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Study of Climate Impacts by Aerosol, UV Aerosol Index and Particulate matter of Northern Part of India through Satellite-Based Data

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Abstract

To presents a comprehensive satellite-based study examining the impact of aerosols, UV aerosol index and $PM_{2.5}$ concentrations on the climate of the Northern Part of India. Aerosols, known to influence atmospheric properties, along with the UV aerosol index and fine particulate matter ($PM_{2.5}$), play pivotal roles in altering regional climate patterns and posing significant health risks. Leveraging satellite-derived data, this research investigates the spatiotemporal distribution and interrelationships of these key atmospheric components across the Northern Part of India. The study employs sophisticated analytical techniques to process and analyze satellite data, providing insights into the variations, concentrations, and trends of aerosols, UV aerosol index, and $PM_{2.5}$ levels over the study area. Results reveal distinct spatial patterns and temporal fluctuations in aerosol distribution, UV aerosol index variations, and $PM_{2.5}$ concentrations, highlighting their diverse impacts on the region's climate and environmental health. Interpreting these findings in the context of climate impacts and public health implications and discuss the significance of understanding aerosol dynamics and their interactions with UV aerosol index and $PM_{2.5}$ concentrations. Moreover, this research identifies potential correlations and underlying causal relationships between these atmospheric constituents, shedding light on their interconnected nature and implications for regional climate and air quality. The study's limitations, including data constraints and uncertainties, are acknowledged, emphasizing the need for further research to deepen our understanding of aerosol-driven climatic influences and their multifaceted effects. Ultimately, this study underscores the importance of satellite-based monitoring and analysis in comprehending the intricate dynamics of aerosols and their consequential impacts on climate and human health in the Northern Part of India.

Keywords: Aerosols, UV aerosol index, $PM_{2.5}$ concentrations, satellite-based study

Introduction:

Agricultural fires, particularly during the post-monsoon season, contribute significantly to air pollution in various regions worldwide, exerting substantial impacts on public health and the environment. Among these, the Indo-Gangetic Plain (IGP) in northern India stands out as a hotspot for intense agricultural residue burning, primarily observed in the states of Punjab and Haryana [1]. These fires, a common practice among farmers for clearing crop residues after harvest, release copious amounts of particulate matter and pollutants, significantly degrading air quality and affecting millions of inhabitants within the region and beyond. The Indo-Gangetic Plain serves as a crucial agricultural hub, experiencing a distinctive biannual crop residue burning pattern: post-monsoon rice stubble burning in October-November and wheat residue burning in April-May. The burning of agricultural remnants releases a complex mixture of aerosols, gases, and particulate matter, significantly elevating pollution levels, particularly fine particulate matter known as $PM_{2.5}$ [2]. Given the escalating concerns surrounding air pollution and its detrimental effects on human health, environmental quality, and climate change, a comprehensive understanding of the temporal and spatial dynamics of these agricultural fires, their resultant smoke aerosols.

The consequential impact on air quality is of paramount importance. In this study, we leverage the comprehensive datasets obtained from NASA's A-train satellite observations covering over a decade (2004–2016) to analyze the long-term trends, spatiotemporal distribution, and the interplay between agricultural fires, smoke aerosols, and air quality across the Indo-Gangetic Plain, with a primary focus on the critical regions of Punjab and Haryana [3]. Our investigation aims to unravel the intricate relationships between fire occurrences, aerosol loading, and their impact on air quality parameters, shedding light on the far-reaching consequences of these agricultural practices on regional atmospheric conditions. Through this analysis, we endeavour to provide crucial insights into the nature of agricultural fires, their evolution over time and their significant influence on air quality across northern India, thereby emphasizing the urgency of effective mitigation strategies and sustainable agricultural practices to curb the adverse effects of this environmental issue.

