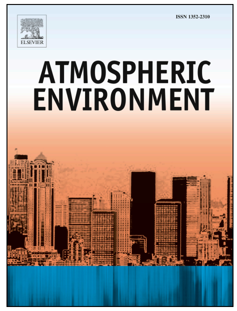

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Assessment of Contribution of Agricultural Residue Burning on Air Quality of Delhi using Remote Sensing and Modelling tools

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Abstract

Application of remote sensing in analysing the pollutant dispersion and concentration in the atmosphere has gained importance over the years amongst the researchers. Particulates, being a threat to human health is being closely monitored for its sources and transport, to implement respective mitigative measures. A study has been carried out to assess the contribution of agriculture residue/stubble burning (SB) in Haryana, Punjab region over the air quality of Delhi region. Monitoring is carried out using multidisciplinary approaches over the region during October and November 2017. A higher baseline value in Delhi is observed throughout the study duration. Both remote sensing and ground data from stations show similar characteristics. Local meteorological condition of study region, observed during the study duration, indicates that particulates from Punjab-Haryana region are not likely to be transmitted over Delhi region. The study performed using Aerosol Robotic Network (AERONET) shows some stubble burning aerosol subtype over Delhi region. Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) study shows that northwesterly winds intersect the agricultural residue burning regions, which might have transported the burnt stubble particulates towards Delhi area but is observed only during the days of November 2017. Further, the stubble burning aerosols are found to be dispersed at a height 3000m above the ground, which is out of the human vicinity. The month of October 2017 showed aerosol subtypes majorly from local emissions and dust. Delhi faces severe air pollution issues around human vicinity due to poor meteorological conditions and majorly because of local emission. The severe conditions, however, are generally short-lived and gradually ameliorates with improved meteorological conditions of the region.

Keywords: Aerosols; Aerosol Optical Depth; Aerosol Robotic Network; Cloud-Aerosol Lidar with Orthogonal Polarization; Hybrid Single Particle Lagrangian Integrated Trajectory Model; Navy Aerosol Analysis and Prediction System; Stubble burning

1. Introduction

Air pollutants have an adverse effect on humans, causing severe health issues. Major source for air pollution is due to unregulated anthropogenic activities such as urbanization, growth in construction works, higher vehicular transportation, etc (Patankar and Trivedi, 2011). Due to the increased risk of mortality and morbidity, air pollution and the science around its measurement and management have gained attention amongst the researchers. 2.1 million total deaths related to outside air pollution are reported in Asian countries for the year 2010 (Lim et al., 2012). A study by (Ghosh & Parida, 2015) reported that 65% of major polluted cities belong to India and are prone to severe problems due to poor outdoor air quality, having pollutant levels higher than the benchmark value set by National Ambient Air Quality Standards – India (NAAQS) .

Presently (WHO, 2014, 2016) has listed New Delhi, Indian capital, as one amongst highly polluted cities in terms of higher particulate matter (PM), reaching a peak value of PM around 350µg/m^3 which is 3.5 times the permissible standard of 100 µg/m^3 (NAAQS, 2009). New Delhi being home to 16.75 million with second highest population density (Census of India, 2011), is a major contributor in terms of air pollution. Delhi as a city has been subjected to very high particulate concentration exceeding the permissible limit set by NAAQS by 1.5 ~ 2.5 times (Mishra et al., 2015; Dey et al., 2012; Apte et al., 2011, Guttikunda & Calori, 2013). Researchers have come up with varied reasons for high air pollution in Delhi such as vehicular emission, industrial emissions, coal-based fuel ignition, blazing of biomass & waste, traffic dust (Pant & Harrison, 2012; CPCB 2016; Sharma et al., 2017; Guttikunda & Goel, 2013; Jethuva et al., 2018) as major contributors.

Higher concentration of pollutant in Delhi has effected human health, as they are continuously being exposed and particulate matter is a major pollutant. Major health issues among Delhi dwellers are respiratory problems like wheeze & cough, cardiovascular morbidity, chronic bronchitis and asthma, cancer risk and related mortalities (Chhabra et al., 2001; Banerjee et al., 2012; Pande et al., 2002; Khillare et al., 2012; Agarwal et., 2006).

Stringent measures by both state and central government are implemented to curb emission levels and to improve the air quality in Delhi. Some of the initiatives such as converting traditional fuels with CNG in buses and autos and odd-even numbered vehicles etc (Guttikunda & Calori, 2013) have made a small difference. Despite the implementation of several policies; rising pollution, the demand for better living standards, increased transportation & industrial sectors have aggravated the particulate concentration level in the region (Gurjar et al., 2016; Khillare et al., 2004). Other than local pollution, (Vadrevu et al., 2008; Jethva et al., 2018, 2019) reported that regional pollution majorly being stubble burning (SB) is a key contributor to aerosol emission and this is being explored here.

(Mishra & Shibata., 2012) reports that India is the second-highest contributor in aerosol emission due to SB after China. Researchers and government bodies are concerned about the SB process and its related emission, along with long-range transportation, as they directly or indirectly is connected with climate change (Chen et al., 2017). During the past decades, several kinds of research are carried out to study climate change activities as a result of aerosol loading (Kaskaoutis et al., 2012; Kedia et al., 2014). However, these emissions are limited to fewer weeks to months but have serious adverse health effects on humans (Choudhury and Dey, 2016). Northern regions of India in Indo-Gangetic plain(IGP) isfound heavily polluted with aerosols reaching optimum during April to May (pre-monsoon) and October to November (post-monsoon) which agrees with the fact that SB is carried after wheat and rice harvests, respectively during the same period (Vadrevu et al., 2011; Venkataraman et al., 2006; Gadde et al., 2009; Sharma et al., 2010; Mishra and Shibata, 2012). Improvised mechanized harvesting method followed by farmers in Haryana and Punjab region leaves with ground bound roots after harvest. Removing these remaining stalk and root is difficult and time consuming resulting in SB (Gadde et al., 2009; Kumar et al., 2015). According to the national and statewide inventory database for India, Punjab and Haryana rank higher in SB which tallies with the fire data reported by (Sharma et al., 2010). (Jethva et al., 2018; Cusworth et al., 2018, Vijaykumar et al., 2016) reported the influence of SB in Punjab, Haryana region over Delhi region using remote sensing data. But the studies lack in establishing a relation between data obtained by remote sensing and ground analysis data subjected to local meteorological conditions over the respective study regions. The aerosol type that corresponds to stubble burning is seldom justified in the mentioned recent studies with respect to the study area.

The present study is aimed at understanding the contribution of stubble burning emissions from Punjab and Haryana on air pollution in Delhi NCR through an integrated multi-sensory approach, consisting of satellite remote sensing data, ground based measurements (AAQMS), meteorological information (wind speed and direction), smoke concentration, vertical transport structure of smoke, back trajectory analysis of wind and aerosol type identification for Haryana, Punjab and Delhi region over the duration ranging from October 2017 – November 2017 using various aerosol analysing tools. The outcome of the study is to provide a satisfactory justification for the question of whether priority needs to be given in managing the local sources within Delhi NCR or the surrounding regional contribution.

2. Study Area & Methodology

2.1 Site Selection

Haryana, Punjab, and Delhi regions are considered for the study as shown in Figure 1. These 3 regions cover significant part of the Indo-Gangetic Plain (IGP), which is highly polluted (Singh et al., 2015) due to various natural and anthropogenic activities (Lodhi et al., 2013).

The study focuses on the state of Delhi in identifying the aerosol subtype and thereby its source using multiple disciplinary approaches as shown in table 1. When it comes to neighboring states of Delhi, Haryana and Punjab are majorly considered as these regions are subjected to heavy SB which might have an impact on Delhi air quality.

2.2 Moderate Image Spectroradiometer (MODIS)

NASA's MODIS Aerosol optical depth (AOD_{MODIS}) over land is retrieved using Dark target (DT) algorithm which is well suited over vegetated surface and Deep Blue (DB) algorithm over bright land (He et al., 2018) using TERRA and AQUA satellite. Studies (Sayer et al., 2014; Mhawish et al., 2017) found both DT and DB to overestimates and underestimates seasonal AOD changes respectively over IGP region. Despite the seasonal bias, studies found DT to be performing best in the region having identical accuracy in retrieving varying aerosol type and the same is preferred for our study. Due to the data gapping in MODIS DT-AQUA, AOD_{MODIS} derived from DT-TERRA reflection with spatial resolution 3 km at 0.55 µm (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD04_3K) is used to characterize the spatial and temporal variation of aerosol optical depth over the study region from October to November 2017.. The study area is extracted using ArcGIS tools. In this, each dataset is converted to point shapefile using Arc tools for spatial interpolation. Generated maps are used for analysing spatial distribution patterns of aerosol.

2.3 Aerosol Robotic Network (AERONET)

Due to the limitation in accuracy of satellite retrieved data in characterising aerosol by extraction of aerosol optical properties, We intend to use ground based sun photometer measurements from AERONET station installed at Gual Pahari (28.426N, 77.150E) for insitu measurements in Delhi region to identify the source and origin of pollutants. Due to unavailability of level 2.0 (quality-assured) AERONET data during the period of data collection, Both direct sun and diffused sky radiance of the range 340 – 1020 nm level 1.5 (cloud screened and quality controlled) is used for the study to analyse Absorption Angstrom Exponent (AAE), Extinction Angstrom Exponent (EAE), volume size distribution and single scattering albedo (SSA) for the study period October to November 2017. Volume size distribution is figured out using inversion algorithm retrieved from AERONET based sun/sky radiance data. Volume concentration is retrieved for particle of size 0.05– 15mm. The volume size distribution is characterized by the sum of two lognormal distributions (Dubovik and King, 2000) as shown in Eq (1).

$$dv/d\ln r = \left({Cv}/{\sigma\sqrt{2\pi}}\right) exp\left[-0.5\left(\frac{\ln({r}/{r_v})}{\sigma}\right)\right]^2 \qquad \text{Eq (1)}$$

Where, Cv is the Columnar concentration of aerosol particulates

σ is the Standard deviation

r_v is the mean volume radius.

2.4 Cloud Aerosol Lidar and Infrared Path Finder (CALIPSO)

CALIPSO satellite launched on April 28, 2006, with the collaboration of NASA and French agency CNES (Winker et al., 2007) as a purpose to serve weather forecasting reports and climate change modelling. CALIPSO operates at an altitude of 705 km and an inclination of 98° as part of the so-called “A-train” with a local afternoon equatorial crossing time of about 13:30 LST (ascending node). In order to understand the uplift of aerosol subtypes over the study regions, CALIPSO level 2.0 vertical feature mask (VFM) is retrieved based on the availability. Data for 7th October 2017 night for Delhi and Haryana, Punjab during the day on 5th November 2017 is retrieved.

2.5 The Navy Aerosol Analysis and Prediction System (NAAPS)

NAAPS is a 3D model developed by the Naval Research Laboratory (NRL) in Monterey uses semi lagrangian horizontal transport and finite element horizontal diffusion to identify the concentration and horizontal dispersion trend of aerosols such as SO_2, sulfate, dust, salt and smoke contributing to air pollution (Christensen, 1997). NAAPS model is available as 1° × 1°, at 6-hour intervals which uses threshold velocity, forecasted stress and ground wetness for dust and satellite fire data for smoke dispersion models (Westphal et al., 2014). In this study, concentration and distribution trend of dust and smoke over the study area during October and November 2017 are analysed to understand the contribution of SB over Delhi region.

2.6 Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT)

HYSPLIT model developed by National Oceanic and Atmospheric Administration (NOAA) Air Resource Laboratory's (ARL) with Meteorology from NCEP Global data assimilation system (GDAS) at spatial resolution of 0.5^o x 0.5^o and temporal resolution 1-6 hours is majorly employed in determining the long-range transport of particulates from biomass burning. Generally starting height for back trajectory analysis range from 100m to 4000m from the receptor locations. SB particles are assumed to be transported along the air mass trajectory without incorporating the effect of particle size, deposition and emission rates. In our study, 72 hours back trajectory analyses is carried at a height 500m, 1500m and 3000m with reference to the previous studies (Mishra and Shibata, 2012; Liu et al., 2018).

3. Results and discussion

3.1 Fire Radiative Power (FRP)

Rabi and Kharif crops are harvested during late winter and monsoon respectively in Indo-Gangetic plain region. (Sahu et al., 2015) reported that, to prepare fields for subsequent harvesting crop residue burnings are carried out in May (Rabi) and October (Kharif) months. FRP data for the previous 4 years ie., 2013, 2014, 2015 and 2016 are analysed to fix the study period. The amount of energy radiated during the time of fire is estimated using FRP

(Wooster et al., 2005). Readily available Visible Infrared Imaging Radiometer Suite-375m (VIIRS) FRP pixel data is retrieved from Fire Information for Resource Management System (FIRMS) (https://firms.modaps.eosdis.nasa.gov/). Figure 2 shows the cumulative value of all pixel level FRPs for the months April – May and October- November for all the 4 years. It can be noted that October- November month has the highest FRP and hence considered as the study period. An overall decrease in FRP pixel by 60% for the year 2017 can be noticed with respect to the previous year. This might be due to stringent norms introduced by government against SB (Bhuvaneshwari et al., 2019; Lohan et al., 2018; Kumat et al., 2015) or due to lower rice production for the year 2017 compared to previous as reported by (Jethva et al., 2019).

