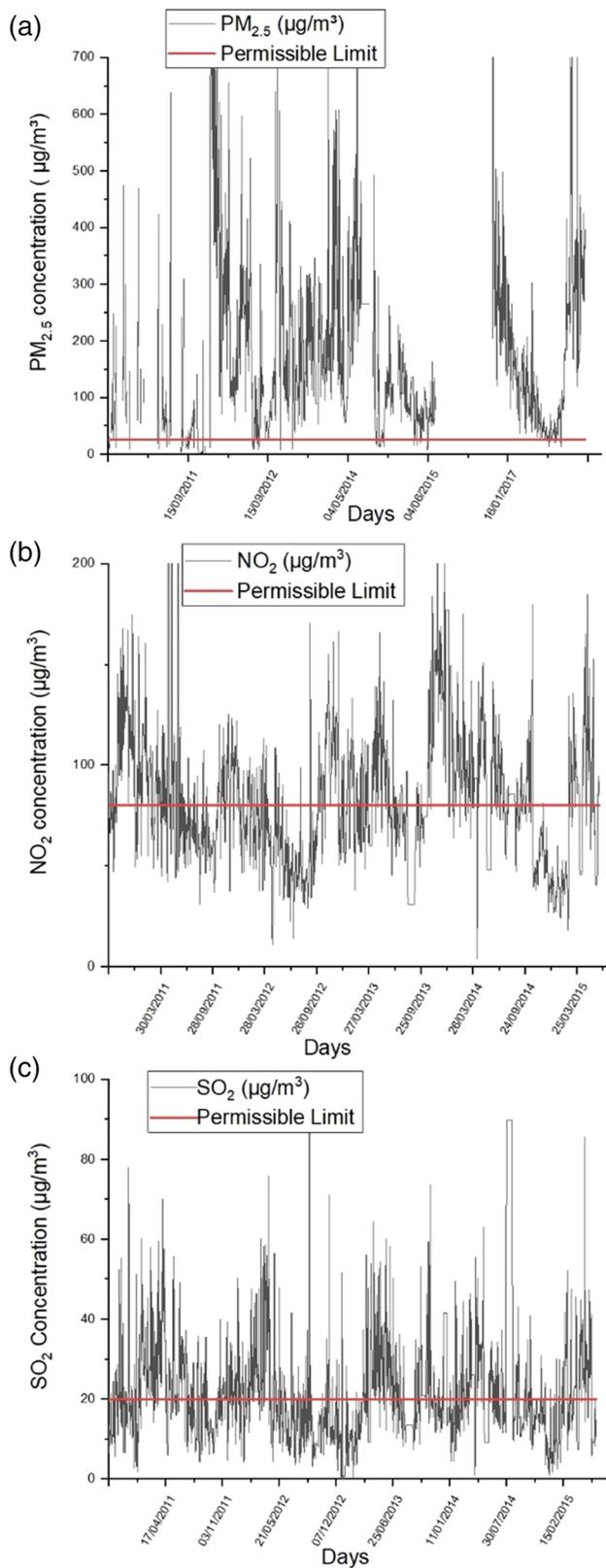


Figure 3. Concentration of air pollutants measured in New Delhi, India. The red line represents the permissible limit of the corresponding pollutant with $PM_{2.5}$, NO_2 , and SO_2 in the image a, b, and c, respectively.

Temperature (D_t) was obtained from NASA's Modern-Era Retrospective analysis Research and Application, Version 2 (NASA-MERRA 2) datasets at a resolution of $0.5^0 \times 0.625^0$. Air pollutant (NO_2 , SO_2 , CO) data and $PM_{2.5}$ data were obtained from globally gridded data from NASA MERRA2 at a resolution of $0.5^0 \times 0.625^0$ (from year 1980 to 2018). Station data for air quality were obtained from the Central Pollution Control Board, India (CPCB <http://cpcb.nic.in/>).

Trend analysis on earth observation data was used to determine the pattern of behavior of outgoing longwave radiation, dew-point temperature, particulate matter less than 2.5 mm, sulfur dioxide, and carbon monoxide using non-parametric Kendall-Tau test.

3. Results and Discussion

Outgoing longwave radiation (OLR) was used as one of the indicators to determine air quality over the entire region. Because an increase of aerosols often leads to a decrease in temperature, it has been suggested that OLR decreases with the increase of aerosols (Lubin, 2002; Ramanathan, 2001). Therefore, any change in OLR can be an indication of the overall quality (not particularly to air pollutants) of ambient air. Gridded OLR data on a monthly scale for the last 15 years (2002–2016) was investigated. The last 15 years window was selected based on media reports on the urgency of intensification of smog episodes in the region.