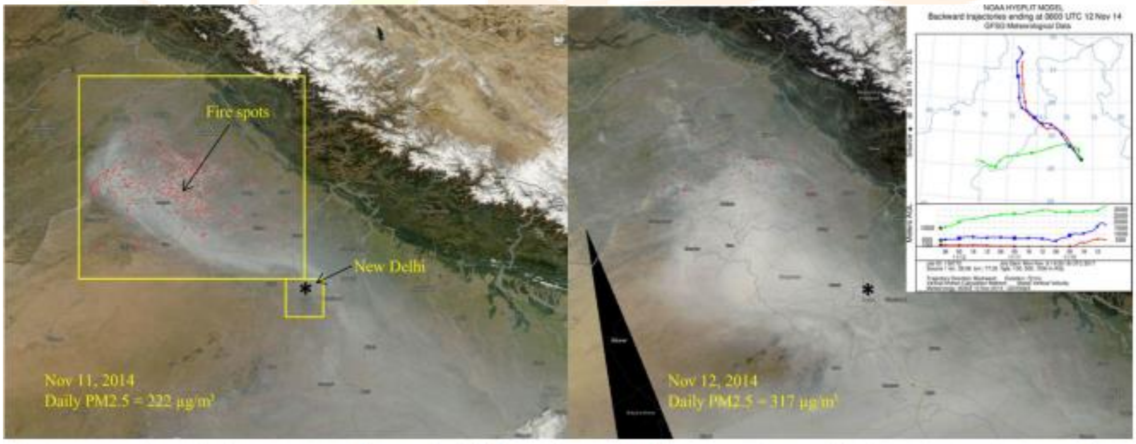

Figure 1 These photos show true-color RGB images combined with thermal anomalies or fire spots detected by Aqua/MODIS over northern India on November 11th (left) and November 12th (right) in 2014. The delineated boxes on the left indicate the precise areas being examined in the present investigation, with an asterisk designating the position of New Delhi. In addition, there is a little section located in the top-right corner that shows a trajectory of the last three days, ending at New Delhi on November 12, 2014.

The Northern Part of India experiences intricate atmospheric dynamics influenced by aerosols, UV aerosol index, and fine particulate matter (PM2.5), all significantly shaping regional climate patterns and posing substantial health risks [4-6]. Understanding their spatial and temporal distribution has become crucial due to their diverse impacts on both climate and human health. This paper delves into a comprehensive satellite-based investigation exploring the interplay and effects of these atmospheric constituents across the Northern Part of India. Leveraging satellite-derived data, this study focuses on unveiling the complex relationships between aerosols, UV aerosol index, and $PM_{2.5}$ concentrations within this region. It employs sophisticated analytical techniques to analyze and interpret the variations, concentrations, and temporal trends of these crucial atmospheric components. By scrutinizing satellite-derived datasets, this research unveils distinct spatial patterns and temporal fluctuations in aerosol distribution, UV aerosol index variations, and $PM_{2.5}$ concentrations [7]. Unveiling the implications of these findings is paramount, considering their profound impacts on regional climate and environmental health. The paper delves into the discussion of these atmospheric constituents' diverse impacts, unraveling their interconnected nature and potential causal relationships. Moreover, it sheds light on the significance of understanding aerosol dynamics, UV aerosol index variations, and $PM_{2.5}$ concentrations in comprehending their combined influence on regional climate and air quality. Acknowledging the limitations stemming from data constraints and uncertainties in satellite-based observations is crucial.

Research Methodology

Study harnesses a diverse array of datasets, combining ground measurements and satellite retrievals to comprehensively explore the correlation between crop residue burning and air quality in the northern region of India. The primary dataset, $PM_{2.5}$ ground measurements, originates from the U.S. Embassy site in New Delhi, providing high-resolution hourly data on fine particulate matter concentrations. These direct measurements offer real-time insights into local air quality, forming a crucial component of our analysis. In addition to ground measurements, satellite data from Aqua/MODIS and Aura/OMI, both part of the A-train satellite constellation, complement our study by capturing daily snapshots of the region [8]. These remote sensing datasets provide valuable information on aerosols, trace gases, and atmospheric composition, albeit with a lower temporal resolution compared to ground-level measurements [9]. Despite their once-a-day capture frequency, these satellite snapshots contribute to a broader spatial coverage, enhancing our understanding of regional air quality dynamics.

Furthermore, our analysis incorporates data collected by the CALIOP lidar instrument aboard the CALIPSO satellite. This dataset delivers vertical profiles of aerosols and clouds over specific points on Earth, albeit with a revisit cycle of once every 16 days. While less frequent in temporal coverage, the CALIOP lidar data offer detailed insights into aerosol properties and their vertical distribution, providing a unique perspective on atmospheric constituents across different layers. The combined utilization of these datasets presents a multi-faceted approach to studying the impact of crop residue burning on air quality in northern India [10,11]. Each dataset contributes distinctive spatiotemporal characteristics and measurement approaches, enabling a more comprehensive assessment of aerosol dynamics, pollutant concentrations, and their potential associations with agricultural activities in the region.

Ground-level $PM_{2.5}$ Measurements

The Air Quality Monitoring (AQM) programme operated by the U.S. Embassy & Consulates in India measures $PM_{2.5}$ levels at ground level in the five main metro cities: New Delhi, Mumbai, Chennai, Kolkata, and Hyderabad. This programme uses advanced equipment, namely the MetOne BAM 1020 instrument. These data conform to the federal reference equivalent level for fine particulate matter ($PM_{2.5}$) set by the U.S. Environmental Protection Agency (EPA). The U.S. Environmental Protection Agency (EPA), known for its ongoing monitoring of $PM_{2.5}$ levels across the United States, partnered with the U.S. Department of State to create PM2.5 monitoring initiatives at diplomatic locations globally, including India starting in 2013. The U.S. Mission in India collects $PM_{2.5}$ data, specifically at the New Delhi Embassy location, which is then transformed into an Air Quality Index (AQI) using the EPA NowCast Algorithm [12]. This change of the Air Quality Index (AQI) assists in streamlining the procedures of making decisions linked to health. The five U.S. Consulates in India have AQM stations that are equipped with BAM-1020 equipment. These instruments are housed in weatherproof units that are environmentally controlled. The stations undertake hourly monitoring of $PM_{2.5}$ concentrations in ambient air samples using the Beta attenuation technique.

