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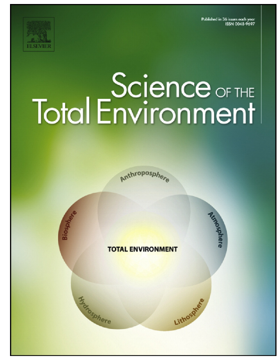

Objective evaluation of stubble emission of North India and quantifying its impact on air quality of Delhi

Gufran Beig, Saroj K. Sahu, Vikas Singh, Suvarna Tikle, Sandeepan B. Sobhana, Prashant Gargeva, K. Ramakrishna, Aditi Rathod, B.S. Murthy

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OBJECTIVE EVALUATION OF STUBBLE EMISSION OF NORTH INDIA AND QUANTIFYING ITS IMPACT ON AIR QUALITY OF DELHI

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Abstract- Crop residue burning during post monsoon season in the neighboring provinces leads to frequent episodes of extreme pollution events, associated with premature morbidity and mortality. A synergistic use of multiple satellite measurements in conjunction with actual field incidences data at the ground led us to develop the realistic high-resolution emission inventory of the hazardous pollutant PM2.5 due to stubble burning. We quantify the share of biomass burning in deteriorating Delhi's air quality during 2018 using the SAFAR chemical transport model that has been validated with dense observational network of Delhi. The impact of biomass burning on Delhi's PM2.5 is found to vary on day-to day basis (peaking at 58%) as it is highly dependent on transportation pathway of air mass, controlled by meteorological parameters from source to target region. Comprehending the multi-scale nature of such events is crucial to plan air quality improvement strategies.

Keywords: Emission, Stubble burning, PM2.5 and Air Quality

Footnotes

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Capsule: Quantified the share of agriculture residue burning in North Indian province in deteriorating the air quality of Mega city Delhi which peaks at 58%.

1. INTRODUCTION

Air pollution is a major planetary health risk that contributes substantially to premature mortality and disease burden globally, with a greater impact in developing and under developed countries (Cohen et al., 2015). Apart from detrimental health effects, air pollutants also play an important role in modulating the atmospheric chemistry processes regionally and globally. Ground level ultra-fine particulate matter $PM_{2.5}$ (size ≤2.5 micron) are a widespread environmental problem in metropolitan cities throughout the world. There are several anthropogenic local sources of emissions leading to deterioration of air quality like fossil fuel, bio-fuel, industrial, re suspended dust, etc (Sahu et al., 2011). Wildfires and the intentional burning of biomass are an integral part of Earth's system since they occur in all major biomes (Keywood et al., 2013) and responsible for deterioration of air quality worldwide (Cusworth et al., 2018; Sigsgaard et al., 2015; Yadav and Devi, 2018). Studies have been conducted on different aspects of biomass burning (Chen et al., 2017) all over the world. It is estimated that every year biomass burning activity deplete about 500–1000 million hectare of open forest and savannas, 1 million hectare of northern latitude and 4 million hectares of tropical and sub-tropical forest (Yadav and Devi, 2018). In India around 20-25% of generated crop residue is burned in open fields (Ravindra et al., 2019b, 2019a) leading to episodic very poor air quality in Indo Gangantic plains of India (IGP) (Ram et al., 2016). The capital city of India Delhi is a highly urbanized landlocked city and has a population of ∼16.5 million (Keywood et al., 2013) that experiences severe winters. Delhi is situated at an elevation of 216m above sea level and in a close proximity with one of the largest agricultural dominating states of Punjab and Haryana where crop residues are burned after Kharif harvest season (October-November) which coincides with weak surface north–westerly winds that favor stagnation of pollution forcing air quality to deteriorate(R. P. SINGH, 2014). Smoke from Biomass burning is one of the main atmospheric constituents that affect the air quality and climate due to their massive plumes that can travel thousands of kilometers downwind (Chen et al., 2017). Intense crop residue burning exerts a much stronger influence on the short-term than long-term variation of PM concentrations (Zhuang et al., 2018).