Kendall-Tau analysis (Figure 1(b)) shows that OLR has a decreasing trend in the last 15 years, except for September, which has statistically insignificant positive Kendall-tau value. Statistically significant decreasing trends were observed during April ($\tau = 0.47$; $p < 0.05$) and October ($\tau = 0.41$; $p < 0.05$) months. Our primary concern is for the autumn months, particularly October when the smog episodes are frequently attributed to biomass burning. OLR results indicate a possible deterioration in the quality of air in the entire region and that it needs further investigation. However, this analysis also shows a significant decrease in the trend of OLR during April (Figure 1(b)), when there is no biomass burning, suggesting that the OLR analysis alone may not be conclusive to quantify smog episodes during October. OLR itself cannot be regarded as the sole indicator or driver of aerosol activity in the region since OLR has complex dependencies on other hydrological and meteorological factors. Therefore, we analyzed $PM_{2.5}$ which is perhaps one of the most vital parameters for assessment of quality of air pollutants that contribute to smog episodes. We found out that the region has statistically significant ($p < 0.05$) positive trends (implying increase in the concentration over time) during non-monsoon (except July, August, and September) months (Figure 2). The dotted points on the figure represent the significant grid points which together with OLR, is suggestive of an increase in aerosol activity around the year except for the monsoon period (July–September).

To further investigate the association of smog episodes, four key air pollutant indicators ($PM_{2.5}$, SO_2 , NO_2 , CO) and wind speeds were analyzed. The primary source of SO_2 and NO_2 is fossil fuel combustion from industries, power plants, and locomotives (Reddy & Venkataraman, 2002; Smith et al., 2011). CO is perhaps one of the best proxy variables to understand ozone depletion (Pollack et al., 2013). CO is produced due to incomplete combustion of carbon-containing fuels such as gasoline, natural gas, wood, coal, and oil (Committee on Carbon Monoxide Episodes