For our current investigation, we obtained and collected hourly $PM_{2.5}$ data from the U.S. Embassy location in New Delhi, covering the years 2013 to 2016. The dataset was acquired via a publicly accessible and freely available URL supplied by the U.S. Embassy & Consulates in India, with a focus on ensuring openness and accessibility of the data used in our study. The precise hourly measurements conducted throughout this period provide a strong basis for evaluating and comprehending the amounts of fine particulate matter in New Delhi during the designated timeframe. The use of this extensive and carefully collected $PM_{2.5}$ dataset from the U.S. Embassy site in New Delhi is an important part of our study. It allows us to thoroughly analyse the levels of fine particulate matter and understand how it may affect air quality and public health in the region during the specified time period.

NASA's A-train Satellite Retrievals

The system categorises each pixel into several classes, including missing data, clouds, water, fire-free zones, areas with fire, or unexplained regions. The detection and separation of cloud and water pixels is achieved by the use of a customised mask, while simultaneously eliminating non-earth images in the process. Subsequently, the algorithm examines the background by analysing neighbouring pixels inside a specific frame that is focused on the probable pixel representing a fireplace. "Obtained the MODIS Thermal Anomalies/Fire 5-Min L2 Swath 1-km data (Collection 006) from both Terra (MOD14) and Aqua (MYD14) platforms through the NASA Fire Information for Resource Management System (FIRMS) website (https://earthdata.nasa.gov/earth-observation-data/near-realtime/firms) for this study [13].

The MODIS Collection 6 Fire user guide provides information on the confidence classes given to observed fire pixels, which are determined based on their computed confidence values (C). The determination of these confidence levels, namely low, nominal, or high, is based on the following criteria: The values of C are divided into three ranges: 0% to less than 30%, 30% to less than 80%, and 80% to less than 100%, respectively. Only fire pixel data with a confidence value (C) higher than 30, which corresponds to the confidence classifications of 'nominal' and 'high', was used. This selection criteria guarantees a greater level of precision in identifying fire pixels, hence reducing the occurrence of false positives in our dataset. Our goal is to use the MODIS Thermal Anomalies/Fire product and strict confidence criteria to get accurate fire and smoke data. We will next analyse the effect of fire occurrences, namely agricultural residue burning, on air quality in northern India."

Table 1 The datasets used in this investigation.

Sensor/Dataset	Characteristics	Data Period
"MetOne BAM-1020, U.S. Embassy, New Delhi	Hourly measurements of PM2.5 in µg m–3	2013–2016
MODIS Terra & Aqua MODIS C006	5-min Level-2 Thermal Anomalies/Fires Product at 1-km pixel resolution (MOD14/MYD14)	2002–2016
Aqua/MODIS Level-2 MAIAC Aerosol Product	MAIAC Aerosol Product at 1-km resolution	2002–2016
OMI OMAERUV Level-2 Aerosol product	UV-AI, AAOD at native pixel resolution of 13 × 24 km² (OMAERUV)	2004–2016
CALIOP Level-2 Aerosol Layer and Profile product	5-km horizontal resolution	2013–2016
HYSPLIT Back-trajectories	NCEP/GDAS 0.5 × 0.5 degree resolution dataset October and November	2013–2016"

MODIS MAIAC Aerosol Optical Depth

The Multi-perspective Implementation of Atmospheric Correction (MAIAC) algorithm is a sophisticated technique used to compute the bidirectional reflectance factor (BRF) and aerosol optical depth (AOD) by examining the sequence of MODIS readings. The device functions by using spectral regression coefficients obtained from MODIS bands, namely at wavelengths of 470 nm, 550 nm, and 2100 nm, to describe the surface. It is capable of operating on both dark vegetated areas and bright targets. MAIAC comprises two exceptional aerosol models: a retrospective model and a dust variant, similar to those used in the MODIS dark target approach. However, in order to detect smoke particles generated by burning biomass, a crucial aspect of this study, MAIAC uses a specialised "smoke test." This analysis distinguishes smoke from clouds by comparing the relative increase in aerosol absorption at MODIS wavelength 0.412 µm to the range of 0.47–0.67 µm. This approach exploits the occurrence of multiple scattering and enhanced absorption caused by organic carbon emissions during the burning of biomass. The tactics used in various satellite devices such as TOMS and OMI, which operate at near-UV wavelengths, have been effectively utilised. Each 1-km AOD size acquired via the use of MAIAC is assigned a corresponding fine indicator, which provides information about the observed conditions and the overall accuracy of the inversion system. This study employs the most sophisticated AOD retrievals from MAIAC by relaxing some stringent flag requirements.