However, the air quality impacts from agricultural fires and reliable estimates on the share of biomass burning in PM2.5 of India's capital city Delhi remain highly uncertain due to differences in global fire emissions inventories of this region that are coupled with atmospheric transport models. We hereby quantify the contribution of stubble burning in Punjab and Haryana in total surface $PM_{2.5}$ concentration over Delhi using the SAFAR chemical transport model based on WRF-Chem methodology(Beig et al., 2019; Srinivas et al., 2016a). For the purpose, high resolution gridded emission inventory of PM2.5 over the states of Haryana and Punjab for Kharif crop residue burning period has been developed by synergising the MODIS (Moderate Resolution Imaging Spectro-radiometer), VIIRS (Visible Infrared Imaging Radiometer Suite) and INSAT-3D /3DR (Indian National Satellite System) satellite data with real filed incidences data using the GIS based bottom up approach. The finding of current study will be useful to better understand the relative share of local versus long range transport of air pollutants during crop residue burning period and to plan comprehensive mitigation strategies.

2. MATERIALS AND METHODS

2.1 SAFAR Frameworks

The simultaneous and continuous measurement of PM2.5 was conducted in Delhi under the project System of Air quality and weather Forecasting and Research (SAFAR) of Indian Government and a pilot project of World Meteorological Organization(Gufran Beig, Dilip M. Chate, Saroj K. Sahu, Neha S. Parkhi, Reka Srinivas, Kausar Ali and Trimbake, 2015). The location of Delhi is shown in Fig.1. The SAFAR consists of dense network of 8-10 air quality monitoring stations (spread around Delhi in different micro-environments so as to represent overall Delhi) coupled with high resolution (1.67km) online chemistry-transport model(Beig et al., 2019; Marrapu et al., 2014; Srinivas et al., 2016b) and emission inventories of pollutants("SAFAR - India," n.d.; Sahu et al., 2012). The mass concentration of PM2.5 was monitored based on the principle of Beta-ray Absorption method using suspended particulate beta gauge monitor (M101M+). The analyzers are maintained and operated as per the standard specifications. They are US-EPA approved and certified by Bureau Veritas Certification (ISO9001) for quality control. The US EPA's Standard Operating Procedures were adopted for instrument calibration and maintenance. The detailed information about calibration procedure can be found by referring to title 40 of the Code of Federal Regulations (CFR) part 50("40 CFR Part 50 - NATIONAL PRIMARY AND SECONDARY AMBIENT AIR QUALITY STANDARDS | CFR | US Law | LII / Legal Information Institute," n.d.) and that of SAFAR network can be found in("SAFAR - India," n.d.).

2.2 Emission Inventory of Stubble Burning

The crop residue-burning period for kharif crop in northern states of India usually starts in the second week of October and lasts for 6 to 8 weeks. In the year 2018, major burning occurred during the period 10th October to 30th November. Present study focuses on this period. The crops grown in the wet season (starting July) are known as kharif crops in the Indian subcontinent. Rice is the major kharif crop. In addition pearl millet, jowar, cotton, soya bean, red gram, green grams, pigeon pea, groundnut, maize are other kharif crops. These all crops harvested in October-November. The scattered, root-bound crop residue left behind by combine harvesters is difficult to remove in a short time before next planning of crop begins. Farmers are mainly choosing the cheaper and fastest method to burn it usually to clear fields for the next planting(Gadde et al., 2009; Kumar et al., 2015). An estimated 7–8 million tones of rice residue associated with post-monsoon agricultural burning are burned each year in Punjab state alone(Kumar et al., 2015). The residue burning release accumulation mode aerosols that mostly contribute to the PM2.5 fraction(Hays et al., 2005). In the present attempt, we have quantified the emission of PM2.5 with a grid resolution of 5 km x 5 km from crop residue burning for Kharif season of 2018 based on the objective evaluation of fire data obtained by MODIS, **VIIRS,** INSAT-3D /3DR and that of field incidences survey data. The real field incidences data collected as a special drive by the local authorities(CPCB, 2019) and used in this work to identify the actual stubble burn areas and its intensity along with duration to reconcile with satellite data and filter out false signals or add undetected signals. The description of MODIS and VIIRS can be found elsewhere("Fire Information for Resource Management System (FIRMS) | Earthdata," n.d.) and hence not included here. The INSAT-3D /3DR are two advanced Indian geostationary satellites with modest resolution and capable of detecting large fires with hyper-temporal capability("Meteorological & Oceanographic Satellite Data Archival Centre | Space Applications Centre, ISRO," n.d.).The algorithm developed for identifying active fire (thermal anomaly) imager data and the multi-channel contextual algorithm has been used for active fire detection(Singh, 2018). Indian satellite has advantage in terms of geostationary orbit and providing data every 15-30 minutes but have a disadvantage because of coarser resolution (4x4 km) that may not detect scattered fire of small sizes that MODIS can detect due to its finer resolution. MODIS and VIIRS could detect a larger number of fires, whereas INSAT-3D due to its better temporal resolution could detect even those fire events which MODIS missed. There are number of instances where anomalies were found on day-to-day basis and rectified carefully. VIIRS was often found to detect additional counts which were never confirmed by ground survey that might have occurred due to festival related firecrackers or sources other than stubble burning. Such data have been further verified with detailed records prepared later by the authorities.