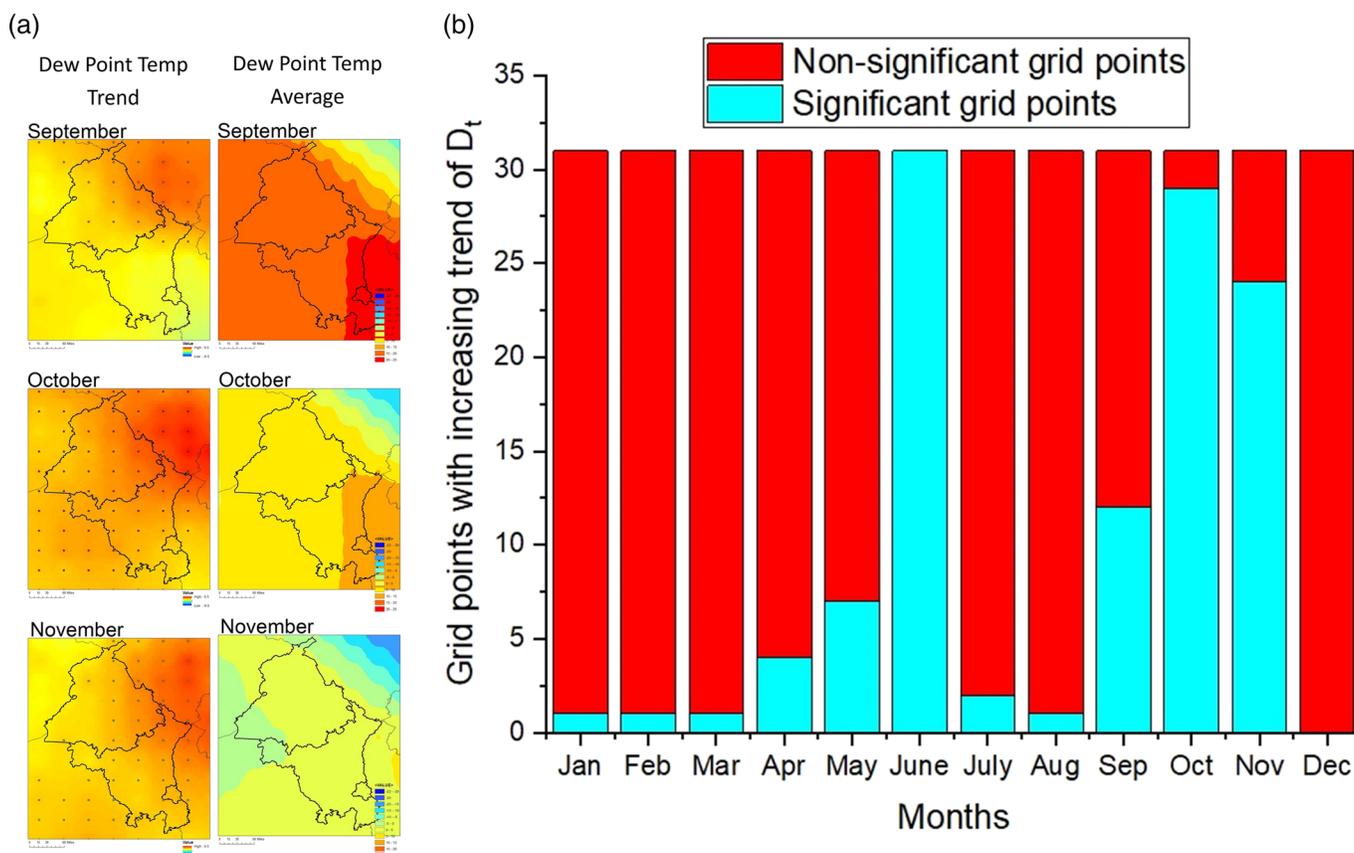


Figure 4. a) Significant dew point temperature trend points and average values over the region at a monthly scale b) grid points from (a) with positive correlation (trend) in dew point temperature (D_t): All of the 31 grid points show an increasing trend in D_t values. In June, October and November have more than 50% of the grid points suggest a significant positive trend in dew point temperature.

in Meteorological and Topographical Problem Areas, Board on Environmental Studies and Toxicology, Board on Atmospheric Sciences and Climate, Transportation Research Board, Division on Earth and Life Studies, & National Research Council, 2002).

$PM_{2.5}$, used in this analysis, constitutes dust particles, black carbon, organic carbon, sea salt, and sulfate (Modeling, 2015). Station data measuring $PM_{2.5}$ in New Delhi (two locations: Indira Gandhi International Airport, Delhi Technological University) show (Figure 3(a)) average concentration of particulates remained above the 24-hour mean threshold of 25 microgram/ m^3 (WHO air quality guidelines: [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)) throughout the year (or nearly 95% of the days). Similarly, station based SO_2 and NO_2 data in New Delhi region (adjacent to Punjab and Harayana) suggested that these variables are above the daily threshold of 20 microgram/ m^3 (WHO air quality guidelines) and 80 microgram/ m^3 (CPCB prescribed standard) respectively for the majority of months during the entire year. About 42% and 50% of the days remained above threshold limits for SO_2 and NO_2 , respectively (Figures 3(b) and 3(c)).

As a complementary analysis, assuming that smog is a region-wide phenomenon and considering that $PM_{2.5}$ concentration remains above the threshold for 95% of the days, it is plausible to expect an increasing trend in $PM_{2.5}$ concentration for all months in a year. Using MERRA-2 spatial data, statistically significant ($p < 0.05$) positive trend values were observed during concerned (October to December) months (Figure 2). The average values of $PM_{2.5}$ exceeded the permissible values defined by WHO throughout the year in the last ten years. Significant ($p < 0.05$) positive trends were observed for SO_2 and CO , using MERRA-2 data, with average SO_2 values exceeding the permissible threshold values throughout the year in the last five years (Figure S1 and S2). Analysis of OLR and key atmospheric pollutants indicate that all the values were