OMI NEAR-UV Aerosol Product (OMAERUV)

The "Ozone Monitoring Instrument (OMI) use the Ozone Monitoring Algorithm for Erythemal Ultraviolet (OMAERUV) method to examine top-of-atmosphere (TOA) radiances at wavelengths of 354 nm and 388 nm. This assessment enables the calculation of overall columnar Aerosol Optical Depth (AOD), single-Scattering Albedo (SSA), and Aerosol Absorption Optical Depth (AAOD = AOD × (1 – SSA)) at a pixel resolution of thirteen × 24 km². The accuracy and global evaluation of these retrievals were extensively established by detailed validation against ground-based direct and inversion measurements obtained from AERONET sunphotometers. The study on Aerosol Optical Depth (AOD) using the OMI-AERONET dataset at 44 prominent sites revealed a correlation coefficient of 0.81, a slope of 0.79, and an intercept of 0.10. Approximately 65% of the comparisons fall within the uncertainty limitations of 30%. Furthermore, the assessment of SSA reveals a settlement level falling between the range of ±0.03 and ±0.05 for about 50% and 70% of the pairs, respectively. These validations verify that the OMAERUV values for AOD and SSA are adequately accurate. The research used the most recent publicly available OMAERUV product (model 1.8.9.1), which exhibits significant enhancements and improved statistical data retrieval in comparison to the prior operational model 1.4.2. The dataset, acquired from NASA's GES-DISC information centre, is a valuable resource for comparing the characteristics of aerosols, with a particular focus on aerosol optical depth and single-scattering albedo." These properties are crucial for understanding the impacts of aerosols, including those originating from biomass burning, in the study area.

NOAA'S Hysplit Back-trajectory Data

HYSPLIT is a commonly used version for computing the trajectory and dispersion of substances inside the atmosphere. The method uses average velocity vectors in three dimensions to track the paths of substances from their initial positions to their projected destinations. Specifically, the most efficient version considers the advection aspect while computing trajectories. The primary sources of uncertainty in lower back-trajectory calculations mostly arise from flaws in determining the initial conditions, known as the "meteorological grid" ensemble, and the parameterization of turbulence, referred to as the "turbulence" ensemble.

Result and Discussion

An analysis of the changes in fires, smoke characteristics, and $PM_{2.5}$ concentration in northern India from 2013 to 2016 provides important information on the relationship between agricultural practices, aerosol dynamics, and air quality. Figure 2 illustrates a detailed chronological depiction of many important indications. The temperature anomalies clearly indicate the occurrence of certain fire seasons, particularly in October and November, which align with the burning of rice residue. In contrast, there is a somewhat lower occurrence of fires in May when wheat residue burning takes place, leading to a decrease in the release of particulate matter and gaseous pollutants (Badrinath et al., 2006). This research mainly examines fire incidents that occur after the monsoon season, while deferring the examination of the effects of wheat harvesting (April-May) for future investigation. This underscores the need of conducting a separate inquiry. An important finding emerges from the comparison of Aqua and Terra MODIS fire counts. The Aqua/MODIS satellite routinely detects a much greater quantity of flames in comparison to the Terra/MODIS satellite. This disparity suggests a temporal imbalance in which farmers often incinerate a significant quantity of agricultural remnants during the afternoon hours prior to the Aqua satellite's traversal of the area at 1:30 PM local time. The findings, validated by true-color photos with fire spots, demonstrate a greater occurrence of fires and the resulting smoke in Aqua/MODIS data over Punjab compared to the fires recorded in Terra/MODIS images.

The correlation between fire incidents and smoke indicators, such as UV-AI, AAOD obtained from OMI, and AOD from MODIS-MAIAC, shows clear increases throughout the post-monsoon season, closely matching the surges in fire counts. The increase in mass concentration of $PM_{2.5}$, recorded at the U.S. Embassy location in New Delhi, shows a consistent trend, rising in the start of November when the number of fires reaches its highest point. Significantly, in the crop burning season of 2016, the levels of $PM_{2.5}$ reached an unprecedented peak, highlighting the extreme effect on air quality at this time. An examination of the $PM_{2.5}$ concentration at the U.S. Embassy location shows a notable violation of India's National Ambient Air Quality Standards, especially in the months of October and November. Approximately 65% of the days during these months exceed the national threshold for 24-hour averaged $PM_{2.5}$, which is much greater than the total number of days exceeding the norm from March to September.

The results further emphasise the significant impact of October, November, and the winter months on increasing the average annual concentration of fine particles. Notably, removing PM2.5 data for these months leads to considerable decreases in the average annual concentration. This research shows the fluctuation in $PM_{2.5}$ levels over the seasons, emphasising the significant impact of the months after the monsoon season and winter in increasing the average annual mass concentrations. The very elevated concentrations of $PM_{2.5}$ observed during these time periods, which may be linked to meteorological conditions that promote pollution and agricultural activities, clearly illustrate the significant impact of crop residue burning and vehicle emissions on air quality problems in northern India.