The GIS based statistical bottom-up approach has been used in this work and accounts for activity data of different types of crops burned along with respective emissions factors. The methodology is discussed elsewhere and hence not included here(Beig et al., 2019; Sahu et al., 2015). The estimated PM2.5 emission from crop residue burning in Punjab and Haryana is found to be 141.65 Gg during 2 months of Kharif crop stubble burning season (Oct-Nov'2018) as shown in Fig.-2B. Punjab and Haryana each generate approx. 17.4 Mt of residue during Kharif season in 2018, where rice crop is dominated followed by millet crop. Kharif crop contributes ~64% of total annual emissions in a span of just ~2 winter months. Punjab emits more $PM_{2.5}$ emissions due to stubble burning as compared to Haryana. The emission hot spots of the order of 150 to 500 Kg per grid ($5km^2$) are dominated over Southwestern part of Punjab as evident from Fig. 2B. A similar trend is also found over some parts of Northwestern Haryana. It is also observed that emissions of the order of 5-20 Kg/grid were confined over Central Haryana and Northern Punjab region. Comparatively very low emission is found over adjoin region of Delhi that explains that Delhi is affected by stubble fire emission only intermittently.

2.3 Model Setup and Methodology

The detail description about the SAFAR air quality forecasting model adopted in this work is provided elsewhere(Beig et al., 2019; Marrapu et al., 2014) hence not discussed here in detail. It is based on WRF–Chem (Weather Research and Forecasting couples with Chemistry) configured with 4-nested domains. There are total of 30 vertical model layers. The National Centre for Environmental Prediction (NCEP) global forecast system (GFS) operational forecast, available every 6 hourly intervals with a global cover at resolution 0.5º latitude x 0.5º longitude was used for the initial and lateral boundary conditions of all meteorological variables. The Copernicus Atmosphere Monitoring Service (CAMS) is provided the chemical lateral boundary conditions. This model configuration enables direct, indirect and semi direct aerosol radiative feedbacks to be included in the analysis. The background emission inventory used in this work for Delhi region is based on the latest SAFAR emission inventory report(“SAFAR - India,” n.d.) and that of other regions as per methodology discussed earlier(Beig et al., 2019; Srinivas et al., 2016b). The background emission inventory used in model is based on the latest report released by Indian government (Beig G., 2018) for Delhi which is based on the bottom up approach. Background local anthropogenic sources of emissions have been classified broadly in 6 sectors namely transport, bio-fuel, power, industrial, resuspended dust and rest others. The relative share of $PM_{2.5}$ emissions by different sectors for Delhi National capital Region is discussed elsewhere (R. P. SINGH, 2014). Transport sector is the most dominant sector contributing 39.1% in total $PM_{2.5}$ emission. Industrial sector is the second most dominating factor contributing 22.3%. The contributions from power sector, biofuel sector, resuspended dust and others are found to be 3%, 5.7%, 18% and 11.7% respectively. The model results under SAFAR project were also routinely validated for Delhi region for normal case as well as for extreme events (Beig et al., 2019; Marrapu et al., 2014; Srinivas et al., 2016b). To account for stubble burning in the Northern part of Delhi, model was subjected to additional emissions over the burning regions on day-to day basis as per the estimate discussed in the previous section.