3.2 Ground Based Measurements (AAQMS)

Delhi has its pollution from various sources such as transportation, industries, biomass burning, diesel gen sets etc. Based on the availability of data, PM_{10}, $PM_{2.5}$, SO_2, NO_x and CO concentrations for the month of October and November 2017 are collected from Central Pollution control Board (CPCB) (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/caaqm-data-availability) source at ITO monitoring station, Delhi which is shown in Table 2. ITO monitoring station is the junction that is close to small industrial clusters and heavy traffics. For those datapoints for which data is unavailable, Anand Vihar station, which is close to ITO is chosen. As reported by (Guttikunda and Calori, 2012) transportation corresponds to 17% of $PM_{2.5}$, 53% of NO_X, 13% of PM_{10} & 18% of CO, whereas SB corresponds to 12% $PM_{2.5}$ & 14% of CO, industries corresponds to 23% of SO_2, 15% of CO & 14% of $PM_{2.5}$ and road dust corresponds to 22% of PM_{10}. From table 2A, for the month of October 2017, higher concentration of PM_{10} and increasing concentration of NO_X during the last weeks of the month could be noticed. These concentrations could imply that road dust and transportation sectors may be the prevalent sources during October month which is detailed in further sections. For the month of November 2017 as shown in Table 2B a higher concentration of PM is observed throughout the month. The stagnation of pollutants due to poor meteorological conditions might be a reason for higher PM concentration. Higher NO_X concentration is observed during beginning of second and end of fourth week. However, the accuracy of monitoring station data remains uncertain. Sources could be multiple during this month for which further in-depth study needs to be carried out.

3.3 Seasonal and temporal variation of AOD_{MODIS} with respect to Local meteorology

The Aerosol Optical Depth (AOD) maps are created every 10 days and on monthly basis for Delhi, Haryana and Punjab region for the months from October to November 2017, which is shown in Figure 3. The maps give spatial distribution patterns of AOD over Delhi, Haryana and Punjab with the corresponding colour range from blue to red.

The blue colour indicates the minimum AOD concentration and the red colour shows the maximum AOD concentration in the study area for MODIS data. Further, Table 3 shows the maximum, minimum and mean aerosol optical depth over the study area for 10 days interval during the month of October and November.

Table 3 summarises the variation in average AOD_{MODIS} from 0.4 to 1.2 during the month of October and November 2017. The maximum AOD_{MODIS} value of 1.873 and 2.157 is observed during the study period 21st -30th October and 1st – 10th November 2017 respectively. Overall AOD_{MODIS} study denoted higher AOD value in Delhi region throughout the study period when compared to any other region which may be due to higher anthropogenic activities and poor meteorological conditions in and around Delhi. This indicates that the baseline value itself is higher in Delhi, and when the condition worsens in terms of meteorology, it faces a comparatively higher impact with respect to other regions studied here.

Remote sensing images observed in Figure 3 shows overall higher AOD_{MODIS} in the northwestern region of Punjab and in Haryana region for the period 1st – 10th October 2017. Delhi had AOD of 0.4 during the period. Meteorological conditions like wind speed, wind direction, temperature play a significant role in dispersing the pollutants attributable to AOD change (Goyal and Krishna, 2002; He et al., 2019a; He et al., 2019b). Low wind speed over Delhi region for the period as shown in Figure 4 has resulted in a stable atmosphere resulting in poor dispersion of pollutants. Observing the wind direction for the same study period, it could be noticed that prominent wind direction is away from Delhi region, ie., towards Haryana Punjab region from Delhi region. AOD_{MODIS} value of 0.8-1.2 is observed in the central part of Haryana & Punjab which signifies crop residue burning after the harvest might have been initiated during the period 11th-20th October 2017. A very low wind speed of about 0.4m/s is observed at higher AOD regions of Delhi during the period. A better meteorological condition over the southern part of Haryana, as in Figure 4 is observed, which must have dispersed the pollutant over fewer regions of Delhi showing higher AOD over those regions in Delhi. Higher AOD for the study period 21st October – 30th October is observed throughout the region of Haryana, Punjab and Delhi. Higher AOD over Punjab and Haryana must be due to stubble burning and in Delhi must be due to local anthropogenic activities. Major regions of Haryana and Punjab show very low wind speed, which stagnates the pollutants in atmosphere. A comparatively higher wind speed of about 2.5m/s is observed over Delhi region dispersing the pollutants away from Delhi in northwestern direction but still a higher value of AOD covered the region of Delhi. This led to a focus towards the meteorological term called "inversion". This occurs mainly during winter due to lower temperatures at low altitudes which develops a boundary layer aiding in the trapping of the particles (Komppula et al., 2012).

Figure 5 shows the mean temperature profile over the study regions at 850hpa and 1000hpa. For the month of October 2017, a higher temperature of the range 21-24^{o}C at 1500m altitude and 29-35^{o}C near the surface has favored environmental lapse rate condition resulting in dispersion of pollutants. For the month 1st – 10th of November, 2017 a maximum AOD_{MODIS} up to 2.15 is observed in the major regions of Punjab. Subsequently, higher values of AOD_{MODIS} are observed in other regions of Punjab, Haryana and Delhi. Higher wind speeds up to 2.7m/s is observed over the central part of Punjab dispersing the pollutant in south east direction i.e., towards Delhi.. During the same period, Delhi also observed high AOD, exacerbated with poorly favored meteorological conditions like low wind speed (Figure 4) and temperature – 1000hpa (Figure 5). This could be due to transport of SB particles if lower smoke aerosol vertical profile at SB region using CALIOP could be identified. Decrease in windspeed is observed while approaching Delhi from SB region which might have hindered the transport of pollutants. Figure 5 shows $T_{1000hpa}>T_{850hpa}$ for the month of November, 2017 showing unlikely potential for inversion condition resulting in favourable dispersion conditions in SB regions. Inversion is commonly reported in Delhi during winters by various studies (CPCB, 2016; Tyagi et al., 2016; Singh, 2016; CPR, 2017). There exists uncertainty in terms of spatial (42Km X 42Km) and temporal (1 month-Avg) resolution for temperature data retrieved from the satellite for the study area. Taking into account this uncertainity, study is further carried out considering the previous studies which state the potential for the formation of inversion layer during November, 2017.

During the period 11th – 20th November 2017 a lower AOD over Haryana and Punjab region is observed irrespective of wind speed and is vice versa in the case of Delhi. This indicates that local emissions are more prominent and is degrading the quality of air around the region. During November 2017 from 21st – 30th a higher wind speed up to 4.0m/s is observed over Delhi region and southern parts of Haryana thereby dispersing the pollutants away from Delhi showing lower AOD as observed in Figure 3.

Figure 6 shows the fire counts data retrieved from FIRMS for the study period and location. The data correlates well with the AOD_{MODIS} generated. A higher fire count (>2500 up to 5000) is observed during the last and first week of October and November 2017 respectively for which the maximum AOD is observed. There is an increase in fire count during the last few days of 2nd week of November 2017 showing poor reduction in AOD compared to subsequent weeks.

3.4 Classification of aerosol type

Aerosol types identification is carried out by retrieving various aerosol characteristics like Single Scattering Albedo (SSA) scatter plot (Dubovik et al., 2002; Giles et al., 2012; Eck et al., 2003; Lee et al., 2010; Srivastava et al., 2012; Tariq et ali, 2015; Mishra et al., 2014; Bibi et al., 2016; Bibi et al., 2017), Absorption angstrom exponent (AAE) Vs Extinction angstrom exponent (EAE) (Russell et al., 2010; Mishra et al., 2014; Tariq et al., 2015; Bibi et al., 2016) and volume size distribution (VSD) (Dubovik et al., 2000; Eck et al., 2003; Omar et al., 2005; Mishra et al., 2014; Tariq et al., 2015) from ground based aerosol network over Delhi region (28^{0}N & 77^{0}E).

Figure 7 shows the scatter plot graph for AAE (440-870 nm) Vs EAE (440-870 nm) over Delhi region for the month of October & November 2017. (Bibi et al., 2016) classified aerosol types for Indo-Gangetic region based on AAE Vs EAE graph as dust ($0.01<EAE<0.4$ & $1.0<AAE<3.0$), SB ($0.8<EAE<1.7$ & $1.1<AAE<2.3$), Urban/Industrial (U-I) ($0.8<EAE<1.6$ & $0.6<AAE<1.3$). As aerosols blend with one another due to meteorological mixing, it is difficult to individually identify the types based on the set of ranges suggested by (Bibi et al., 2016). Hence, the classifications used by (Mishra et al., 2014) for his study are employed here. The study classifies ($0.05<EAE<0.8$ & $1.3<AAE<2.2$) as type 1 which is dominated by dust which is moderately mixed with U-I. Type 2 ($0.45<EAE<0.76$ & $0.7<AAE<1.3$) distinguish the presence of higher black carbon pollutants from industries and vehicles coated with moderate dust. Combination of black carbon (BC) due to incomplete combustion of stubble or fossil fuel with SB aerosols ie., organic carbon (OC) is classified as type 3 aerosols (0.85<EAE & 0.7<AAE<1.4). From Figure 7, it is observed that type 2 aerosols are prominent over Delhi region during the month of October. The same is observed by (Dey et al., 2008; Srivastava and Ramachandran, 2012; Mishra et al., 2014). This mainly may be due to the increased number of vehicles and stagnation due to poor met conditions in the study area. (Rizwan et al., 2013) in his study reported an average growth estimate of 7% every year in vehicular population. Brick manufacturing, which is one of the most polluting factories in north India is found operational during the months of October (Guttikunda & Calori, 2012). Hence industrialization can also be a reason for higher type 2 aerosols. As our study is majorly focusing on the effect of stubble burning over Delhi region, we focus on type 3 aerosols which are observed during 6th, 7th and 9th of November 2017.

For a further robust decision in identifying the aerosol type, VSD and SSA are plotted as shown in Figure 8(a), (b) and 9(a), (b) respectively. Aerosol categories are additionally classified as polluted dust (PD: High dust + low U-I), Polluted continental (PC: Low dust + High U-I), Black carbon (BC), organic carbon (OC) and non-absorbing aerosols (NA) (Sulphates & Nitrates) (Srivastava et al., 2012; Mishra et al., 2014). From Figure 8(a), it is evident that 3 different cases, as reported by (Xu et al., 2015), existed during the month of October and November 2017 over the Delhi region. Case (A) during 5th, 6th, 7th and 9th of October 2017 dominated by coarser particle. Case (B) during 8th, 10th October and 5th November 2017 showing a well-mixed combination of both fine and coarse particles. Case (C) dominated by fine mode particles during 6th, 7th and 9th of November 2017. It is evident from VSD that type 3 aerosol showed the highest fine concentration of the range 0.18 - 0.25 $\mu m^3/\mu m^2$ at 0.25 -0.3 µ during 6th, 7th and 9th of November. Type 2 aerosol showed a maximum coarse mode concentration of 0.12 $\mu m^3/\mu m^2$ which is approximately 50% lesser than the type 2 aerosol coarse concentration reported by (Mishra et al., 2014) over Delhi region during pre-monsoon season. This justifies that type 2 aerosols majorly fall under the classification of PC. However, the portion of fine particle concentration increased during the first week of November 2017 which might be due to long-range transport of smoke particles at higher heights beyond human vicinity from Haryana, Punjab region. As it is clear from local meteorological data that chances of stubble reaching Delhi area from far areas of Punjab and Harayana is extremely difficult. Further investigation is carried out in section 3.5. Single scattering albedo (SSA) procured from almucantar retrieved aerosol properties shows different spectral properties depending upon the type of aerosol. SB/U-I aerosols solely exhibit a decreasing trend with increasing wavelength (λ) and vice versa for desert dust (DD) aerosols solely (Dubovik et al., 2002). SSA can also be used to identify absorbing and non-absorbing aerosols (Bibi et al., 2017; Kedia et al., 2014). SSA from Figure 9(a) & (b) is compared the previous studies carried by various researchers as mentioned in table 4 to identify the range of absorptivity for each aerosol type. Comparing table 4 with SSA graph, it can be noted that SSA_{438} for 6th, 7th, and 9th of November 2017 satisfies the SSA_{438} for OC+BC as defined by (Mishra et al., 2014). SSA for 6th and 7th October 2017 is eliminated due to higher uncertainty as these days showed AERONET-AOD value less than 0.4 (Jo et al., 2017). 8th and 10th October 2017 showed enhanced absorption showing lower SSA due to dominance of both coarse mode dust and fine mode BC aerosol. Lower SSA value with respect to increasing wavelength during 6th, 7th, and 9th of November 2017 might be due to fine mode absorbing aerosol particles. A similar increase in SSA trend with wavelength is noticed by (Kaskaoutis et al., 2014) during late burning period in the initial weeks of November over Delhi region which is due to the mixing of pollutants and aging process. The SSA graph for the last 3 study days of November 2017 is consistent with study carried out by (Kedia et al., 2014) during postmonsoon season for Kanpur region in which, a similar pattern is observed showing abaudance of black carbon in the region. Weaker scattering for coarse over fine particles is observed during study period. An increasing trend in SSA_{438} is observed throughout the study period which is an indication showing a shift towards fine mode BC as major pollution source.