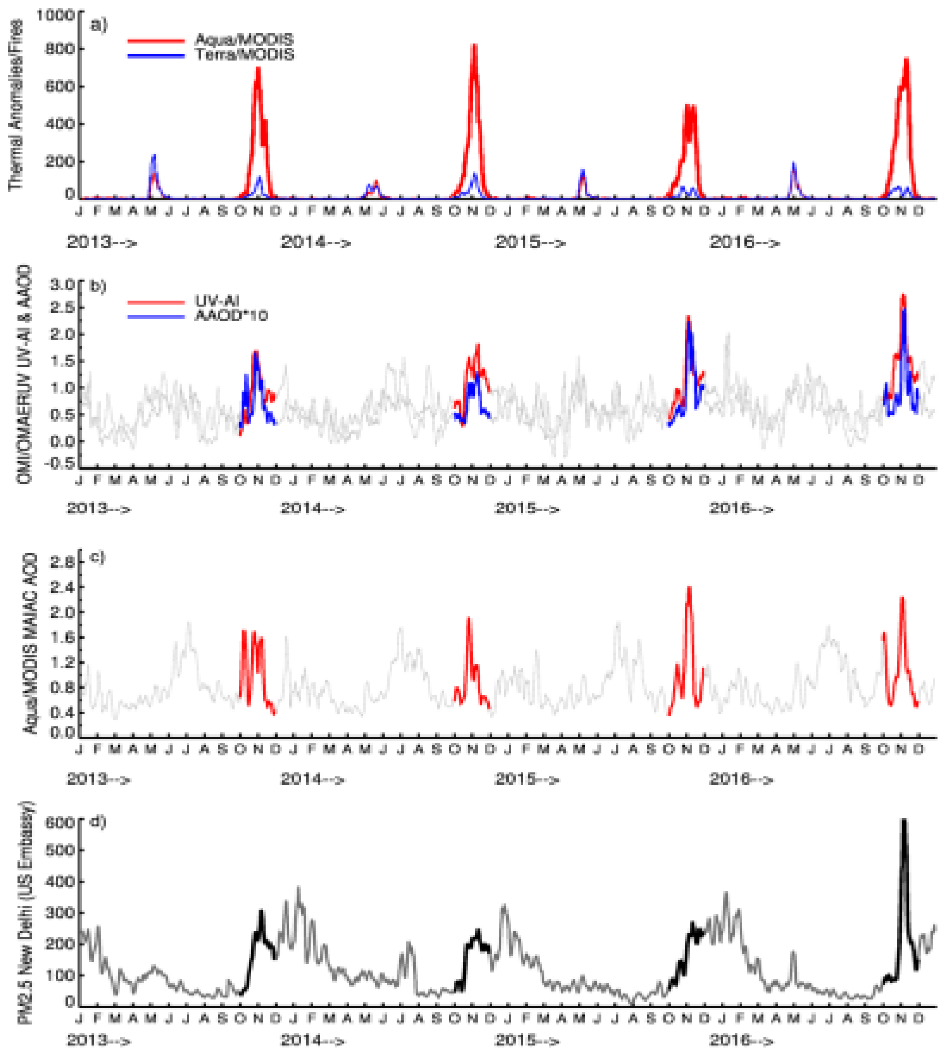

Figure 2 The time-series displays the 7-day moving average of various data sets. These include (a) fire counts from Terra-Aqua/MODIS Collection 006, (b) UV-AI and AAOD (388 nm) from OMAERUV, (c) AOD (470 nm) from Aqua/MODIS MAIAC, all of which pertain to the agricultural fire region in Punjab, with coordinates ranging from 74°E to 77°E longitude and 29°N to 32°N latitude. Additionally, (d) PM2.5 measurements from the U.S. Embassy site in New Delhi are also included. The data shown in a vivid, intense hue represents the months of October and November.

Analysing the correlation between ground-level PM2.5, satellite fire counts, and aerosol retrievals

The persistent movement of smoke particles from the origin area to the destination site, as shown by New Delhi in this analysis, is influenced by several elements such as wind patterns, elevation, scattering, and elimination processes along the transit route. In order to create a significant connection between satellite measurements taken from the source locations and the levels of $PM_{2.5}$ at the receptor site, it is essential to choose the most suitable time period that takes into consideration the influence of meteorological factors. The findings emphasise that flight paths via eastern Punjab, located about 185 km away from New Delhi, demonstrate the least amount of time required to reach the receptor location. In contrast, flight paths that pass over western Punjab need the greatest amount of time to reach New Delhi, with durations of 51, 42, and 24 hours at altitudes of 100, 500, and 1500 metres, respectively.

According to this research, it was determined that the best time period for averaging satellite retrievals and $PM_{2.5}$ readings from New Delhi is a three-day window, which includes the day being considered and the two days before it. The chosen three-day period includes the day being examined and the two days before it. This period represents the range of time it would take for the air mass to travel from different places and elevations where crop burning occurs to New Delhi, with durations ranging from 15 to 51 hours. The objective of this strategy is to reduce the fluctuations in climatic conditions and transportation routes, in order to enable a more reliable comparison between independently recorded values in the two neighbouring areas. This approach is expected to improve the precision of linking satellite observations with $PM_{2.5}$ data, offering vital understanding of the connection between aerosol dynamics and air quality at the receiving location.