In order to find out the relative role of local emissions versus stubble burning contributions from distant regions on the distribution of $PM_{2.5}$ over Delhi NCT region, several sensitivity simulations were performed as follows:

Scenario-A:	Standard normal run with prescribed background emissions, atmospheric transport processes, initial conditions, lateral boundary conditions, and additional emissions of stubble burning as per the estimate discussed in previous section.
Scenario-B:	A control run, where additional emissions due to stubble burning were set to zero while other factors remained the same.
Scenario-C:	The difference of PM2.5 mass concentration over Delhi region for Scenario-A to that of Scenario-B provided the contribution solely attributed to additional emissions of stubble burning in the neighboring region.

3. RESULT AND DISCUSSION

Fig. 2A shows the comparison of observed and model simulated (scenario-A) daily averaged PM2.5 mass concentration during the period 10^{th} October to 10^{th} December 2018 that mainly includes the stubble-burning period. The observed data is averaged across 10 stations spread in different microenvironments of Delhi. Averaging removes the in-homogeneity in the data sets and is representative of the overall city area ("40 CFR Part 50 - NATIONAL PRIMARY AND SECONDARY AMBIENT AIR QUALITY STANDARDS | CFR | US Law | LII / Legal Information Institute," n.d., "SAFAR - India," n.d.). The comparison is found to be quite reasonable. During the period of winter number of meteorological factors along with transport pathways influences the air quality of Delhi. The local weather factors like calm wind speed and direction plays an important role to prevent dispersion as Delhi is a landlock city. In addition to this, as the temperature becomes cooler, the inversion layer height likely to go down and prevent the vertical mixing thereby influencing in accumulation of pollutants. However, the aim of this work is to understand the impact of stubble burning and role of transport pathways and hence only relevant discussion is included here in detail. In Figure 2A, a sharp peak in the level of PM2.5 on 7th November (620μg/m^3), was related to Diwali festival (heavy pyrotechnic display) and kept out of scale as it is irrelevant in the present context. The contribution of finer particles in PM10 also remains high during Diwali fire work (Fig. 3). Fig. 2B shows the time series of the percentage share of PM2.5 over Delhi attributed to stubble burning from the neighboring region as simulated by the SAFAR model on day-to-day basis (Scenario-C). The absolute mass concentrations of PM2.5 attributed to stubble burning are plotted in Fig. 2 C with triangle marks (red line). Fig. 2C also shows the mass concentration of PM2.5 without the contribution of stubble burning as calculated from observed data by subtracting the magnitude of stubble only contribution of PM2.5 based on percentage share of stubble burning calculated by the model. Although the stubble burning was a regular process during the said period, with varied fire count, the impact of biomass burning on Delhi's PM2.5 is found to vary on day-to day basis with percentage contribution of stubble burning ranging from 1% to 58% as it is highly dependent on transportation pathway of air mass, controlled by source to target region meteorological parameters led by wind direction and wind speed at 900-800mb level. As the winter sets in, level of PM2.5 slowly increases from the first week of October due to fall in temperature and local calm winds. However, as evident from Fig. 3, the relative contribution of stubble burning was in general significant from 20th October until the last week of November. This is evident from Fig. 2D which shows that % ratio (PM2.5 /PM10) get elevated during this period due to larger contribution of biomass burning which finer particles PM2.5 increases more rapidly. It is observed that the stubble contribution was highest on 5th November (58%) when the PM2.5 level crossed 300μg/m^3 and the ratio (PM2.5/PM10) was above 65%. It is also to be noted that although there was a large contribution of biomass on 16th November owing to favorable wind speed and direction, the overall magnitude of PM2.5 was low (~110μg/m^3) due to rainfall in Delhi during that period. Fig. 4A,C shows the special distribution of PM2.5 (μg/m^3) over Delhi region along with realistic fire counts over Northern part of India, during 2 contrasting days when contribution of stubble burning was minimum (17th November) and highest (5th November) as simulated by SAFAR model. Fire counts were reasonably high on both days (slightly higher on 5th Nov) along with comparable high upper level winds at intrusion level (850-900mb) and calm surface winds speed and southerly wind direction at receptor site (Fig. 4B,D). However, the difference in the % share was mainly due to the fact that the wind trajectory reaching Delhi on 5th November was from North-North-West direction (stubble burning site) and that of 17th November was from Southern site where no biomass activity was noticed as shown in Fig. 4B,D. It implies that the impact of stubble burning on Delhi's air quality depends not only on amount of biomass burned in Punjab and Haryana but a combined effect of high wind speed at intrusion height, wind direction and air residence time in the Delhi airshed. It should be noted the stubble contribution is not the only factor differentiating these two contrasting cases for example on November 5th highly polluted day (PM2.5 more than 300μg/m^3) the ceilometer measured (Murthy et al., 2019) daily average mixed layer height where only 162 m compared to 434 m on November 17th. The mixed layer confining to near surface on 5th November has led to maximizing the impact of stubble fire as well as other emissions and manifested in high PM2.5 surface concentrations.