For even further clarity in analysing the aerosol types are classified based on particle size and absorptivity (Higurashi and Nakajima, 2002; Wang et al., 2015) as carbonaceous (Absorbing & Fine mode), Soil/Dust (Absorbing & Coarse Mode), Sulphate (Non absorbing & Fine mode) and sea salt (Non absorbing & Coarse Mode) clubbing both VSD and SSA. Employing the classification made by (Higurashi and Nakajima, 2002) it can be noticed that soil/dust aerosols are prominent during the month of October 2017. This can be very much related to (Khemani et al., 1985) in which it is reported that Delhi constitutes of dusty soil. (Kedeia et al., 2014) in her study reported that lower SSA value over IGP region (25.871N, 84.128E) is due to the dominance of either only BC or BC + dust. Wood burning and fossil fuel are the major sources reported by previous studies (Sharma et al., 2003; Chowdhury et al., 2007; Wang et al., 2015) for the carbonaceous type of aerosol observed during the month of November, 2017. For distinguishing OC & BC from type 3 aerosols, NAAPS & HYSPLIT model must be analysed which is carried out in further section.

3.5 NAAPS & HYSPLIT study

Figure 10(a) shows the PC type aerosol being dominant over Delhi region during 7th October 2017 which satisfies the AERONET data. Polluted dust is the second dominant aerosol subtype that can be observed which is due to dust elevated from topsoil due to convection activities (Srivastava et al., 2012). A smaller fraction of smoke could be noticed over the same region which might be due to local carbonaceous emission. The same is supported with NAAPS model as in Figure 11(a) interpreting higher concentration of dust (40-80 µg/m^3) followed by lower smoke concentration (1-2 µg/m^3) over Delhi region. Based on the availability of data, the vertical profile of aerosol subtype for Punjab Haryana region is derived for 5th of November 2017 as shown in Figure 10(b). The vertical profile shows the dominance of smoke from 2Km height above ground with a thickness of 1.5km along with combination of PC. (Sharma et al., 2010; Shaika et al., 2019) reported a vertical aerosol layer up to 3Km over the Central India region due to heavy agricultural crop burning activity.

The same vertical smoke profile is observed by (Vijay Kumar et al., 2016) for his study on Indo-Gangetic region during the month of November and is concluded as an effect of crop burning. Vertical convection of biomass particles may be due to substantial amount of heat produced during SB activity carried at night time near the ground (Freitas et al., 2006; Trentmann et al., 2008) resulting in forced convection. This forced convection mixes with pollutants within human zone of existence assisted by sunlight rising to higher vertical heights (Mishra & Shibata, 2012). No CALIOP data for Delhi, Haryana, and Punjab could be retrieved for the required days ie., 6th, 7^{th,} and 9th of November 2017. Due to unavailability of data, the study is advanced considering the CALIOP vertical smoke profile for Punjab Haryana region retrieved on 5th November 2017 for the remaining study periods of November 2017.

Figure 11(b)(c) exhibits a higher smoke concentration of range 64-128 µg/m^3 during 28th (12hrs), 29th (18hrs) and 5th (18 Hrs) November in Haryana, Punjab region due to heavy stubble burning and the same is observed during 6^{th} November (06 Hrs) for the same region. This data correlates well with fire count retrieved for the study duration as shown in Figure 6. A dispersion trend in both Figure 11(c) & (d) could be Figured out, dispersing smoke more towards Delhi region showing a concentration of 32-64 μg/m^3 on 6th November 2017 (12 Hrs).

To study the aerosol dispersion trend, HYSPLIT back trajectory (Draxler and Hess, 1998) for the height 500m, 1500m and 3000m are retrieved for 6^{th}, 7^{th} and 9^{th} of November, 2017. HYSPLIT back trajectory altitude is assumed on the basis of vertical smoke profile for Haryana region (Figure 10(b)). HYSPLIT depicted in Figure 12(b) shows all the 3 back trajectories at defined altitudes intersect with the SB region retrieved for 6^{th} November 2017. Northwesterly wind at an altitude 3000m intercepts the major part of Haryana Punjab region at an altitude ≃3200m above the ground on 5^{th} of November 2017 (18Hrs) which in turn has higher smoke concentration as retrieved from NAAPS model for the same duration (Figure 11(c)). Researchers (Jethva et al., 2018; Mishra and Srivastava et al., 2014) also reported that northwesterly winds intersected SB region of Punjab Haryana before advection of particulates over Delhi region. Overall SB for Haryana region is lower compared to that of Punjab region. Trajectories at an altitude 500m and 1500m are due to easterly winds which intersect with major part of Haryana at altitude ≃1000m and ≃2000m respectively where overall SB is less. 1500m trajectory intersects with minor SB region of Punjab at a height ≃2000m for which the vertical smoke profile is observed and eventually might get dispersed before reaching the Delhi region. It can be observed that contribution of Punjab SB towards ground level pollution (≃500m) is nil and with respect to Haryana is minor. This shows that SB had a lower impact on Delhi air quality at ground level, major being the BC released from fossil fuel combustion for 6^{th} of November 2017.

Assuming the same vertical smoke profile altitude in Haryana Punjab region on 6^{th} and 8^{th} of November 2017 as that of 5^{th} November 2017, HYSPLIT back trajectory is retrieved as shown in Figures 13 & 14. Back trajectories at all 3 altitudes for 7^{th} and 9^{th} November 2017 shows wind from northwesterly side before reaching Delhi area intersecting the SB regions majorly in Punjab as SB is less in Haryana for the observed days. However, the findings remain same when interpreting on the basis of CALIOP vertical profile. It is important to take into consideration that, this study purely depends on the data retrieved from various ground and remote sensing based sensors holding some limitations/uncertainties. To fill these data gaps, sensor based results need be validated knowing the ground truth. Authors do not oppose any previous findings which explicitly stated the contribution of SB from neighbouring states on Delhi air quality. After all, the overall analysis depends on the meteorological conditions which are highly uncertain leaving any predictions dubious. As a matter of time, it is vital to develop and incorporate robust validation tools/techniques to overcome limitations/uncertainties so as to improve the quality of study.

3.6 Conclusion

The effect of stubble burning in Punjab Haryana region over Delhi air quality is scrutinized in this study using remote sensing and ground sensor instruments employing various models in identifying the aerosol subtypes.

The results are summarized as follows.

1. Remote sensing data showed a higher AOD value throughout the study period in Delhi which then aggravated during the initial weeks of November. The AOD data retrieved for the month of November 2017 for Haryana-Punjab region goes handy with the fire data and NAAPS model during the same period indicating that the region faced heavy stubble burning.

2. Local meteorological data (wind speed, direction) during stubble burning period is found to be stable over Delhi region which has resulted in the stagnation of pollutants. The smoke from stubble burning regions is prominent over a height above 2Km, hence the influence of local meteorology is negligible in transporting the stubble burning aerosol over Delhi. This leads to the conclusion that local anthropogenic activities along with meteorological condition within Delhi area are the major reason that detriment Delhi's air quality during the study period

3. AERONET study showed a shift towards carbonaceous type of aerosol during the first week of November, 2017. Concluding a particular source can be inexact due to existence of insitu carbonaceous sources in the region. HYSPLIT data shows that North-western wind intersects stubble burning regions of Haryana, Punjab at a height of the range 500-3000m benefiting long-range transport of smoke particles. Moreover, the study also leads to the conclusion that most stubble particles are stagnated at a height 2Km above SB region, which

is dispersed effectively by westerly wind at higher heights approx. 3000m towards Delhi. The dispersion trend is well captured by NAAPS model as well. Hence, the effect of stubble burning in the human vicinity can be considered negligible.

4. Considering the multidisciplinary analysis viewed with respect to the assumptions specified in the study and the 3 episodic days of study ie., 6^{th} ,7^{th} and 9^{th} of November, 2017, it can be safely concluded that the effect of agricultural residue/stubble burning on air quality of Delhi is very small. Delhi has its own emission, which becomes a problem during the period due to stagnation and inversion layer formation. The local meteorology does not help in the dispersion of pollutants leading to alarming accumulation of pollution. The small effect of agricultural burning which can be seen is from the immediate vicinity of the city and long range transport from Punjab and Haryana are unlikely. It is worthwhile to mention that atmospheric behaviour changes from time to time and detailed study should be carried out while making detailed abatement plans. Further, a detailed ground truthing and molecular marker study would be helpful in making more robust conclusions and can form a future scope of research.

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Disclosure statement

Declaration of interest: NONE

List of tables

Table 1: List of data sets along with retrieval location

Sl. No	Data collected	Retrieval location
1	Aerosol optical depth (AOD)	Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center (LAADS DAAC)
2	Ground based measurements for particulate matter (PM_{10}, $PM_{2.5}$, NO_X, SO_2, CO) concentration	Central pollution control board, India (CPCB)
3	Temperature	European Centre for Medium-Range Weather Forecasts (ECMWF)
4	Fire radiative product (FRP)	Fire Information for Resource Management System (FIRMS)
5	Metrological information such as Wind speed (WS) & Wind direction (WD)	Prediction Of Worldwide Energy Resources (POWER)
6	Smoke concentration and its horizontal distribution	Navy Aerosol Analysis and Prediction System (NAAPS)
7	Vertical distribution profile of smoke	Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)
8	Aerosol type identification using Absorption amstrong exponent (AAE), Extinction amstrong exponent (EAE), Volume size distribution, Single scattering albedo (SSA)	Aerosol Robotic Network (AERONET)
9	Back trajectory analysis of wind	Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)

Table 2A: Pollutant concentration for the month of October, 2017

	Anand vihar	**ITO**	**ITO**	**Anand Vihar**	**Anand Vihar**
Date	**PM_{10} (µg/m³)**	**$PM_{2.5}$ (µg/m³)**	**NO_X (µg/m³)**	**SO_2 (µg/m³)**	**CO (mg/m³)**
01	NA	7	41.4	NA	NA
02	NA	3	43.9	NA	NA
03	NA	13	17.1	NA	NA
04	NA	15	8.5	NA	NA
05	NA	4	24.4	NA	NA
06	NA	13	19.5	NA	NA
07	NA	14	17.1	NA	NA
08	NA	14	26.8	NA	NA
09	NA	16	53.6	NA	NA
10	NA	0	74.3	NA	NA
11	NA	0	52.4	NA	NA
12	NA	0	36.6	NA	NA
13	NA	0	35.3	NA	NA
14	NA	0	52.4	NA	NA
15	NA	0	36.6	NA	NA
16	NA	0	31.7	24	4
17	NA	57	20.7	18	4
18	NA	150	40.2	22	3
19	NA	135	30.5	23	3
20	NA	0	25.6	46	4
21	NA	51	32.9	24	5
22	NA	0	41.4	19	3
23	728	22	52.4	31	4

24	594	0	59.7	21	4
25	698	0	62.2	24	4
26	730	0	90.2	26	5
27	449	3	70.7	21	3
28	517	24	79.2	39	3
29	459	0	68.2	32	2
30	690	3	47.5	27	4
31	486	134	46.3	25	3

NA- Not Available

66 **Table 2B:** Pollutant concentration for the month of November, 2017

	ITO	**ITO**	**ITO**	**Anand vihar**	**Anand vihar**
Date	**PM_{10} (μg/m^3)**	**$PM_{2.5}$ (μg/m^3)**	**NO_X (μg/m^3)**	**SO_2 (μg/m^3)**	**CO (mg/m^3)**
01	NA	0	0.0	13	3
02	NA	76	18.3	21	2
03	NA	241	58.5	15	1
04	NA	252	68.2	34	3
05	NA	298	59.7	28	4
06	NA	247	86.5	29	4
07	NA	461	191.3	16	5
08	NA	513	508.2	23	5
09	NA	597	683.7	16	6
10	NA	360	1202.9	21	4
11	NA	348	1228.4	14	6
12	NA	451	NA	17	5
13	NA	285	299.8	16	4
14	254	209	91.4	16	4
15	219	175	140.2	20	4
16	185	154	96.3	25	2
17	152	121	31.7	20	2
18	144	124	23.2	17	2
19	126	112	23.2	22	2
20	178	154	40.2	17	2
21	209	169	56.1	18	3
22	222	175	39.0	17	3
23	205	157	56.1	18	3
24	213	164	62.2	14	3

25	212	164	109.7	18	3
26	241	202	180.4	19	4
27	191	173	85.3	18	3
28	141	142	163.3	17	4
29	176	178	258.4	23	6
30	170	176	204.7	20	4

Table 3: AOD_{MODIS} variation in Delhi, Haryana, and Punjab region for the month of October & November, 2017.

Duration(Days - 2017)	**Minimum**	**Maximum**	**Mean**
01-10 Oct	0.085	0.876	0.477
11-20 Oct	0.216	1.352	0.601
21-30 Oct	0.263	1.873	0.958
01-10 Nov	0.446	2.157	1.247
11-20 Nov	0.151	1.876	0.658
21-30 Nov	0.118	0.882	0.447

Table 4: Single scattering albedo (SSA) study carried out by researchers for various aerosol types over IGB region.