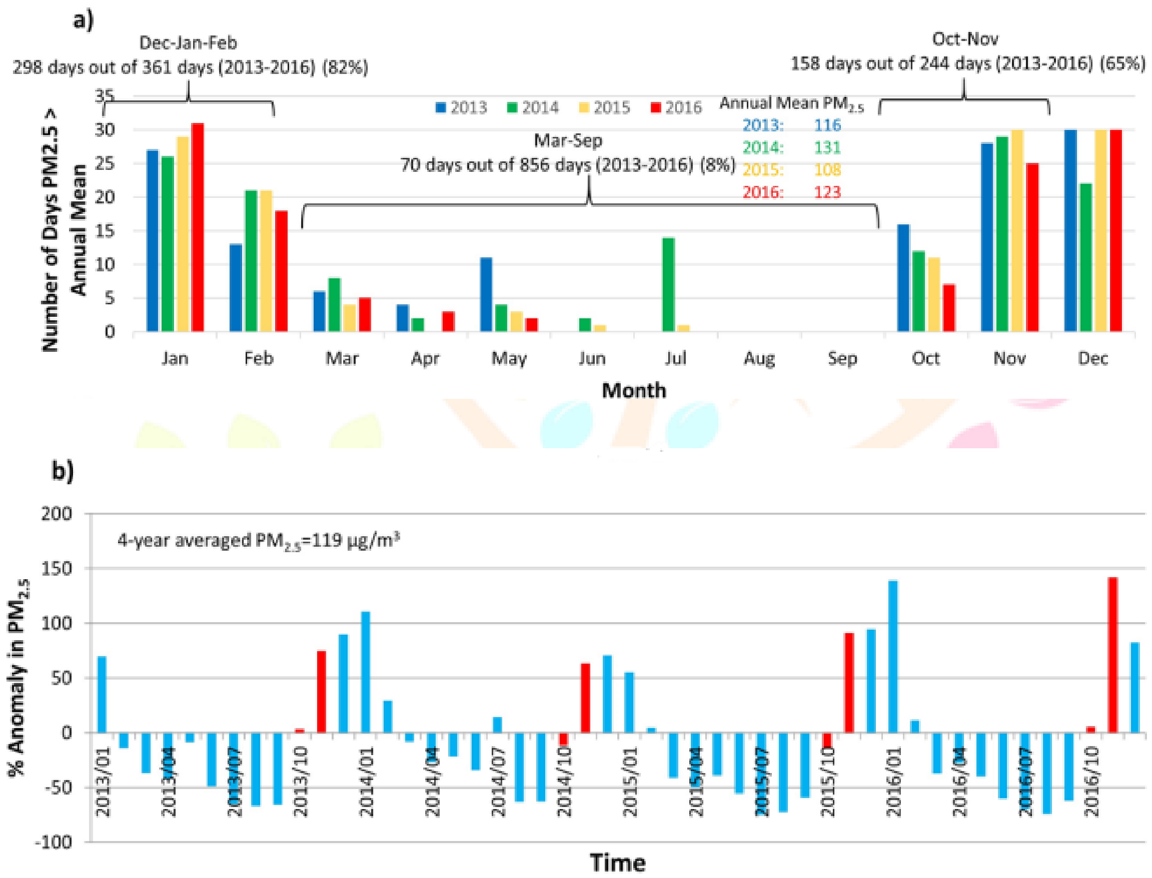

Figure 3 (a) The bar chart displays the number of days in each month from 2013 to 2016 where the PM2.5 concentration exceeded the annual mean concentration. (b) The time-series graph shows the percentage monthly anomaly in PM2.5 compared to the average value of 119 µg m–3 measured at the U.S. Embassy site in New Delhi over a 4-year period. The data for October and November are highlighted in red, while the data for other months are shown in blue.

Table 2 The duration (in hours) of the trajectories that intersect the areas where crops are being burned in Punjab, India, along the transportation routes that lead to the receptor location in New Delhi (77.2°E–28.58°N).

“Approximate Distance from New Delhi (in km)	**Time taken by trajectories ending at New Delhi**		
Altitude	100 m	500 m	1500 m
Eastern Punjab (76E–30N)	185	26 hours	21 hours
Central Punjab	275	35 hours	25 hours

(75.50E–30.75N)			
Western Punjab (74.60E–31.75N)	420	51 hours	42 hours

Figure 4 exhibits the graphs illustrating the $PM_{2.5}$ levels recorded at the U.S. Embassy location in New Delhi in relation to (a) the number of fires identified by Aqua/MODIS, (b) the Aerosol Optical Depth (AOD) at 470 nm recovered by Aqua/MODIS MAIAC, (c) the Ultraviolet Aerosol Index (UV-AI) and (d) the Absorbing Aerosol Optical Depth (AAOD) derived from OMI using the two-channel OMAERUV algorithm. Significantly, MODIS true-color RGB pictures showed continuous haze over the region, which corresponded with elevated $PM_{2.5}$ concentrations (> 150 μgm^{-3}) detected by ground-based sensors in New Delhi during this time period. As a result, there was a greater spread in the $PM_{2.5}$ data when there were fewer instances of fires. In general, there was a close to direct correlation between the number of fires (up to 600) and $PM_{2.5}$ levels. This led to an estimated rise of 33 μgm^{-3} in $PM_{2.5}$ for every increase of about 100 in fire counts. Nevertheless, after the count exceeded 600, the association with $PM_{2.5}$ diminished, but still remained within the range of 200–250 μgm^{-3}.

Vertical Structure of Smoke Aerosols

The vertical distribution of aerosol layers over the crop-residue burning area of Punjab and Haryana during post-monsoon months from 2013 to 2016 was examined via an independent examination of CALIOP lidar data. During nighttime overpasses, CALIOP observed a greater proportion of aerosol layers (~20%) compared to daylight. The altitude distribution exhibited a prominent peak at around 1.2 km during both daylight and evening. However, there was a much greater occurrence of strata observed above 2.0 km during nighttime. During the day, around 62% of the total aerosol layers were found below 2.0 km, whereas during the night, about 42% were discovered at the same altitude. These aerosol layers are directly related to the quantity of $PM_{2.5}$ particles at the surface. The mean vertical distribution of the overall backscatter coefficient at wavelengths of 532 nm and 1064 nm, obtained from aerosol measurements during both daylight and nighttime, exhibited elevated levels of aerosol backscatter slightly above the surface and at around 975 hPa (roughly 250 metres above ground level). Subsequently, the profiles showed a rapid reduction with scale heights of around 1.0 km and 0.5 km (1.5 km and 0.75 km) for measurements made during the day and night, respectively. In the NCR area, which includes New Delhi, the vertical structure exhibited comparable patterns, but with higher peak magnitudes closer to the surface.

Comparing observations during the day and night, it was found that data taken at night showed greater total backscatter coefficients, particularly at a wavelength of 1064 nm. This suggests that there are higher concentrations of particulate matter near the surface during nighttime passages. The $PM_{2.5}$ mass concentration, as recorded at the U.S. Embassy location during the CALIOP flyover period, exhibited a notable rise during nighttime as comparison to daylight. At the months of October and November in New Delhi, the values of $PM_{2.5}$ at nighttime were consistently higher, ranging from 50% to 80%, compared to the measurements taken during daylight. The 532-nm backscatter signal, which is used to identify aerosol-cloud layers, encountered constraints, especially when there was a high concentration of smoke aerosols. This led to weakened signals and decreased signal-to-noise ratios for the lower layers. On the other hand, the 1064-nm signal was able to penetrate aerosol layers to a greater extent, providing a more accurate representation of the vertical arrangement of particles. Furthermore, further data comparing the strength of backscatter signals at 532 nm and 1064 nm wavelengths under intense smoke aerosol presence in northern India confirms the superior capacity of the 1064-nm signal to penetrate aerosol layers.

Long-term record of fires and smoke aerosols detected by satellite technology

Illustrates the chronological progression of fire incidents throughout the region where crop burning occurs in the months after the monsoon season. Aqua/MODIS saw a significant rise in the number of fires during the burning season after the monsoon, as compared to the burning season in spring. There was a noticeable change in the bulk of fires occurring in November instead of October throughout the years. There was a consistent upward trend of about 500 instances of fires each year, indicating a rise in fire incidents from 2009 to 2016 in the Aqua/MODIS database. In the year 2016, there was a notable occurrence of an unusually high number of fire hotspots reported throughout the Punjab-Haryana region. The research also identified substantial spikes in the number of fires in the years 2005, 2007, 2012, 2014, and 2016. Remarkably, in 2016, there was a notable surge in the number of fires, setting a new record and surpassing the fire counts of prior years. The number of fires identified in November exhibited a significant positive trend correlated with higher levels of MAIAC AOD and OMI UV-AI, indicating an increase in aerosol concentration during this period. Although there are factors that naturally influence the data, such as cloud contamination and uncertainties in measurement retrieval, there are consistent and positive trends in Aerosol Optical Depth (AOD) and Ultraviolet Aerosol Index (UV-AI) across the larger Indo-Gangetic Plain (IGP) region. These trends coincide with an increase in fire activities in northwestern India, suggesting that the effects of increased fire occurrences on air quality extend beyond the immediate burning area and affect downstream regions as well.

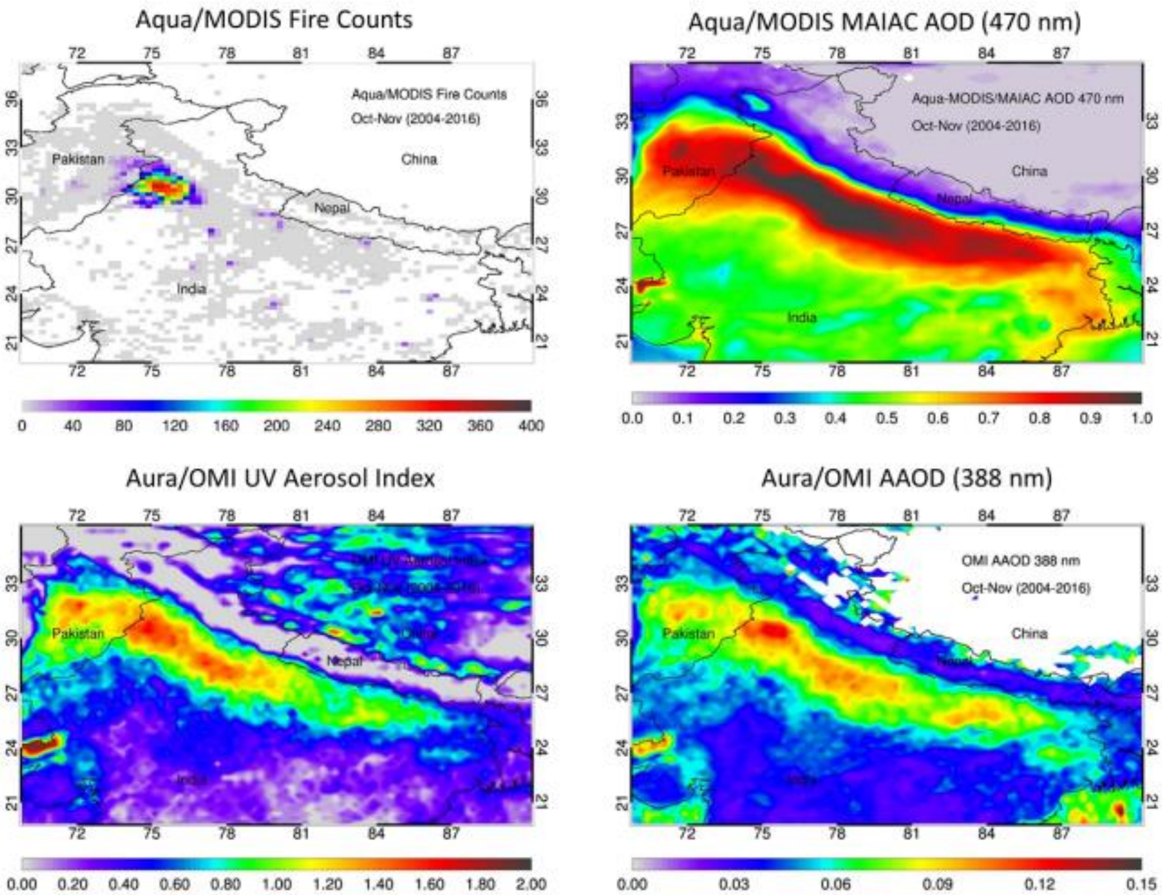

Figure 4 The data presented consists of averaged and gridded maps of total fire counts detected by the Aqua/MODIS satellite between the years 2004 and 2016. The maps cover the months of October and November and have a resolution of 0.25° by 0.25°. The top-left map shows the total fire counts, while the top-right map displays the Aqua/MODIS MAIAC AOD (470 nm). The bottom-left map represents the Aura/OMI UV Aerosol Index, and the bottom-right map shows the Aura/OMI AAOD (388 nm). These maps specifically cover the northern Indian subcontinent.

Conclusion

The extensive examination of NASA's A-train satellite observations, which covers a period of 13 years from 2004 to 2016, offers valuable understanding of the changes over time and space in agricultural fires and the resulting smoke aerosols in northern India, specifically in Punjab and Haryana, during the period when residue burning occurs after the monsoon season. Upon analysing climatology maps depicting fire counts, columnar Aerosol Optical Depth (AOD), Ultraviolet Aerosol Index (UV-AI), and Absorbing Aerosol Optical Depth (AAOD) simultaneously, it was seen that Punjab had the highest level of intense fire activity, exceeding other areas by a wide margin. The geographical gradient of aerosol concentration in the Indo-Gangetic Plain (IGP) indicates the movement of smoke particles from the source region to distant places, particularly the eastern sections, as a result of prevailing northwesterly winds.

An analysis of the chronological development of fire incidents revealed a significant rise in the number of fires during the period after the monsoon season, namely in November. This increase has been consistently seen throughout the years, with a gradual shift from October to November. The year 2016 emerged as an anomalous period, registering the highest number of fire hotspots over Punjab-Haryana, marking a significant increase compared to previous years. Distinct peaks in fire counts in specific years, alongside consistent positive trends in Aerosol Optical Depth (AOD) and Ultraviolet Aerosol Index (UV-AI) during November, underscored elevated aerosol loading during this period. Despite inherent data limitations such as cloud contamination and retrieval uncertainties, the results highlighted a pronounced impact of increased fire activities in northwestern India on air quality, not confined merely to the local burning region but extending downstream. This comprehensive analysis underscores the need for heightened attention to manage and mitigate agricultural fire practices, particularly in Punjab and Haryana, considering their substantial impact on regional air quality and the far-reaching consequences on public health and environmental well-being across the Indo-Gangetic Plain. Efforts aimed at understanding and addressing the root causes of increased fire occurrences during the post-monsoon season are imperative for sustainable environmental management and improved air quality in this critical region.

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