4. CONCLUSION

Air pollution is increasingly becoming a serious issue in the mega cities of the world due to its impact on climate and health. The high-resolution emission inventory of agriculture stubble burning in the North Indian states of Punjab and Haryana has been developed in this work for the first time by objective evaluation of satellite fire counts reconciled with empirical ground survey data to narrow down uncertainties. Emissions are validated by incorporating them in a chemical transport model and comparing the predictions with observational data. Although biomass burning occurred almost every day during the study period, the share of biomass in deteriorating Delhi air quality in 2018 varied from 1% to 58%. The results of the current study will be useful to better understand the relative contribution from various internal and external sources during crop residue burning period and to plan comprehensive air quality improvement strategies.

5. ACKNOWLEDGEMENTS

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Conflicts of Interest

There are no conflicts to declare regarding publication of this paper.

Fig 1. The Study location, Delhi and 278 **Stubble burning location of Haryana and Panjab Provinces**

FIG.2. (A) A comparison of model simulated PM2.5 with that of observed data during the study period; (B) The relative contribution of stubble burning related impact (in%) in total PM2.5 in Delhi; (C)The absolute share of PM2.5 with and without stubble burning related contribution in the observed data using the model derived % share as per 2b; (D) The observed ratio of PM2.5/PM10 (%)during the above period.

FIG. 3. The total PM2.5 gridded emissions (Gg/grid/Kharif) due to stubble burning Of Kharif season (10th October-30th November 2018) in Punjab and Haryana regions as obtained in this work by reconciling the fire data from satellites and ground based techniques.

Fig.4. Distribution of PM2.5 (μg/m3) over Delhi and surrounding regions (top panels) along with fire counts (bottom panels) considered in this work for two specific days when impact of stubble burning was minimal (17th November) and when impact was maximum (5th November 18). The relevant weather parameters are also given in the bottom panel.

Graphical abstract

Highlights

- Provided complex mechanism of particulate pollution, local meteorology and transport pathways to understand the extreme pollution events in a Mega city.
- First estimate of high resolution emission inventory of PM2.5 by synergising multiple satellite measurements and actual field incidences data for stubble burning in Northern India.
- Quantified the share of agriculture residue burning in North Indian province in deteriorating the air quality of Mega city Delhi which peaks at 58%.
- Highlighted the relative contribution from various internal and external sources during crop residue burning period to plan comprehensive air quality management strategies.