Srivastava et al., 2012	Tiwari et al., 2015	Mishra et al., 2014	Kaskaoutis et al., 2014
PD: $SSA_{675} \simeq 0.915$	PD: $0.87 < SSA_{438} < 0.92$	PD: $SSA_{438} \simeq 0.88$	
PC: $SSA_{675} \simeq 0.895$	PC: $0.87 < SSA_{438} < 0.91$	PC: $SSA_{438} \simeq 0.89$	
BC: $SSA_{675} \simeq 0.87$	BC: $0.87 < SSA_{438} < 0.89$	BC+OC: $SSA_{438} \simeq 0.83$	BC: $SSA_{438} \simeq 0.91$
OC: $SSA_{675} \simeq 0.905$	OC: $SSA_{438} \simeq 0.92$		
NA: $SSA_{675} \simeq 0.95$			

List of Figures

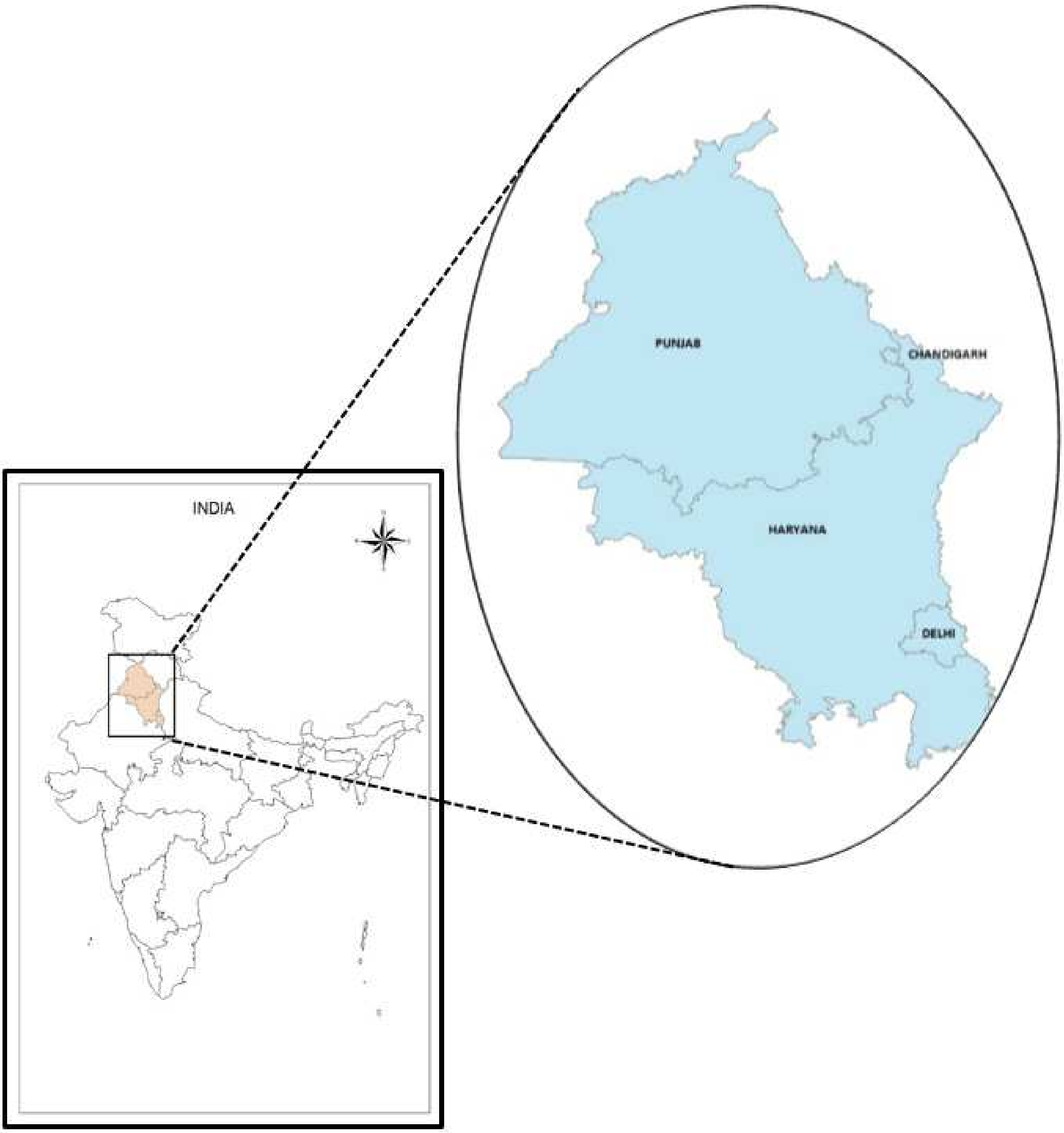


Figure 1: Study area showing Punjab, Haryana and Delhi region

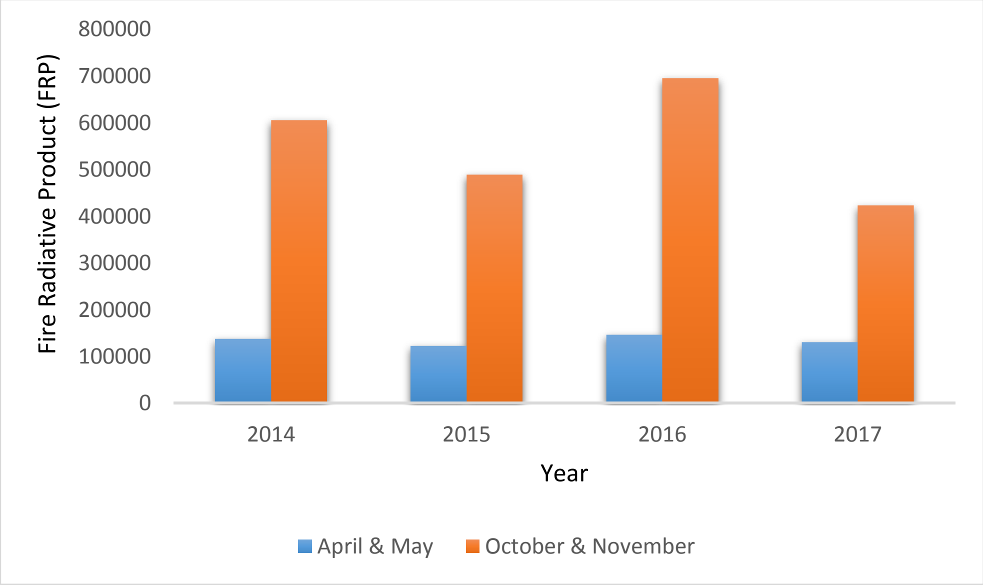
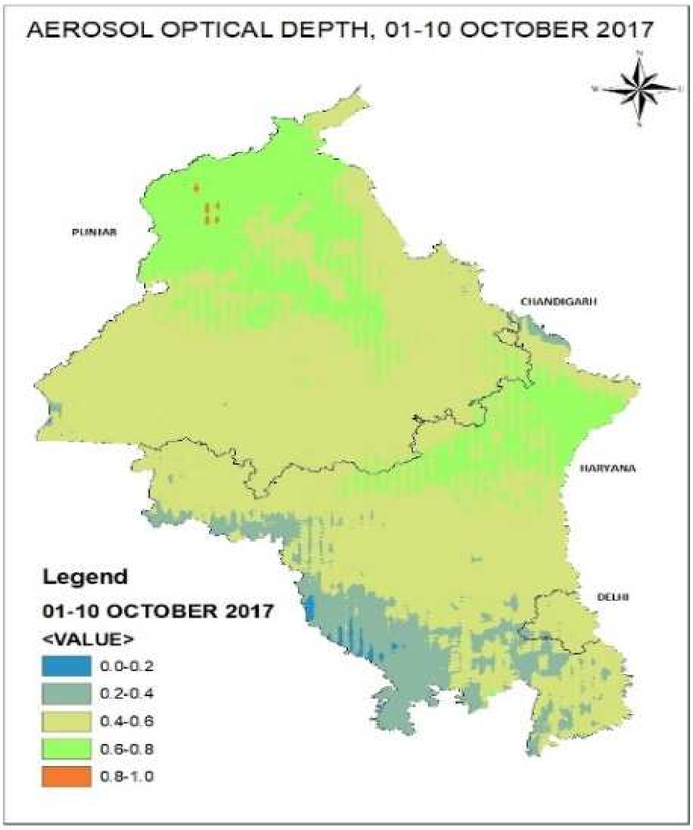
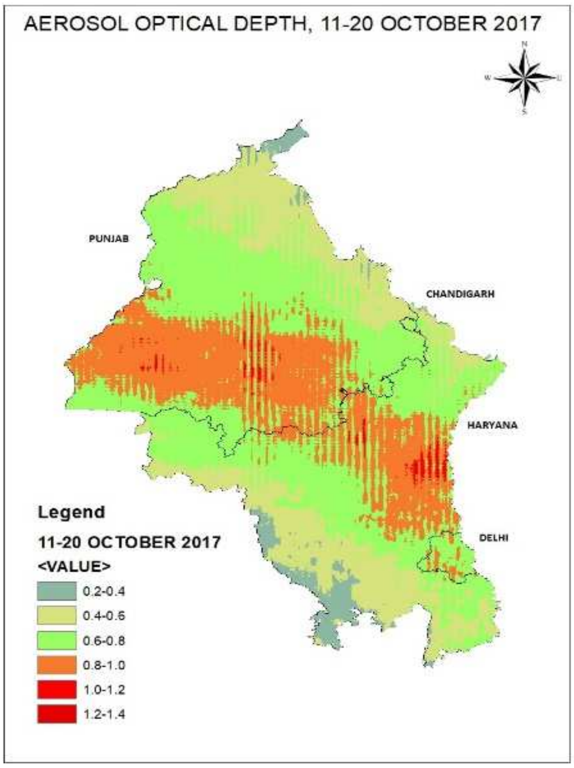
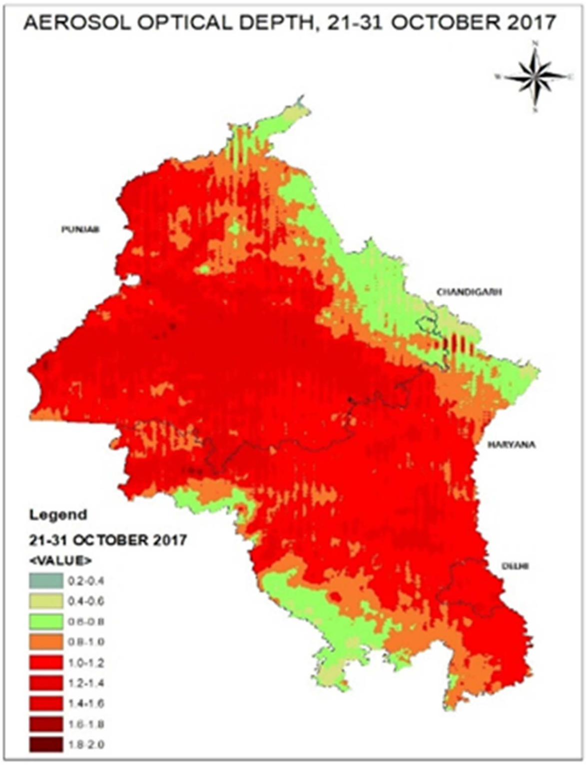


Figure 2: Fire radiative power (FRP) data for the year 2014, 2015, 2016 & 2017.


AEROSOL OPTICAL DEPTH, 01-10 OCTOBER 2017
PUNJAB
CHANDIGARH
HARYANA
DELHI
Legend
01-10 OCTOBER 2017
<VALUE>
0.0-0.2
0.2-0.4
0.4-0.6
0.6-0.8
0.8-1.0


AEROSOL OPTICAL DEPTH, 11-20 OCTOBER 2017
PUNJAB
CHANDIGARH
HARYANA
DELHI
Legend
11-20 OCTOBER 2017
<VALUE>
0.2-0.4
0.4-0.6
0.6-0.8
0.8-1.0
1.0-1.2
1.2-1.4