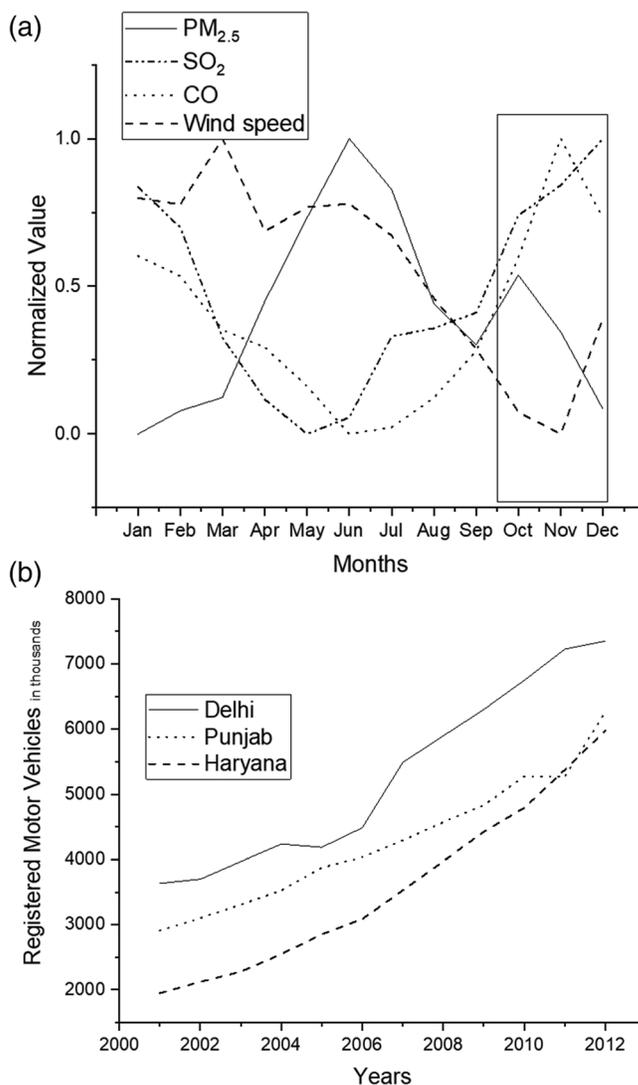


Figure 5. (a) seasonality of wind speed and air pollutants over the study region. (b) registered motor vehicles in the study region.

higher than the permissible limits for most of the year. Since the long-term time series suggest a positive trend in all the variables of interest, therefore, this an argument to reason that biomass burning is perhaps not entirely attributable to smog episodes in the region.

The question remains as to why recurrent smog is observed during the months of October and November. In order to answer this question, dew point temperatures (D_t) and wind speed datasets were analyzed. Increasing trends in the dew point temperature will be a partial indication that the region may have more moisture during those months. Smog consists of condensed water droplets, which forms when either the ambient air temperature drops down to the dew point temperature or such temperature increase to ambient air temperature (Wallace & Hobbs, 2006). Thus, D_t was examined as a surrogate variable as an indicator of the availability of moisture. Using MERRA-2 dataset, overall, the value of D_t decreased from September to November (Figure 3(a)). However, during the two concerned months (October and November), D_t values showed a significant increase over the entire area (Figure 3(a)), indicating a space wide increase in the moisture content in those months. Regionwide, October (29 significant grid points) and November (24 significant grid points) show a significant increase in the value of D_t . The month of June (31 significant grid points) is an exception where the regionwide increase in trends in D_t were observed. However, June is the onset of

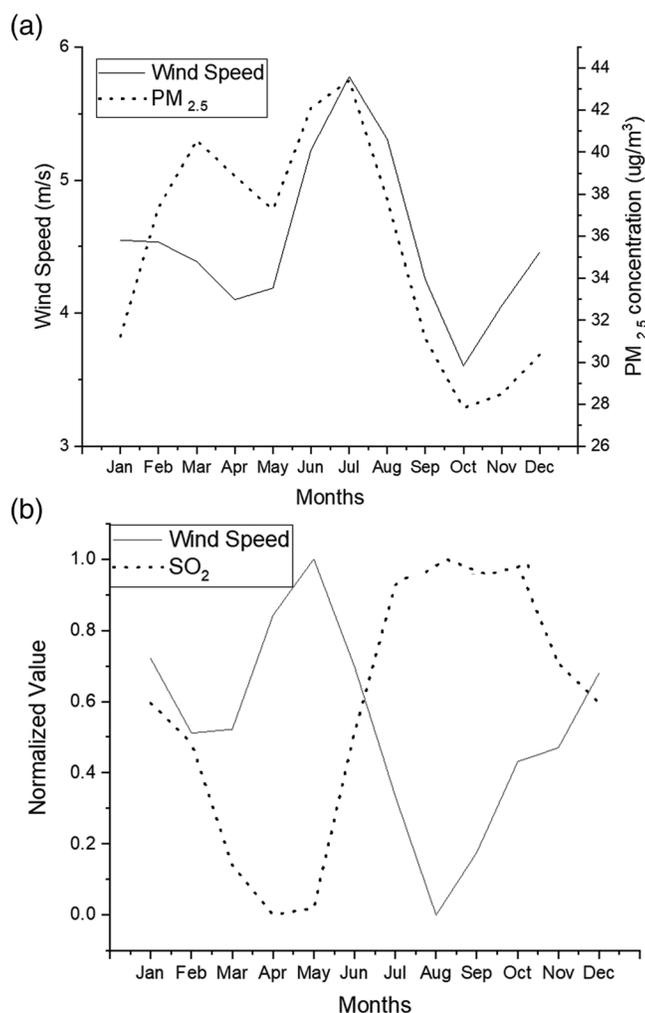


Figure 6. (a) wind and PM_{2.5} seasonality over Saudi Arabia. (b) wind and gaseous pollutants seasonality over Beijing, China.

monsoon in that region, and it has been documented that the amount of rainfall is increasing in the Indus basin (Kumar et al., 2010). Therefore, it is reasonable to expect high D_t values during June.