Figure 1

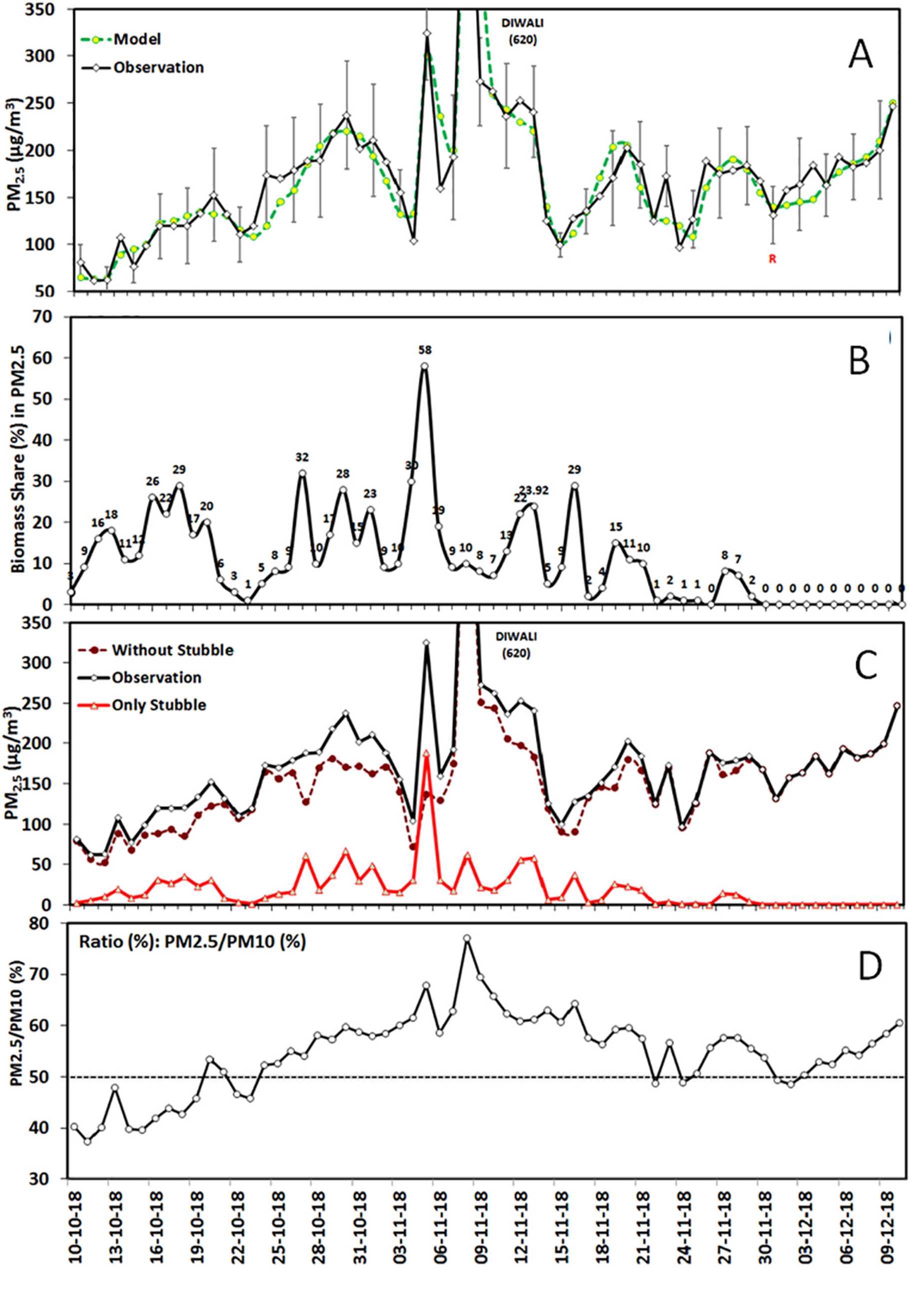
A
Model
Observation
DIWALI
(620)
$PM_{2.5}$ ($\mu g/m^3$)
R
B
Biomass Share (%) in PM2.5
C
Without Stubble
Observation
Only Stubble
DIWALI
(620)
$PM_{2.5}$ ($\mu g/m^3$)
D
Ratio (%): PM2.5/PM10 (%)
PM2.5/PM10 (%)
10-10-18
13-10-18
16-10-18
19-10-18
22-10-18
25-10-18
28-10-18
31-10-18
03-11-18
06-11-18
09-11-18
12-11-18
15-11-18
18-11-18
21-11-18
24-11-18
27-11-18
30-11-18
03-12-18
06-12-18
09-12-18

Figure 2

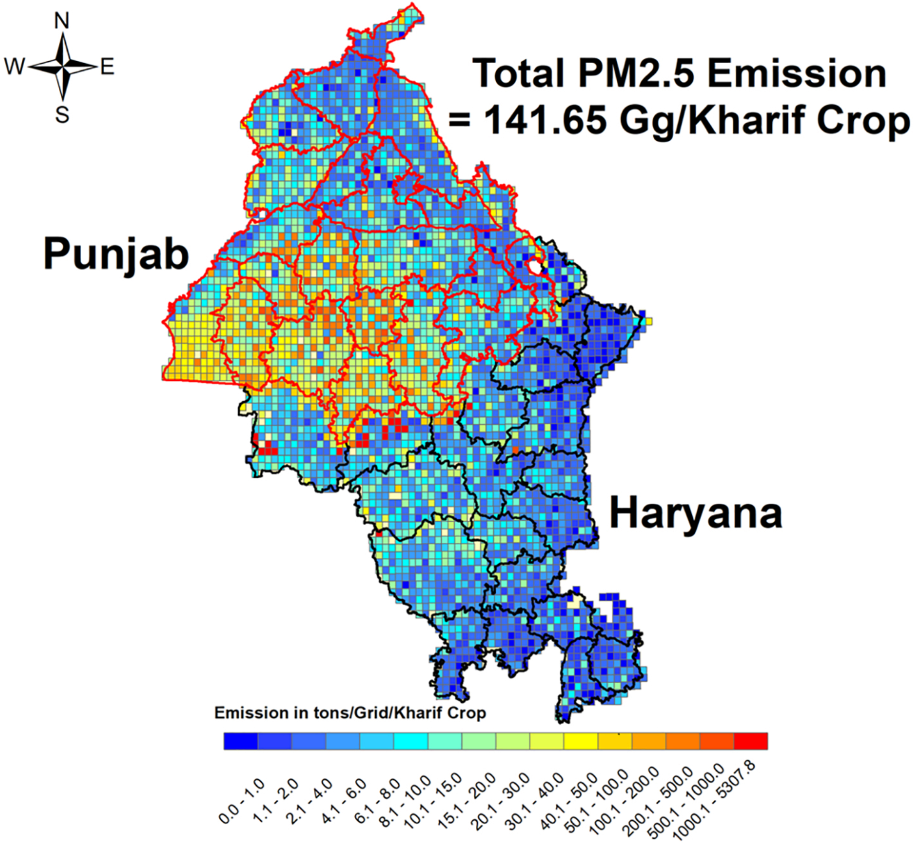
N
W
E
S
Total PM2.5 Emission
= 141.65 Gg/Kharif Crop
Punjab
Haryana
Emission in tons/Grid/Kharif Crop
0.0 - 1.0
1.1 - 2.0
2.1 - 4.0
4.1 - 6.0
6.1 - 8.0
8.1 - 10.0
10.1 - 15.0
15.1 - 20.0
20.1 - 30.0
30.1 - 40.0
40.1 - 50.0
50.1 - 100.0
100.1 - 200.0
200.1 - 500.0
500.1 - 1000.0
1000.1 - 5307.8

Figure 3

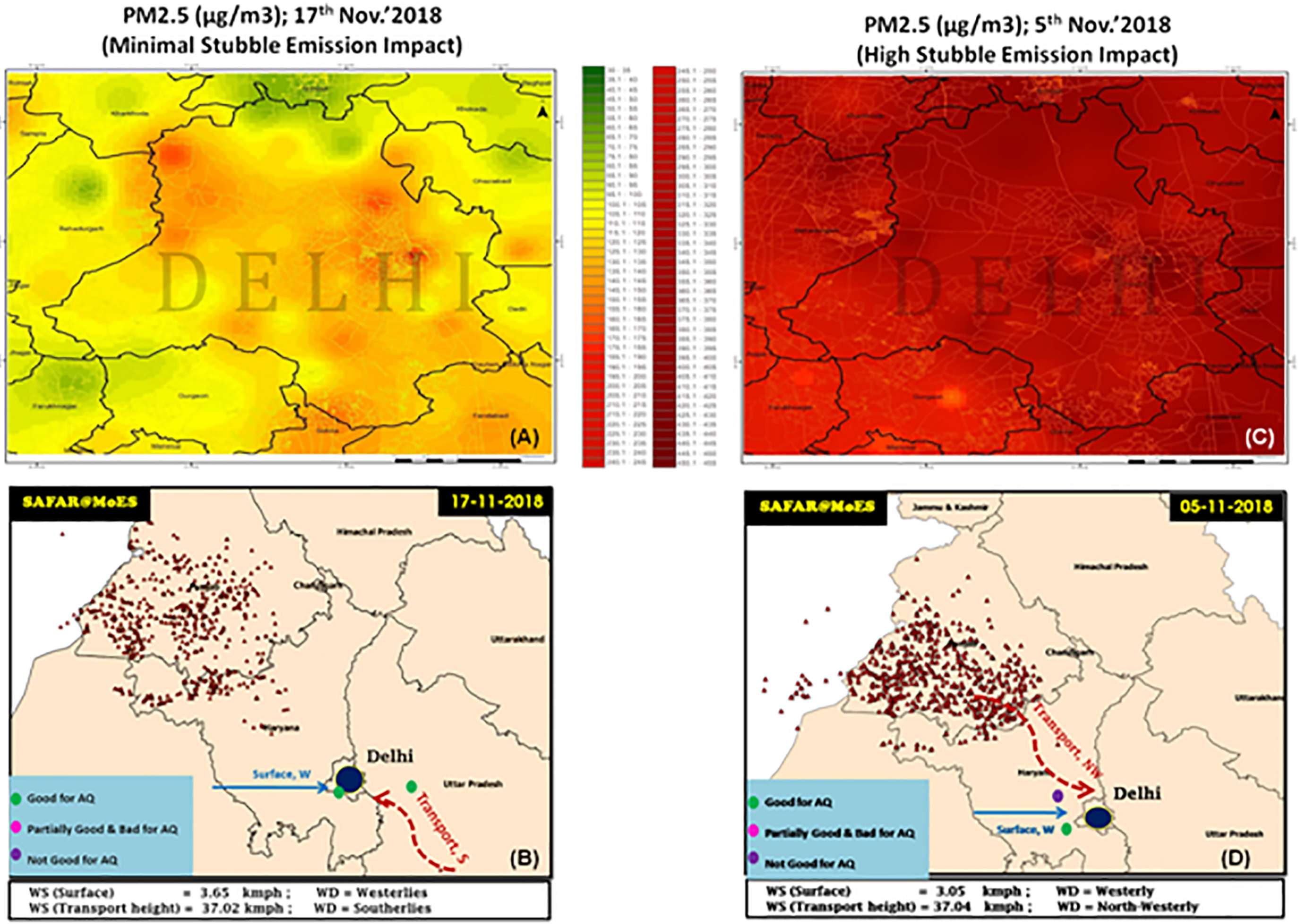
PM2.5 (µg/m3); 17th Nov.'2018
(Minimal Stubble Emission Impact)
PM2.5 (µg/m3); 5th Nov.'2018
(High Stubble Emission Impact)
DELHI
(A)
DELHI
(C)
SAFAR@MoES
17-11-2018
Delhi
Surface, W
Transport, S
Good for AQ
Partially Good & Bad for AQ
Not Good for AQ
(B)
WS (Surface) = 3.65 kmph ; WD = Westerlies
WS (Transport height) = 37.02 kmph ; WD = Southerlies
SAFAR@MoES
05-11-2018
Transport, NW
Delhi
Surface, W
Good for AQ
Partially Good & Bad for AQ
Not Good for AQ
(D)
WS (Surface) = 3.05 kmph ; WD = Westerly
WS (Transport height) = 37.04 kmph ; WD = North-Westerly

Figure 4