AEROSOL OPTICAL DEPTH, 21-31 OCTOBER 2017
PUNJAB
CHANDIGARH
HARYANA
DELHI
Legend
21-31 OCTOBER 2017
<VALUE>

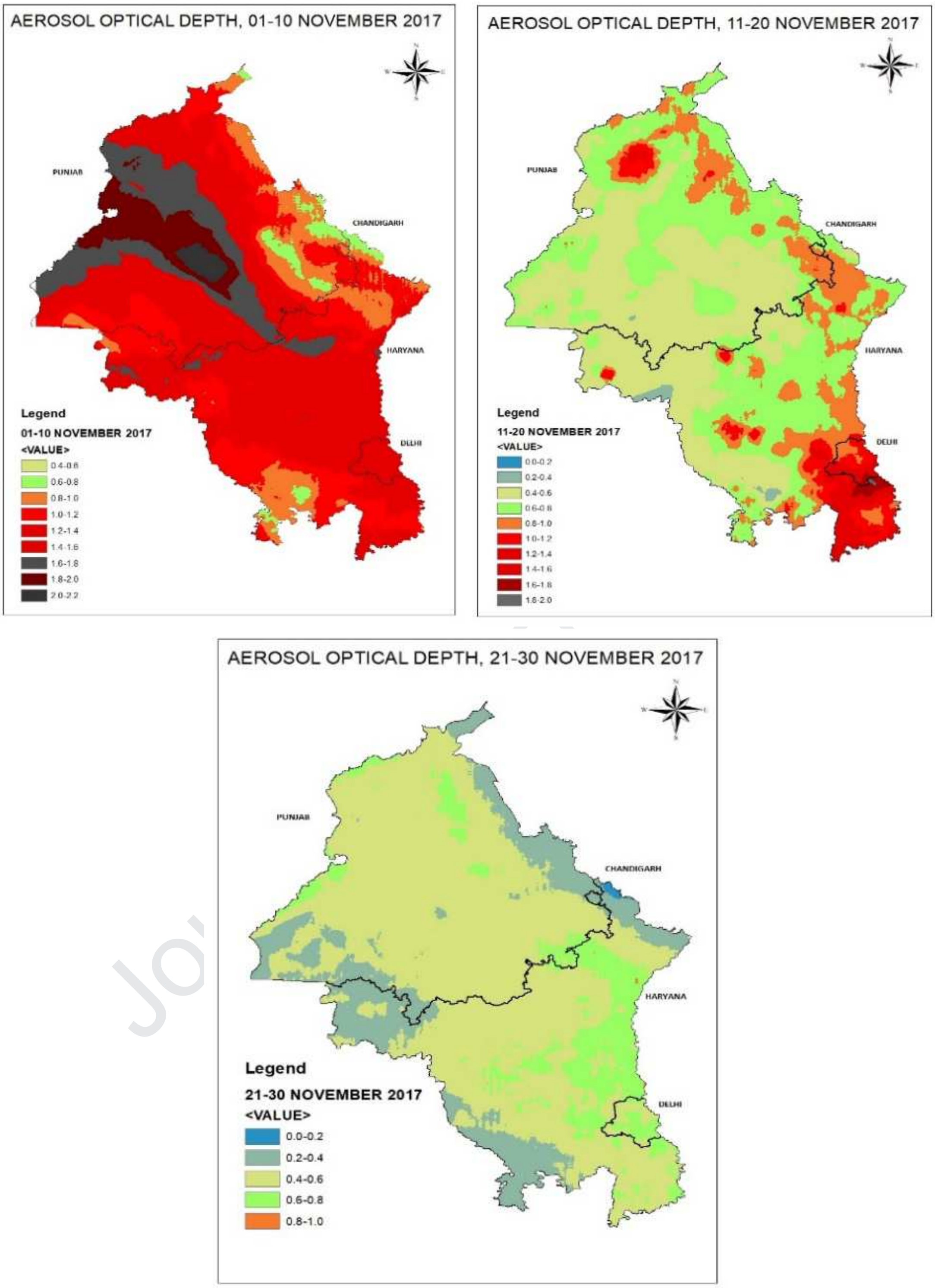
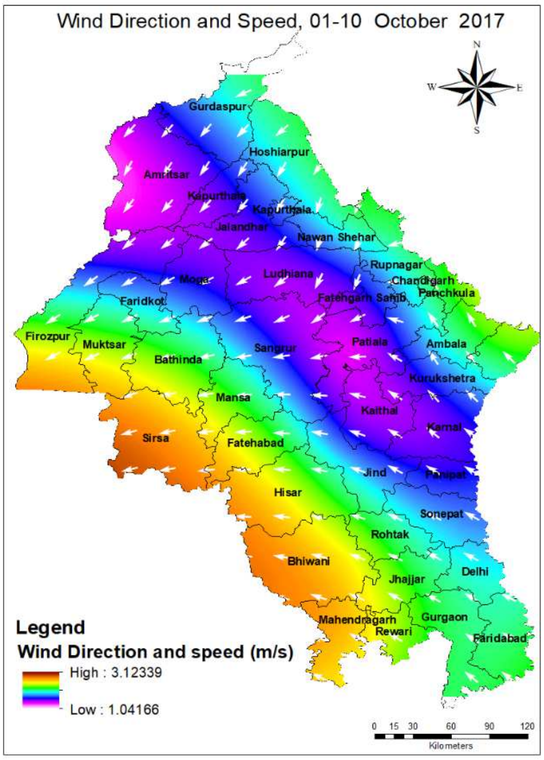
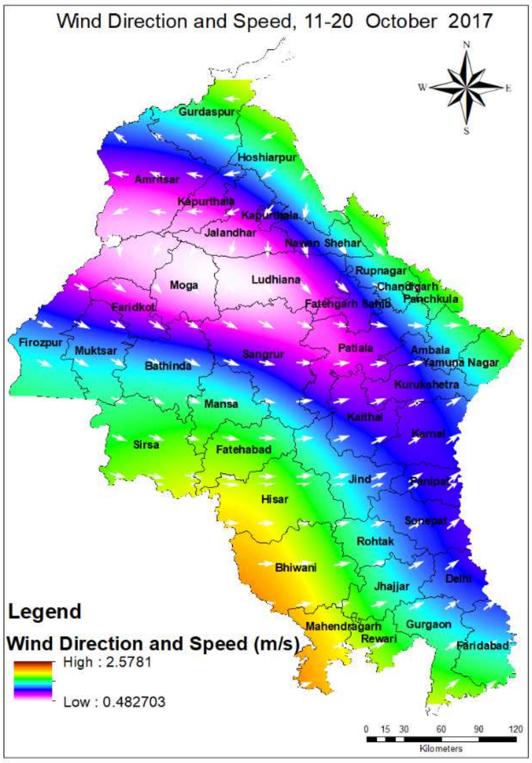
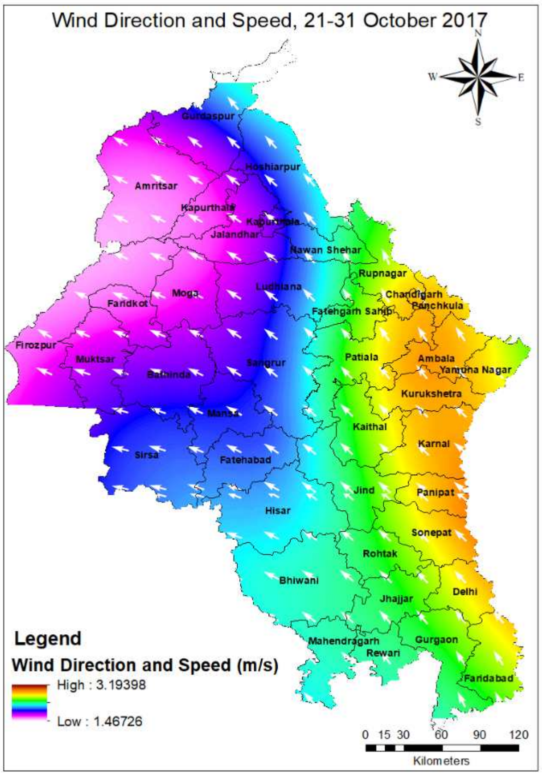
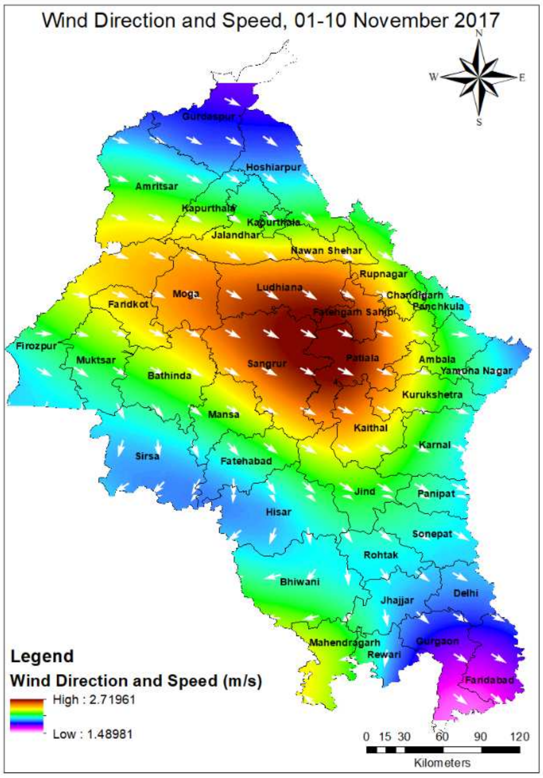


Figure 3: Temporal variation of Aerosol optical depth (AOD_{MODIS}) for the month of October & November 2017 over Haryana, Punjab and Delhi region


Wind Direction and Speed, 01-10 October 2017
Legend
Wind Direction and speed (m/s)
High : 3.12339
Low : 1.04166
0 15 30 60 90 120
Kilometers


Wind Direction and Speed, 11-20 October 2017
Legend
Wind Direction and Speed (m/s)
High : 2.5781
Low : 0.482703
0 15 30 60 90 120
Kilometers


Wind Direction and Speed, 21-31 October 2017
Legend
Wind Direction and Speed (m/s)
High : 3.19398
Low : 1.46726
0 15 30 60 90 120
Kilometers


Wind Direction and Speed, 01-10 November 2017
Legend
Wind Direction and Speed (m/s)
High : 2.71961
Low : 1.48981
0 15 30 60 90 120
Kilometers

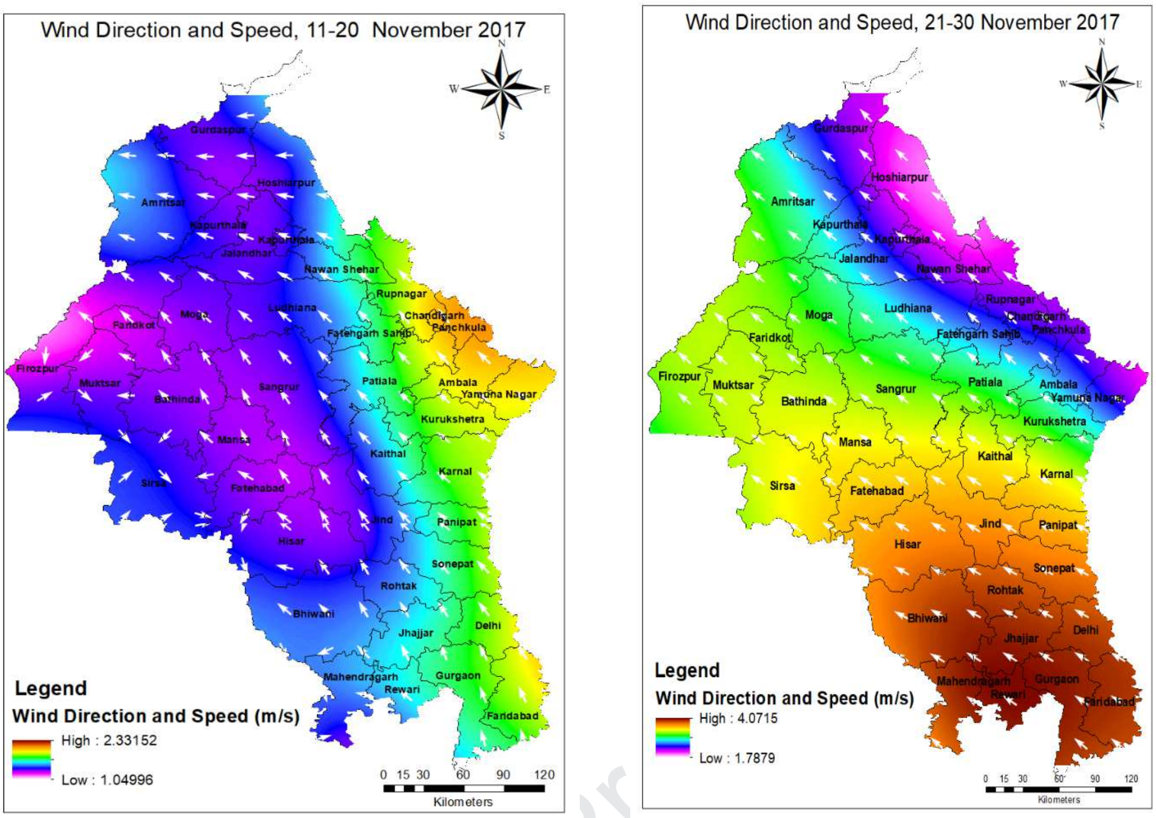


Figure 4: Wind speed & Direction at 10m altitude for Haryana, Punjab and Delhi region for the month of October and November, 2017.

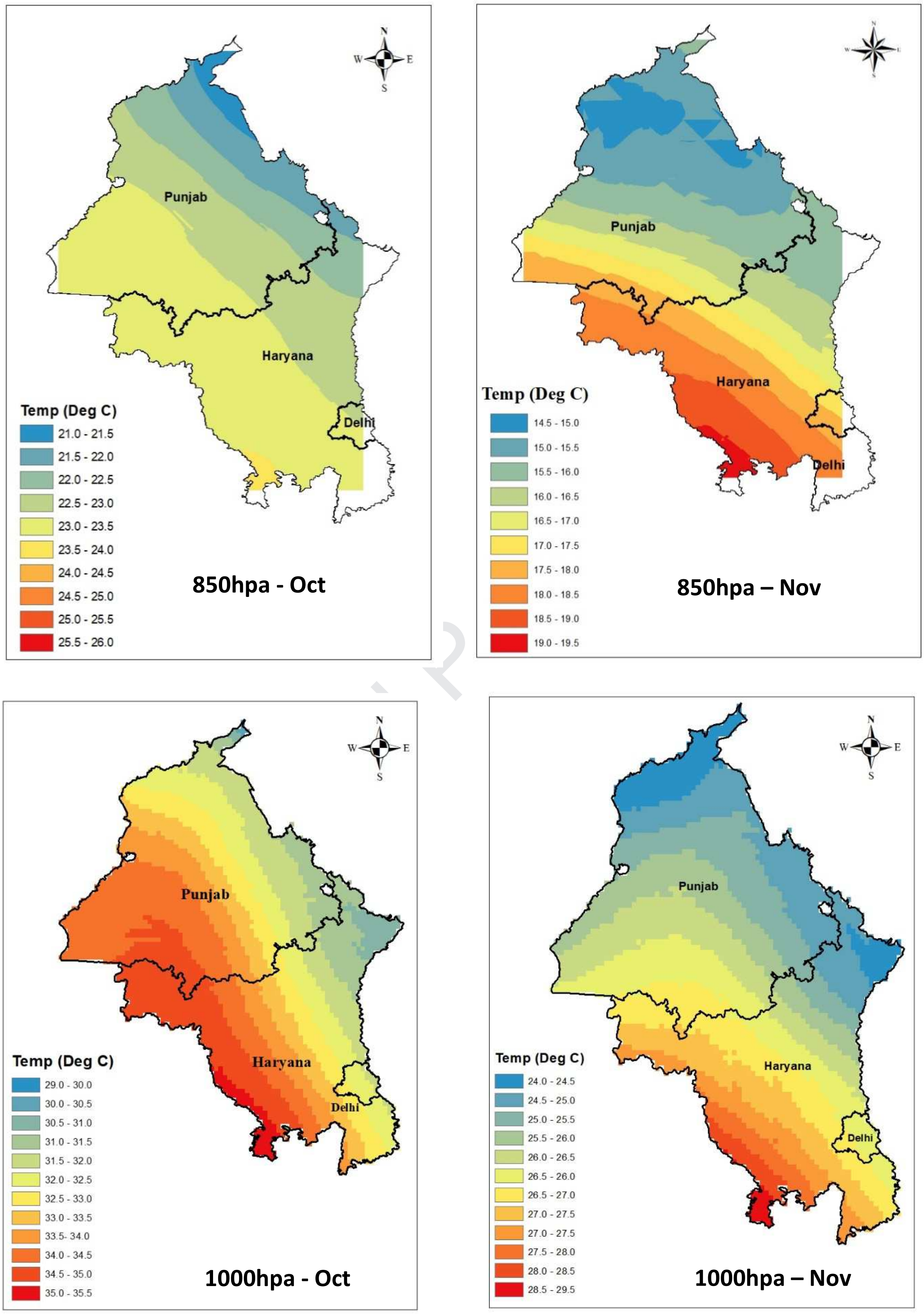


Figure 5: Mean temperature at 850hpa and 1000hpa for the month of Octoberand November, 2017 over Haryana Punjab and Delhi region.