The absence of winds is likely to create conditions where atmospheric pollutants tend to accumulate at one location. The concerned months for biomass burning, October and November, experience some of the lowest wind speeds during the year, and it is perhaps an indication that due to absence of high-velocity winds, the atmospheric pollutants may accumulate at one place for an extended period. A similar association between wind speed and atmospheric pollutants was reported in Japan and Poland (Cichowicz et al., 2017; J. Wang & Ogawa, 2015). October and November are the only two months in the region when the wind speed has exhibited statistically significant ($p < 0.05$) negative correlation ($r = -0.45$ and $r = -0.34$, respectively) with PM_{2.5}. The negative association implies that if the wind speeds are low, then the concentration of particulate matter is high, further suggesting that particulate matter tends to house at a particular location.

Thereafter, seasonality of wind speed and PM_{2.5} were analyzed. Figure 5(a) shows that PM_{2.5} has a dual seasonal peak, one during May–June and the second during the months of October–November. The entire region of Indus basin experiences high winds during February through June, while low wind speeds typically characterize the months of October and November. Intense dust storms during May and June are perhaps responsible for an increase of PM_{2.5} during those months (Dumka et al., 2019; Kaskaoutis et al., 2012; Srivastava et al., 2014; Tiwari et al., 2015). As complementary evidence, a similar relationship between wind speed and PM_{2.5} has been determined over Saudi Arabia (Figure 6(a)). Therefore, under high wind speeds, PM_{2.5} increase is likely to be attributable to intense dust storms.

4. Conclusion

The motivation for this study was to provide an assessment of the association of the contribution of burning agricultural biomass with the smog episodes in the Indus basin. Using station data from New Delhi, India, it

was observed that key air quality (as indicative from PM_{2.5}, NO_x, SO₂) were above permissible limits throughout the year. The satellite data further verified this observation and suggested a region-wide increase in the values of these variables over vast agricultural areas. This suggests that farming practices alone cannot be the sole contributors to these intense smog episodes in the region.

Data gathered from three provinces (Punjab, Haryana, and New Delhi) showed an exponential increase in registered motor vehicles in the region (Figure 5(b)). The number of vehicles plying on the road, with inadequate traffic infrastructure that aid in traffic jams, may result in decreasing air quality in the region. In the past, vehicular traffic has been considered as one of the primary sources of air pollution in urban regions like Delhi (Kathuria, 2002). Major air pollutants emitted from vehicular traffic are PM, CO₂, CO, SO₂, HC, and NO_x. In our study region, vehicular registrations have increased by the factor of 2.5 between 2001 and 2012 (Figure 5(b): Government of India, MOTOR VEHICLES - Statistical Year Book India 2016- <http://www.mospi.gov.in/statistical-year-book-india/2016/189>), which has the potential to pollute such that it can increase the amount of pollutants to above the permissible limits. This study argues that the air quality during October and November experience high ambient moisture content, low wind speeds (limiting dispersion potential), and consisted of already saturated air pollutants. Any perturbation during this period will likely lead to smog incidence. Burning of stubble after harvesting paddy provides such an event that there is an overwhelming perception that farming practices may lead to deteriorating air quality in the region. Burning biomass (residual crop stubble) is a transient event, which can act as a catalyst for smog

episodes, but is inadequate to pollute the region for an entire year. A complementary analysis of PM_{2.5} (Figure S3) over Ludhiana District in Punjab further confirms that the values remain high during all the year and is not sensitive to October and November months alone. In addition, analysis of SO₂ from the city of Beijing, where smog events are commonly reported and attributed to traffic (Fu et al., 2001; Samet, 2015; Xie et al., 2018), shows a negative seasonal association between SO₂ and wind speed (Figure 6(b)) indicating the role of stagnant air pollutants over the region.

Nonetheless, we do not advocate the biomass burning after paddy harvesting; instead, it is essential to focus on the holistic environmental sustainability policies to reduce smog incidence. We conclude with a statement that importance should be given to innovative agricultural solutions, which holds the potential to change the sociological perception of farming practices and strengthen policies of limiting the practice of stubble burning in the region.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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