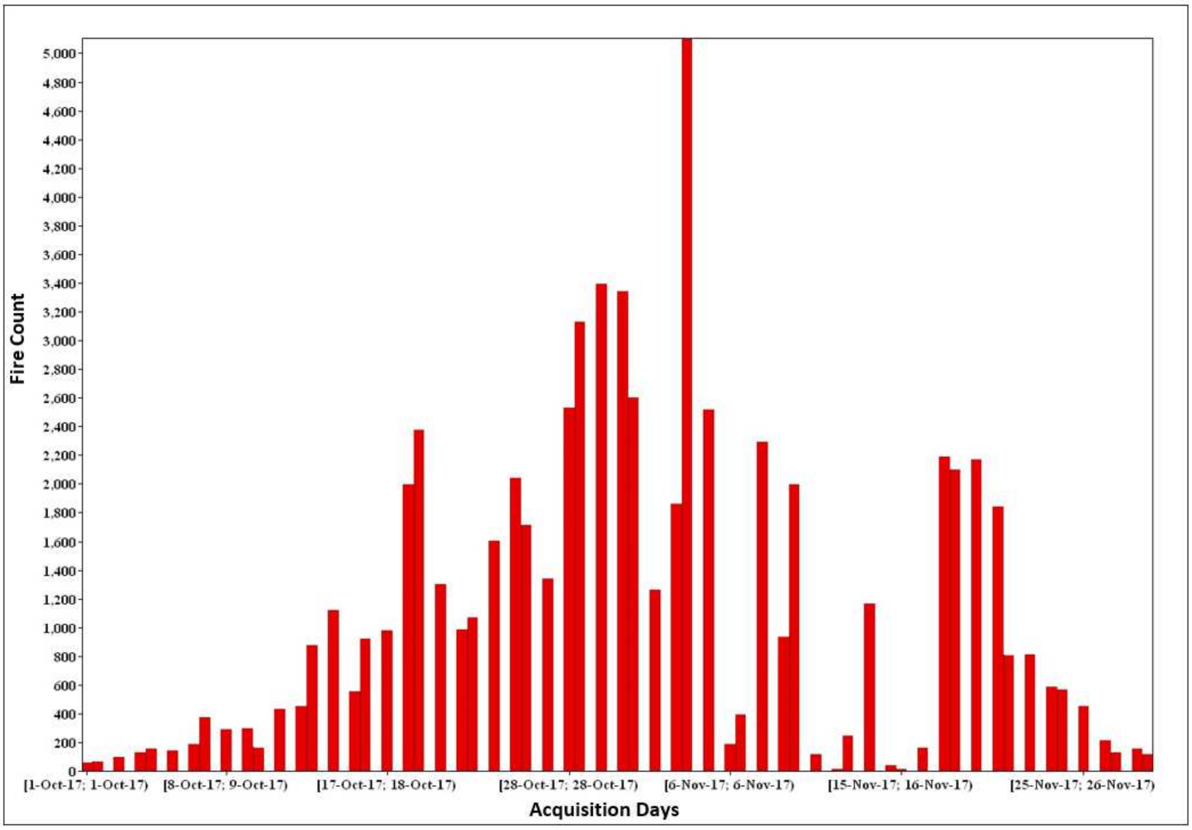


Figure 6: Fire Count retrieved from FIRMS for the month October & November 2017 over Haryana, Punjab region.

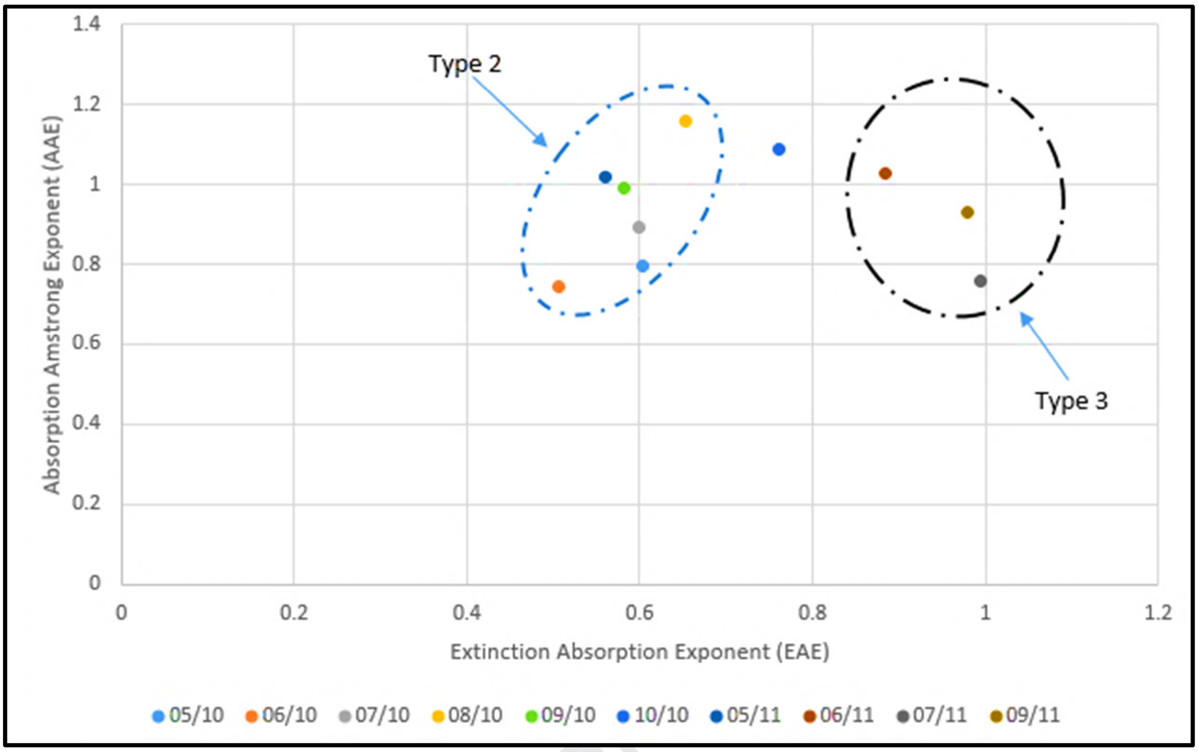


Figure 7: Scatter plot graph of AAE Vs EAE for October and November month of 2017 over Delhi region. Where, Type 2 is pollutant mix dominated by BC and moderate dust; Type 3 by BC and OC.

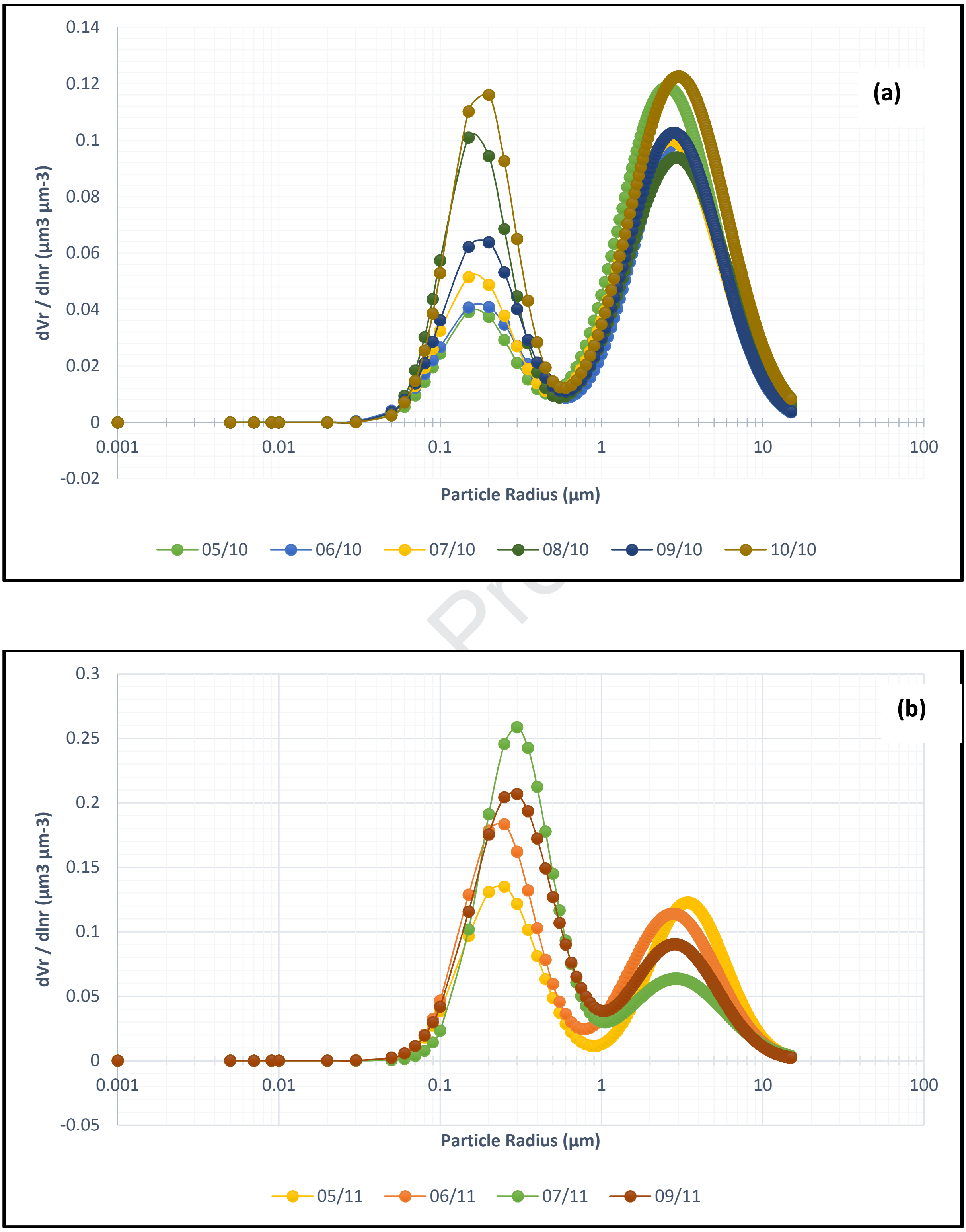


Figure 8: Daily average Volume size distribution graph for (A) October month of 2017 (B) November month of 2017 over Delhi region.

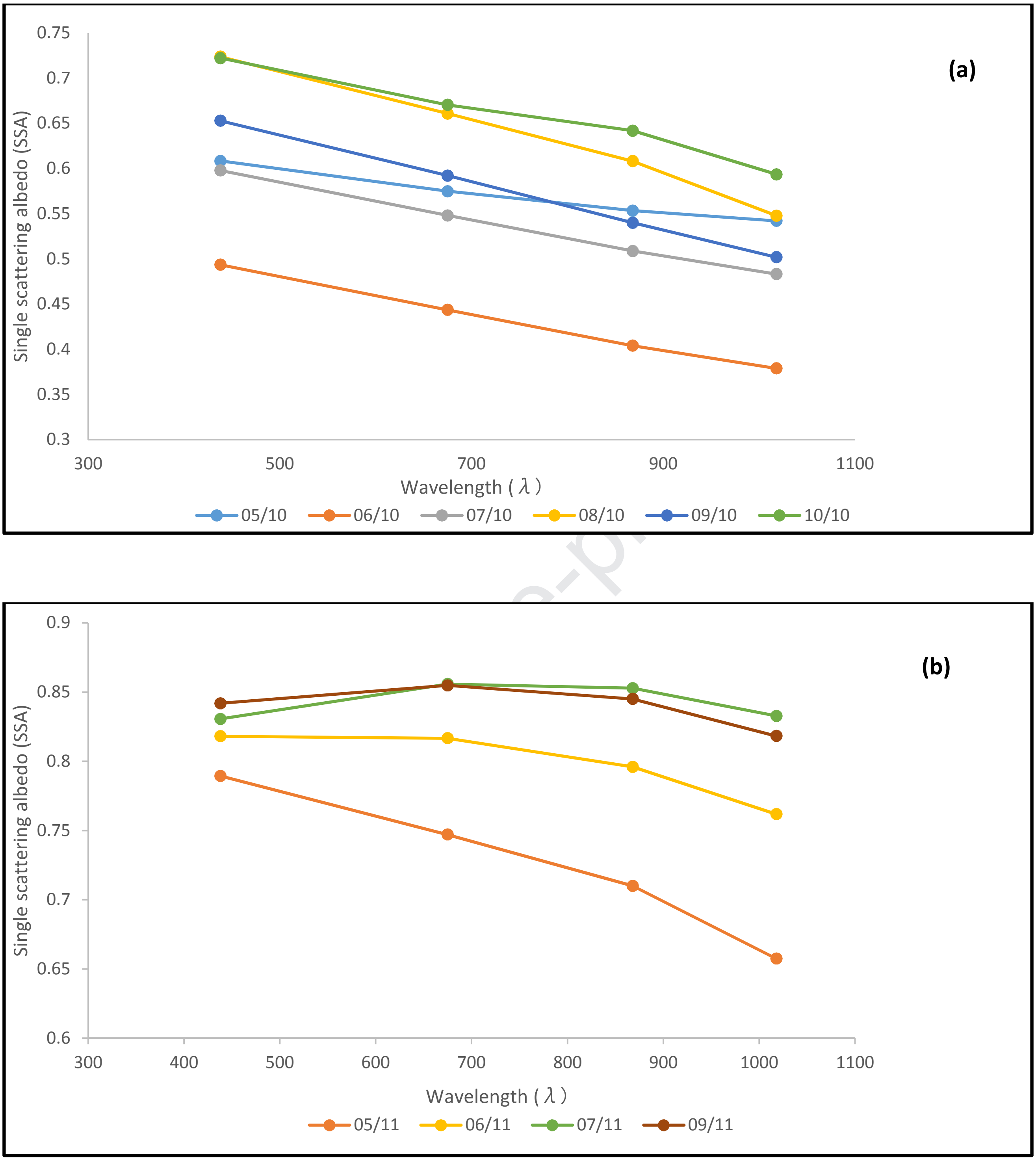


Figure 9: Daily average single scattering albedo (SSA) for (a) October month of 2017 (b) November month of 2017 over Delhi region.

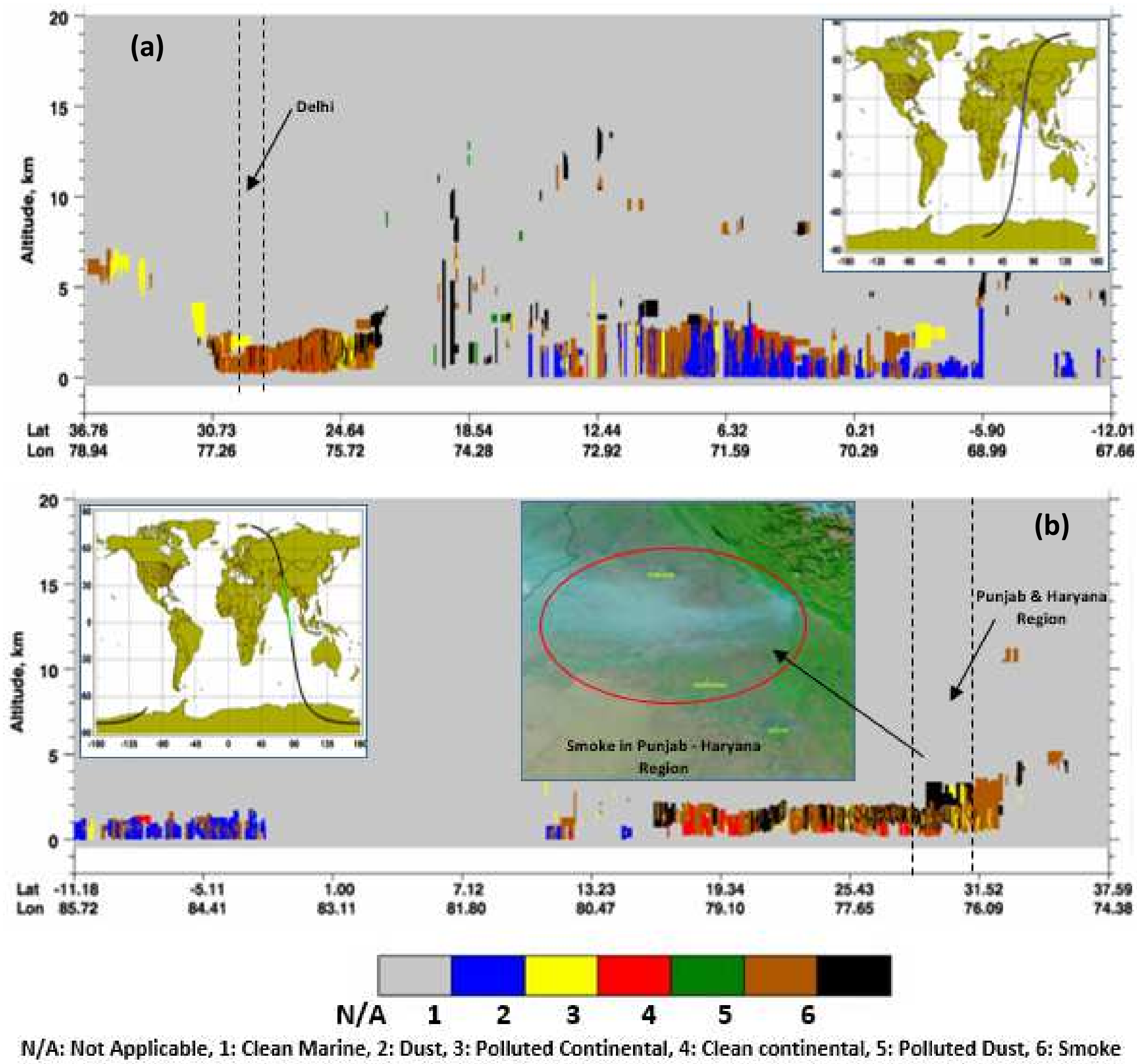
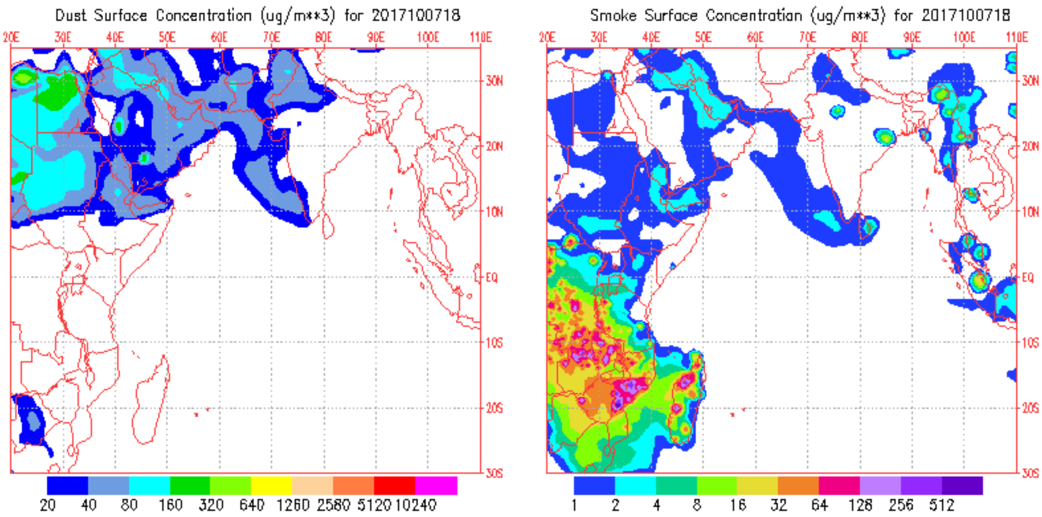
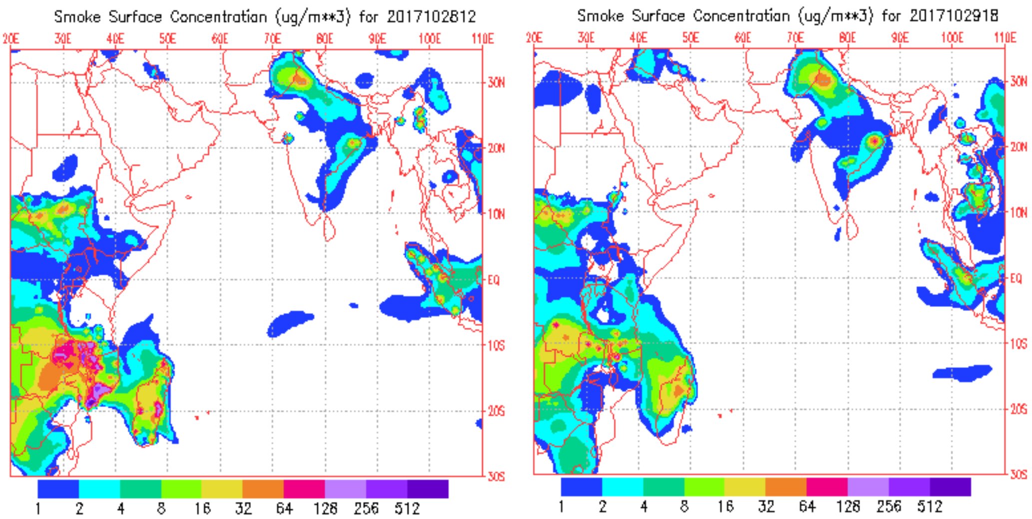


Figure 10: CALIOP derived Aerosol Subtype for a) Delhi (7th October 2017) b) Punjab - Haryana (5th November 2017)

(a)


Dust Surface Concentration (ug/m**3) for 2017100718
20 40 80 160 320 640 1280 2580 5120 10240
Smoke Surface Concentration (ug/m**3) for 2017100718
1 2 4 8 16 32 64 128 256 512

(b)


Smoke Surface Concentration (ug/m**3) for 2017102812
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Smoke Surface Concentration (ug/m**3) for 2017102918
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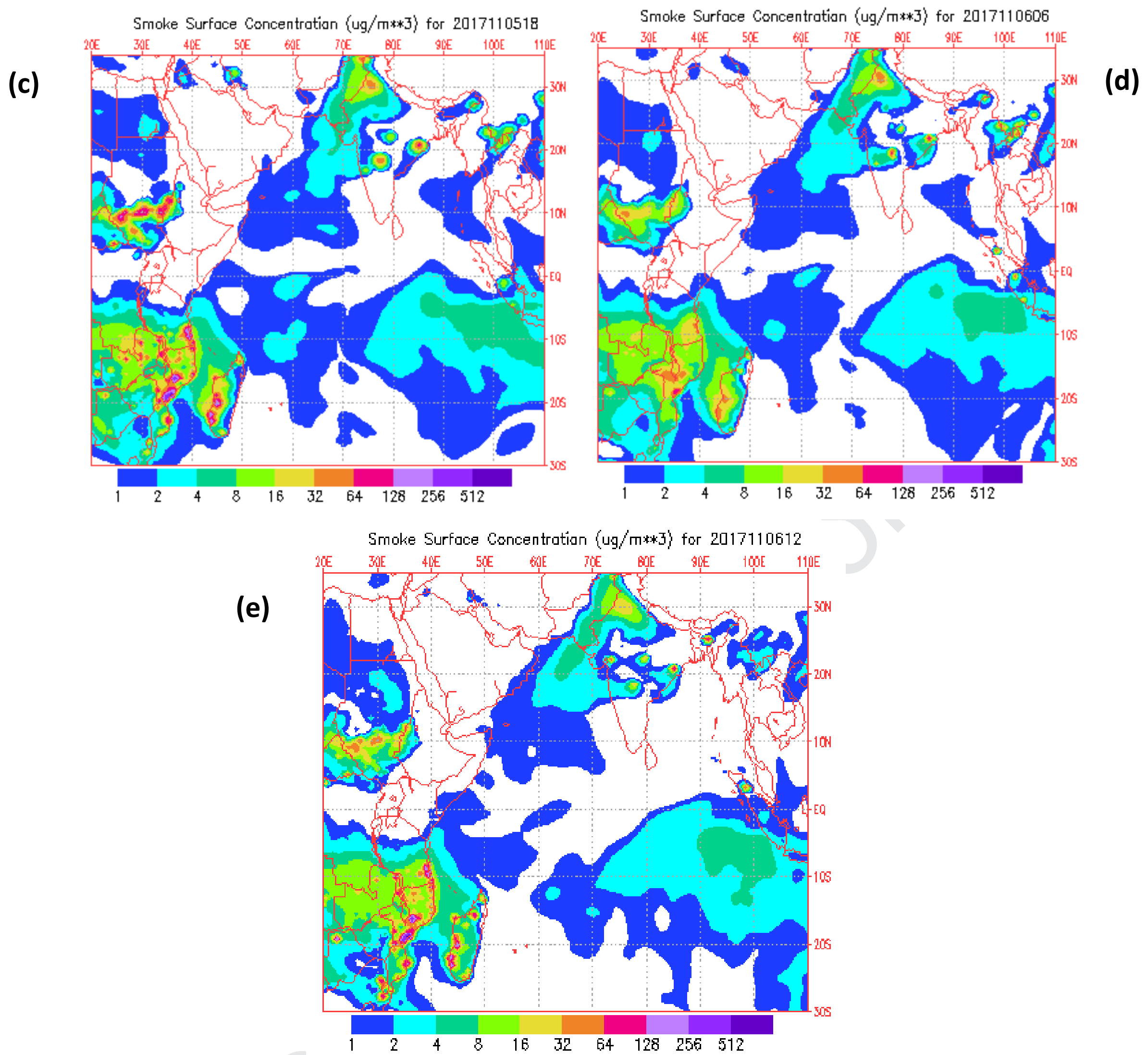

Figure 11: NAAPS derived a) Dust and smoke concertation over Delhi region on 7th October 2017 (After dawn) b) Somke concentration over Haryana-Punjab region on 28-10-2017 (12hrs) and 29-10-2017 (18hrs). c) Smoke concentration over Haryana Punjab region on 5-11-2017 during (18 Hrs). d) Smoke concentration over Haryana Punjab region on 6-11-2017 during (06 Hrs). e) Smoke Concentration over Delhi region on 6-11-2017 during (12 Hrs).

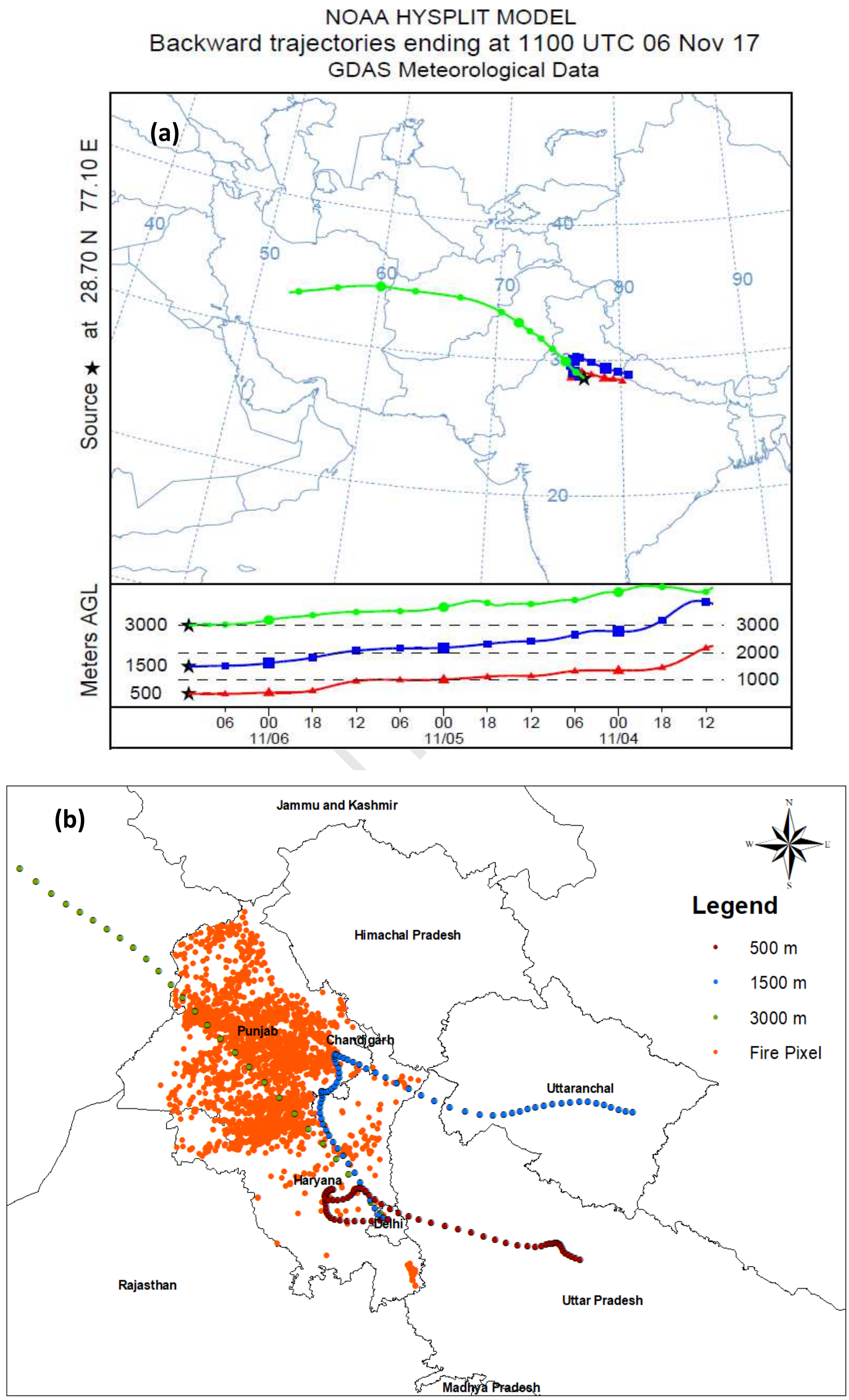

Figure 12: a) HYSPLIT back trajectory retrieved for 6th November, 2017 b) Fire data retrieved for 5th and 6th November, 2017 Overlapped with HYSPLIT back trajectory retrieved for Delhi Region.

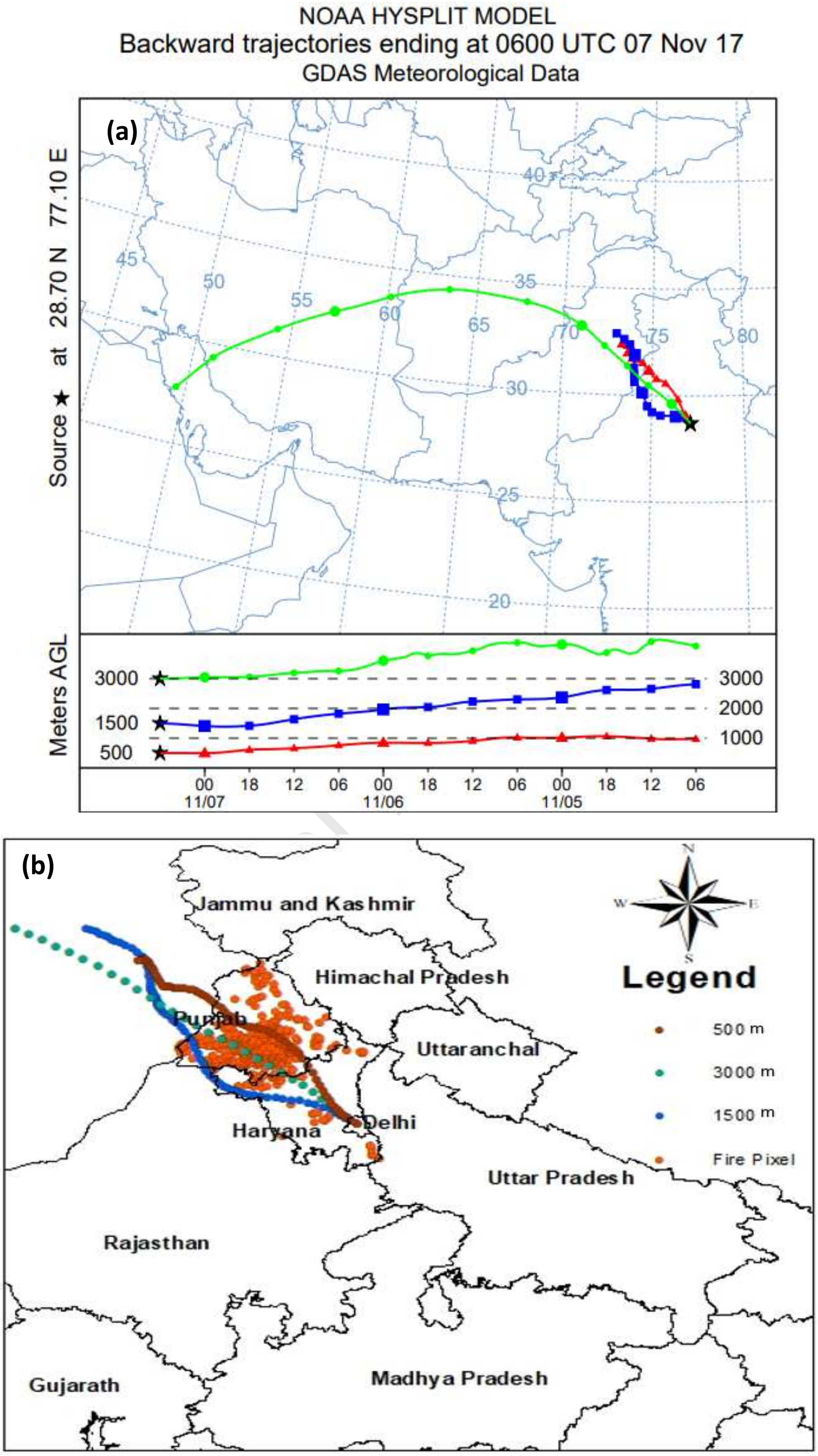

Figure 13: a) HYSPLIT back trajectory retrieved for 7th November, 2017 b) Fire data retrieved for 6th and 7th November, 2017 Overlapped with HYSPLIT back trajectory retrieved for Delhi Region.

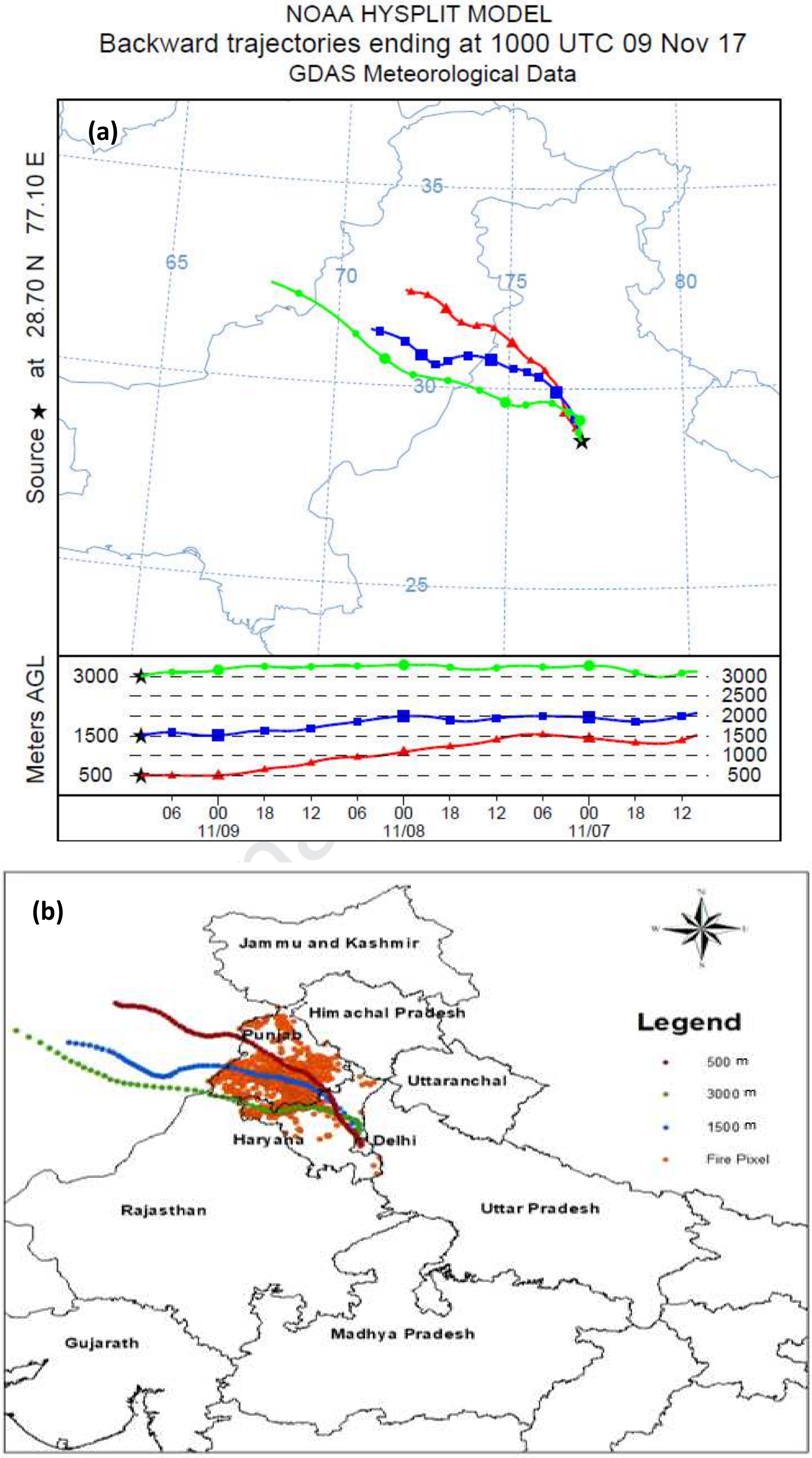

Figure 14: a) HYSPLIT back trajectory retrieved for 9th November, 2017 b) Fire data retrieved for 8th and 9th November, 2017 Overlapped with HYSPLIT back trajectory retrieved for Delhi Region.

Highlights

- Baseline concentration of Delhi during Oct-Nov 2017 was higher than surrounding.
- Stubble Burning (SB) had minor role in deteriorating air quality of Delhi
- Local anthropogenic emissions are the major source of pollution at Delhi
- Transboundary movement of SB was favoured with dispersion beyond human vicinity

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: