



Spatial distribution and temporal variation of biomass burning and surface black carbon concentrations during summer (2015–2021) in India

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Abstract

Historical biomass burning in summer season (April–June, during 2015–2021) was assessed by studying active fire spot data recorded by the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard NASA/NOAA Suomi NPP satellite and mapping the same over Indian landmass. The fire spots often formed regional clusters and most profusely covered the states of Odisha, Chhattisgarh, Andhra Pradesh, Telengana, Madhya Pradesh, Maharashtra, Jharkhand, Karnataka, Punjab, Uttar Pradesh, Haryana, Gujarat, Tamil Nadu, Manipur, Nagaland, and Mizoram during April but their number decreased conspicuously in May and further in June. Forward movements of air masses potentially carrying fire-induced air pollutants from five principal fire cluster regions (northern, south eastern, western, north-eastern, and central) of India during April and May in 2021 were traced by 6-day forward airtrajectory modelling. It was observed that many parts of India were the recipients of air coming from the above principal fire clusters. In each year, the surface mass concentration of black carbon (BC), one of the most prominent markers of biomass burning, was higher in April over May and June in the affected regions, commensurate with the most active period of fire. The BC surface mass concentrations progressively declined thereafter in May and June with decreasing number of active fire spots along with declining average monthly height of the planetary boundary layer (PBL), indicating integral connection of surface BC levels with biomass burning. The study suggests that in spite of more favourable meteorological conditions in summer, extensive biomass burning may have had a crucial role to play in perturbing local and regional air quality over India by generating BC and other air pollutants.

Keywords Atmospheric reanalysis · Hysplit · Planetary boundary layer · Satellite remote sensing · Trajectory modelling · VIIRS

Introduction

Biomass burning is known to be prevalent in many parts over the globe since the late twentieth century (Crutzen and Andreae 1990; Kaufman et al. 1990; Andreae 1991; Hao and Liu 1994). Biomass burning is a form of vegetation fire triggered by arson for clearing land for agriculture, fire induced by friction in dry biomass and natural lightning-induced burning. World's most biomass burning incidences occur in the tropical forests, reportedly about

90% of which could be arson for land clearing and initiating land-use changes (Levine 2003). As per one estimate, Savannah fires, forest fires, shifting cultivation (or slash and burn agriculture), wood fuel burning, and crop residue burning (CRB) had shares of 50, 24, 10, 11, and 5%, respectively, in total tropical biomass burnt during the late 1970s (Hao and Liu 1994). Worldwide, stubble burning accounts for about 25% of biomass burnt that included forest fires (Zhang et al. 2016; Yadav and Devi 2018). It is reported that about 730 Tg biomass was burnt annually in Asia that included forest and grassland fires and CRB wherein India contributed about 18% (Streets et al. 2003). As per Venkataraman et al. (2006), around 18–30% of crop residue was burnt in India while the same in the western Indo-Gangetic plain was 30–40% and much lower in other parts (12–18%) during 1995–2000. In more recent times, about 15.9% of crop residue was reportedly burnt on crop fields in India

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(Jain et al. 2014). In central and lower Northern Thailand, paddy residue burning has become a common practise due to very short period in between harvesting of standing crops and sowing of the next paddy (Junpen et al. 2018). The mean interval between paddy harvest and wheat sowing is about 15 days, prompting farmers to put paddy residues on fire during October–November in India while on the contrary, the interval between wheat harvest and paddy sowing during April–May is about 46–48 days (Vadrevu et al. 2011). The short period in between harvesting of paddy and sowing of wheat is one of the primary reasons behind burning of paddy stubble in India (Ravindra et al. 2018). The ministry of agriculture in India attributed the escalation in CRB to paucity of agricultural labour (NPMCR, http://agricoop.nic.in/sites/default/files/NPMCR_1.pdf). A detailed account of policy interventions to minimise CRB India is documented (Bhubaneshwari et al. 2019).

Information on biomass burning can be quickly and effectively provided by satellite remote sensing of active fires by detecting infrared (electromagnetic) radiation emitted from fires. Remote detection of biomass fires was initiated in the early 1980s by using low earth orbit (LEO) satellites that mapped the location and timing of landscape fire occurrences while from the early 2000s, global-scale fire information started to get updated multiple times in a day (Wooster et al. 2021). Active fire spots captured by radiometric sensors installed on satellites are now used to track and study regional and global biomass fire activities (Schroeder et al. 2010; Csiszar et al. 2014; Schroeder et al. 2014a, b). Fire radiative power (FRP), representing instantaneous radiative energy released by active fires, is used as a surrogate of the intensity of fire for identification of fire spots (Freeborn et al. 2016; Roy and Kumar 2017).

Biomass burning is known to contribute significantly to local and regional air pollution (Gurjar et al. 2016). In China, CRB contributed about 60% in total emissions coming from biomass burning (Zhang et al. 2015). In the early nineties, biomass burning reportedly contributed around 20–30% of CO₂, hydrocarbons, CO, and NO_x emitted globally (Andreae 1991). The PM₁₀ and PM_{2.5} are known to be emitted by paddy straw burning (Chang et al. 2013) while its incomplete combustion produces black carbon (BC) that contributes significantly to global warming by absorbing solar radiation, estimated as the second largest contributor after CO₂ (Bond et al. 2013). Studies indicate that when combined with other aerosol components, BC absorbs more strongly than pure, uncoated BC (Fierce et al. 2020). Bond et al. (2004) estimated that biomass burning contributed about 42% of BC and 74% of primary organic carbon (OC) in the atmosphere. In India, paddy stubble burning after rice harvest during October–November at the onset of winter had devastating short-term effects on regional air quality. The deleterious effect of CRB on air quality is higher during

October–November, as ushering winter conditions start to produce increasingly stable atmospheric conditions (Chawala and Sandhu 2020). Stubble burning in summer has not garnered as much attention as winter stubble burning did in India, possibly due to more favourable meteorological conditions in the former that aided in the dissipation of air pollutants far more easily, leading to less aggravated local and regional air quality. But, biomass burning can also have significant impacts on sustainable living in urban centres and their peripheries by negatively affecting climatic comfort via altering vegetative cover, water resources and surface temperature (Cetin et al. 2019; Cetin 2020a). It has been reported that the majority of bioclimatic comfort zones in Trabzon Province in Turkey consisted of agricultural, followed by natural and semi-natural areas, forest areas, and settlements (Cetin and Sevik 2020), implying that forest and crop fires can have negative impacts on zones of climatic comfort. Increase in heat island effect due to deforestation and escalated urbanisation causes reduced bioclimatic comfort that potentially affects tourism also, apart from impacting sustainable human settlements (Cetin 2019; Adiguzel et al. 2019, 2022). Also, emissions from biomass burning can have disastrous impacts on global climate change, landscape management, and settlement planning efforts (Cetin et al. 2020; Cetin 2020b). Escalation in summer heat waves as a direct result of aggravation in urban heat island effect caused by reduction in green cover, urbanisation and climate change is posing substantial roadblocks on urban planning and management (Cetin 2020b).

The spatial distribution and temporal variations in biomass burning were studied during 2015–2021 in India. The potential distribution of air pollutants generated from biomass burning over Indian landmass with moving air masses was assessed by 6-day air trajectory modelling in April and May in 2021. Simultaneous surface concentrations of BC, a strong marker of biomass combustion, were estimated over the entire Indian landmass during April–June (2015–2021) and linked with biomass burning as a source, with the help of air mass trajectories and resultant monthly wind vectors over India. The monthly average planetary boundary layer height (PBLH) over Indian landmass during April–June in 2020 and 2021 was also studied to understand its potential influence on temporal variation of BC surface mass concentrations. The majority of earlier papers originating from all over the globe, including India, have reported short-term crop and biomass burning in winter and their potential impacts on regional air quality over limited geographical expanse. This paper analyses summer fires for a 7-year long period over the entire landmass of a large country like India and its potential impacts on countrywide BC surface mass concentrations in summer. Apart from highlighting the seemingly un-scrutinised case of summer biomass burning in India, this study showcases the application of

methodologies like geospatial mapping of biomass fire spots, simulation of monthly resultant wind vectors over landmass, wind trajectories originating from various fire cluster regions and atmospheric reanalysis to simulating BC surface mass concentrations and PBLH, as a package of tools to interpret the potential role of biomass fires on BC surface mass concentrations over India. The information is likely to help researchers and policymakers alike to evaluate the impacts of biomass burning on BC surface mass concentrations and its potential role on radiative forcing and regional climate change. Also, the combination of tools used in this study can be replicated by others for similar regional-scale studies. This would eventually lead to the development of wider information on vulnerable regions to biomass fire incidences and scale of fires that would go on to assist in improved forest and biodiversity conservation, sustainable urban planning and delineation of bioclimatic comfort zones.

Materials and methods

Background of study area

The study was conducted for the entire Indian landmass consisting of 28 states and 8 union territories, covering an area of 32, 87, and 263 sq. km (Govt. of India, <https://www.india.gov.in/india-glance/profile>). Indian landmass is restricted by 8°4' and 37°6' North latitudes, 68°7' and 97°25' East longitudes. The north-to-south distance is 3214 km while east to west distance is 2933 km. India's land frontier is of about 15,200 km and the coastline length of the mainland, Andaman & Nicobar and Lakshadweep Islands together is 7516.6 km (Govt. of India, <https://www.india.gov.in/india-glance/profile>).

In the total amount of paddy stubble generated each year in India, about 14 million tons accounting for about 63.6%, is put on fire (IARI 2012) with the states of Haryana and Punjab contributing about 48% (Gadde et al. 2009). Paddy is customarily transplanted around June/July and harvested in and around October/November while wheat is normally sown mostly during December and harvested in summer in the next year. In recent years, CRB in summer coinciding with winter wheat harvest season in India has been reported but has not garnered much scientific attention (Jitendra et al. 2017, <https://www.downtoearth.org.in/coverage/agriculture/river-of-fire-57924>). The authors reported that about 80% of CRB was observed during April–May and November–December (post-harvest periods) and attributed it to the required adjustment in crop calendar, implying that only limited time remained in between two consecutive crops to effectively clear the

fields. The rationale behind wheat crop residue burning in summer is reported to be costly labour, mechanised harvesting of crop leading to non-viability of animal grazing of short stubbles and increasingly lower importance given to wheat straw as an animal fodder (Jitendra et al. 2017, <https://www.downtoearth.org.in/coverage/agriculture/river-of-fire-57924>). Apart from CRB, summer forest fires are also prevalent in many regions of India that are reportedly rising in recent times (Roy 2022).

Retrieval of biomass fire data

Data on active biomass fire spots detected on April 25th, May 25th, and June 25th and reported by active fires air reanalysis product (ARP) were extracted through the Fire Resource Management System of NASA. The active fire data captured by VIIRS (I-band 375 m) on board Suomi NPP and processed by NASA LANCE FIRMS, were extracted and fire spot maps of India were developed by integrating the data with shape files of India that included country boundary and first level administrative division (i.e. state), on a GIS platform. The generated fire maps demonstrated biomass fires as spots over Indian landmass marked with state borders. Gas flares are not picked up by VIIRS fire products as they are primarily designed to detect wildfires having larger surface area and those burning at lower temperature than small and bright hot sources like the former (Sharma et al. 2017). Fire spots detected by VIIRS are small, intense or burning over a broader area within the pixel, implying that the entire pixel is on fire. The VIIRS swath of 3040 km ensures a $\approx 15\%$ image overlap between successive orbits over the equator, thus having a 12-hourly worldwide coverage.

Air trajectory and wind vector simulation

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to compute air parcel trajectories to assess the distance and direction of moving air parcels carrying air pollutants (Air Resources Laboratory, NOAA, <https://www.arl.noaa.gov/hysplit/>). In this study, HYSPLIT was run in forward trajectory mode for 144 h (6 days on 4th week of each month, overlapping the period of observed fire spots), separately from five locations situated in five different parts of India (North, West, Central, South-East and North-East) that were found have either hosted the majority of biomass burning clusters or located adjacent to the clusters. The selected source locations were Ludhiana in state of Punjab in North India (30.9010°N, 75.8573°E), Vizag in state of Andhra Pradesh in South-Eastern India (17.6868°N, 83.2185°E), Mumbai in state of Maharashtra

in Western India (19.0760°N, 72.8777°E), Agartala in state of Tripura in North-Eastern India (23.9408°N, 91.9882°E), and Bhopal in state of Madhya Pradesh in Central India (23.2599°N, 77.4126°E). HYSPLIT was run on the 25th day onwards in April and May in 2021 with archival meteorological database (3-hourly) of global data assimilation system (GDAS1; National Weather Service's National Centres for Environmental Prediction, NCEP). Forward air movements originating from these source locations, potentially carrying smoke and air pollutants generated by biomass fires could be fundamental in influencing local and regional air quality *vis a vis* surface BC over India. The HYSPLIT model has been used earlier for tracking the movements of air masses and interpreting their role in governing atmospheric chemistry in a mega city in India (Majumdar and Adhikary 2022).

Furthermore, monthly resultant wind vectors at 1000 mb (near surface) were simulated by using the atmospheric reanalysis tool of the National Centres for Environmental Prediction/National Centre for Atmospheric Research to visualise and understand resultant airflow over Indian landmass that would also have immense bearing on transfer of smoke and air pollutants generated by biomass fires. The wind direction and wind speed contours were plotted and presented through the reanalysis tool.

Assessment of BC surface mass concentrations

Black carbon is one of the best aerosol markers of wildfires and biomass burning (Cheng 2014; Duc et al. 2020). The BC surface mass concentrations over India were extracted from version 2 of Modern-Era Retrospective Analysis for Research and Applications (MERRA-2), an atmospheric reanalysis product of the Global Modelling and Assimilation Office (GMAO) of National Aeronautics and Space Administration (NASA) that uses Goddard Earth Observing System Model (GEOS-5). The GEOS-5 is radiatively coupled to the Goddard Chemistry Aerosol Radiation and Transport (GOCART) aerosol module to simulate dust, sea salt, sulphate, BC, and organic carbon and is used to generate aerosol products (Gelaro et al. 2017; Randles et al. 2017). In reanalysis, a data assimilation system consistently reprocesses meteorological observations, typically historical, by using an inbuilt forecast model to combine different observations to produce gridded data sets even for variables that may not be directly observed (Gelaro et al. 2017). Upgradation from MERRA to MERRA-2 has empowered the latter with the ability to perform aerosol reanalysis including BC (Gelaro et al. 2017). MERRA-2 utilises data assimilation techniques to analyse aerosol optical depth (AOD) data received from Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High-Resolution Radiometer (AVHRR), Multiangle Imaging Spectro-Radiometer (MISR) and

Aerosol Robotics Network (AERONET) stations (Level-2 AOD) (Buchard et al. 2017; Gelaro et al. 2017). MERRA-2 has been successfully used to model aerosol optical properties during the Californian wildfires of 2013 that agreed well with aircraft observations (Buchard et al. 2017). The conformity of actual observations with reanalysis exhibited the prospects for successful implementation of MERRA-2 in the optimal representation of surface BC during bushfire events (Duc et al. 2020). For this study, monthly average BC surface mass concentrations from MERRA-2 aerosol diagnostics were obtained at $0.5^\circ \times 0.625^\circ$ resolution over India during April, May and June of 2015 to 2021 and their maps were generated by the MERRA-2 reanalysis tool, that were used to assess temporal and spatial variations in surface BC during biomass-burning periods in summer (April–June).

Variation in planetary boundary layer height (PBLH)

Eventual manifestation of local and regional air pollution on the regional air quality is largely controlled by the structure (height) and processes involved with the planetary boundary layer (PBL) (Miao et al. 2015). Temporal and spatial variation in the height of the planetary boundary layer (PBL) is crucial in controlling concentrations of air pollutants including BC. The PBLH over India as monthly averages were extracted into overlay maps and histograms with statistical summary, generated by Merra-2 reanalysis tool, for the months of April, May and June of 2020 and 2021 via MERRA-2. Sathyanadh et al. (2017) has earlier validated PBLHs reanalysed by MERRA-2 against PBLHs derived from radiosonde flight observations over India and found that MERRA-2 and radiosonde-derived PBLHs had correlation coefficients in the range of 0.74–0.83 for selected stations over Indian landmass, confirming the reliability of PBLH data reanalysed by MERRA-2.

Results

Spatial distribution of biomass fires

Biomass burning spots in summers of 2015–2021 were found to be primarily concentrated in parts of Northern India, South-Eastern India, Central India, Western India, and parts of North-Eastern India. However, the month-wise spatial distribution patterns of fire spots were variable over 2015–2021. The fire spots are often observed to have formed clusters, indicating firing over adjacent stretches of land (Fig. 1p–u), as VIIRS 375 m active fire product is known to provide higher response for fires burning over smaller areas due to better spatial resolution and night-time performance

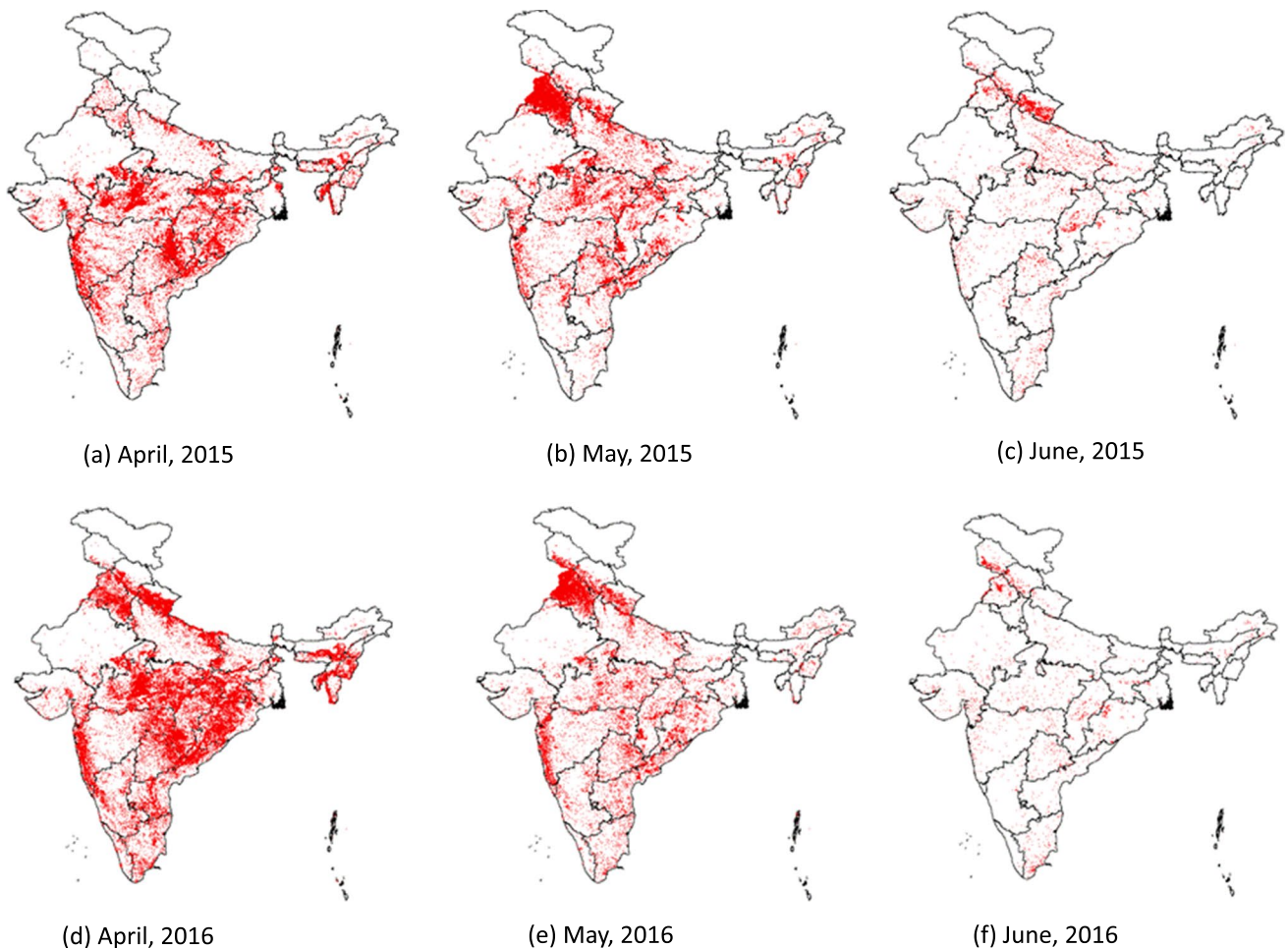


Fig. 1 a–u Active fire spots (denoted by dots) detected by the 375-m VIIRS in April, May and June during 2015–2021 on Indian landmass

(Schroeder and Giglio 2016). But, the closely located fire spots in clusters on the maps may be further apart on land, considering the given scale of maps against the huge expanse of the Indian landmass. The fire clusters largely covered states of Odisha, Chhattisgarh, Andhra Pradesh, Telengana, Madhya Pradesh, Maharashtra, Jharkhand, Karnataka, Punjab, Uttar Pradesh, Haryana, Gujarat, and Tamil Nadu that are known to be major wheat-growing states of India. Also, Manipur, Nagaland, and Mizoram in mountainous North-East India hosted substantial number of fire spots. Fire clusters were comparatively less pervasive in parts of Eastern (West Bengal, Bihar), Western (Rajasthan), Northern (Jammu and Kashmir, Ladakh, Himachal Pradesh), Southern (Kerala), and North Eastern India (Upper Assam). The fire clusters were heavily loaded with fire spots in April while diminished coverage of clusters by fire spots and increased isolation of fire spots from each other were starkly evident in May and further in June, implying much lesser fire incidences.

Movement of air masses

Air trajectories emanating from the selected location in Northern India (Ludhiana) during April and May in 2021 showed movement of air masses primarily towards eastern and south-eastern directions, covering over 900 km in 6 days' time, potentially affecting air quality in several regions on the way, expectedly more so in the first 2–3 days when moving air masses are more heavily loaded with air pollutants generated by biomass burning. A few specific air trajectories travelled over 2700 km in the eastern direction, reaching beyond Indian landmass on that direction. In May 2021, some air masses travelled beyond 2000 km in South-Eastern direction to cover parts of Madhya Pradesh, Telengana, and Andhra Pradesh primarily. Air trajectories from South-Eastern location (Vizag) mostly moved into specific eastern and southern parts of India in two opposite directions in April 2021 covering > 600 km in each direction and

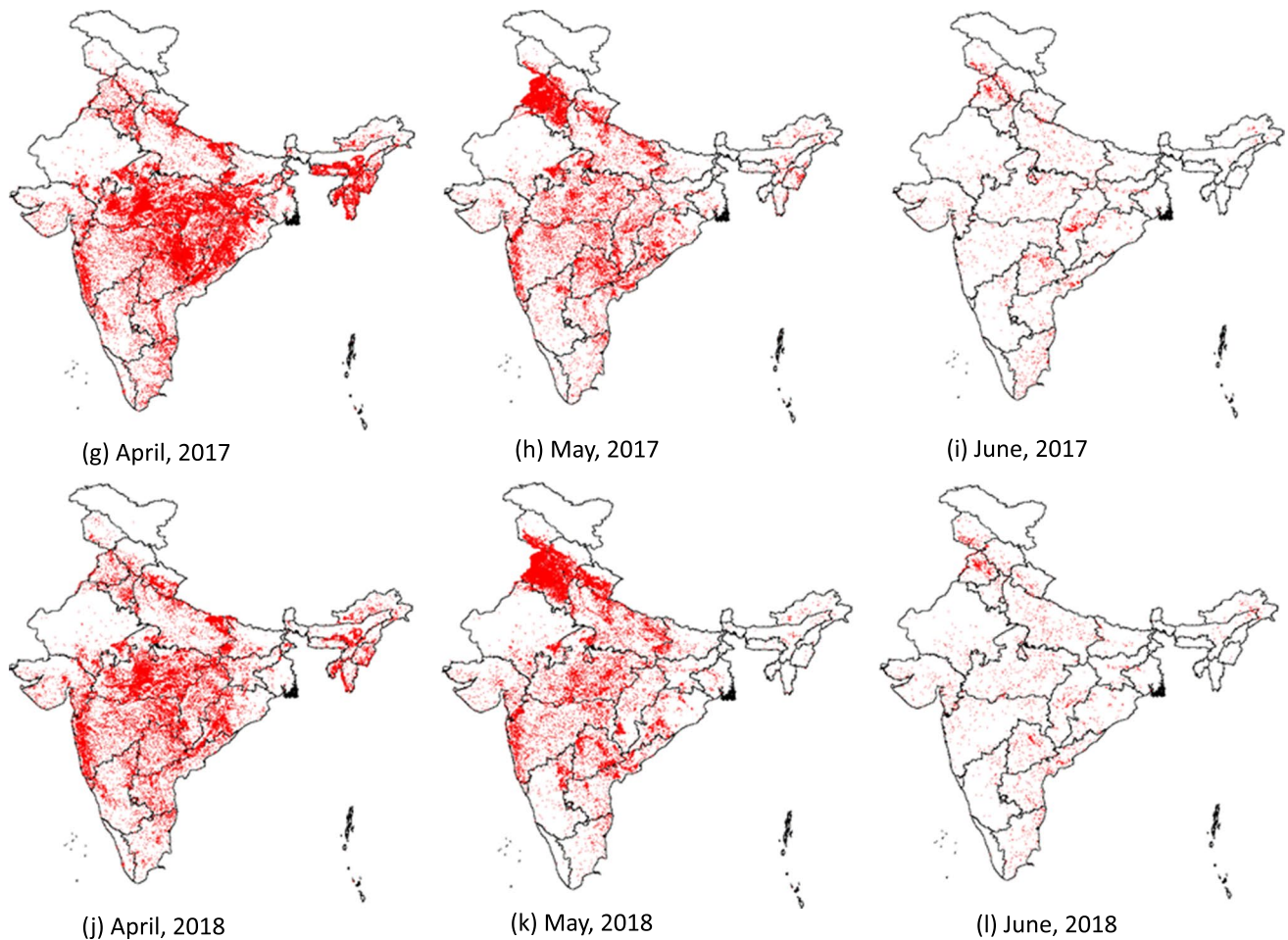


Fig. 1 (continued)

Eastern and North-Eastern Region (NER) in May 2021. In the latter case, trajectories moved over Bay of Bengal to re-enter Indian landmass in east. Several trajectories in May 2021 travelled beyond 2500 km on eastern direction in 6 days, transcending Indian boundary. Air trajectories from the Western cluster (Mumbai) encompassed coastal (west) southern India in April 2021 but changed direction in May 2021 to enter parts of south-eastern and eastern India in states of Andhra Pradesh, Telengana, Odisha and West Bengal, partly moving over Bay of Bengal in a path covering > 1600 km in 6 days. On the other hand, trajectories from the north-eastern location (Agartala) travelled further into other north-eastern parts of India, except upper Assam, Meghalaya and Arunachal Pradesh in April 2021. Many trajectories travelled to Bay of Bengal and some other beyond Indian boundary in eastern direction. In May 2021, entire eastern (West Bengal, Bihar, Jharkhand) and parts of North-East India was covered by the trajectories, some transcending Indian landmass in north-east direction. In April 2021,

the air trajectories covered the entire Indian peninsula from the Central location (Bhopal), covering states of Maharashtra, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, and Telengana. On the other hand, the trajectories covered a part of South-Eastern India before moving to the Bay of Bengal and then entering Indian landmass in May 2021 (Fig. 2a, b).

The simulated monthly resultant wind vectors over Indian landmass in April and May 2021 (Fig. 3a, b) showed that majority of winds flowing within Indian landmass moved from Northern India towards Central India and from Western India towards Eastern India. Furthermore, maritime winds from the Bay of Bengal moved inside Indian landmass through the South-Eastern, Eastern and also from Southern and South-Western directions and penetrated further into Indian landmass in April and May. The observed wind vectors underlined the scope of inland transfer of biomass smoke to various parts of India from prominent fire clusters. Over April to May, spatial shifts in wind speed contours

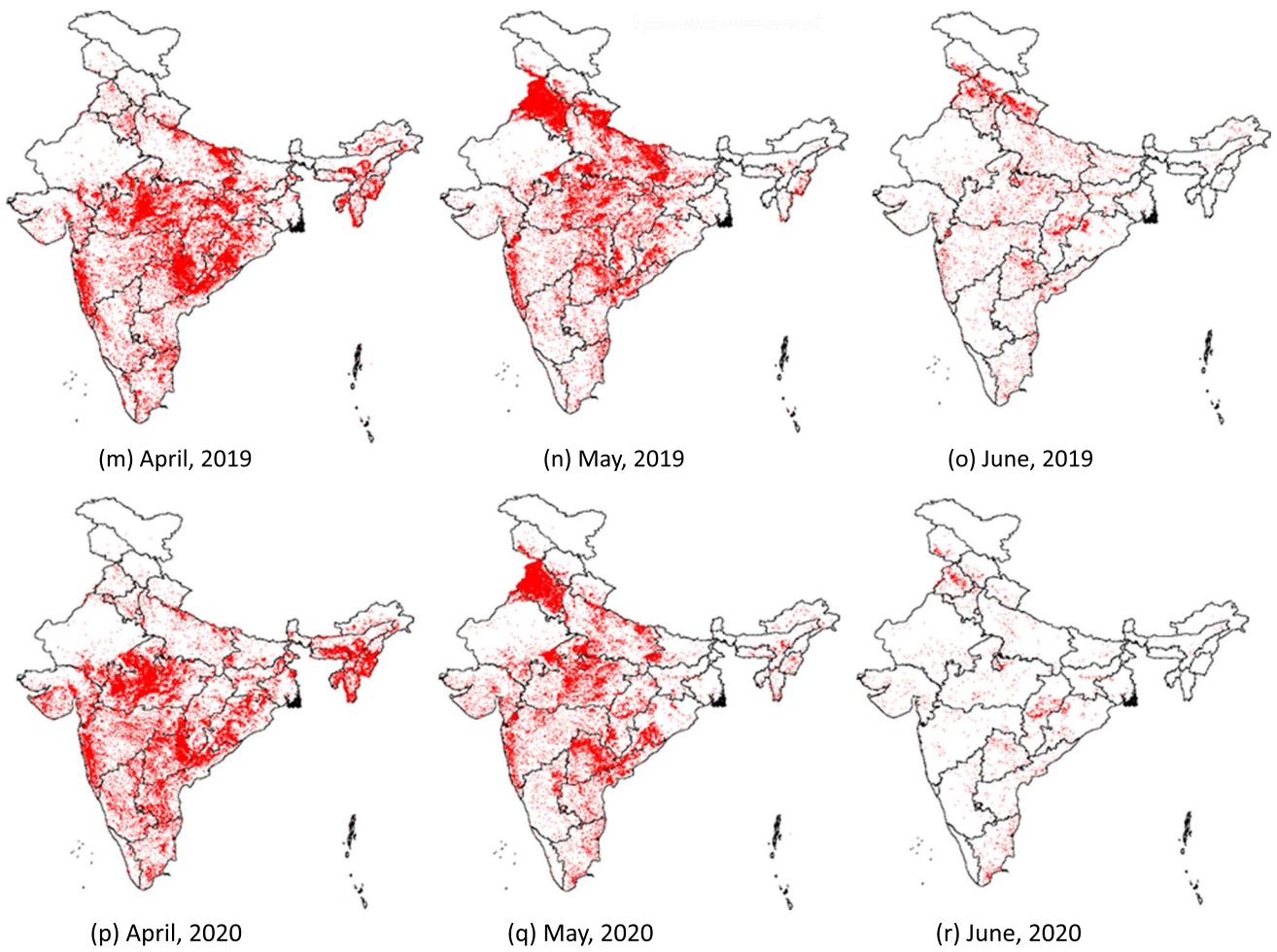


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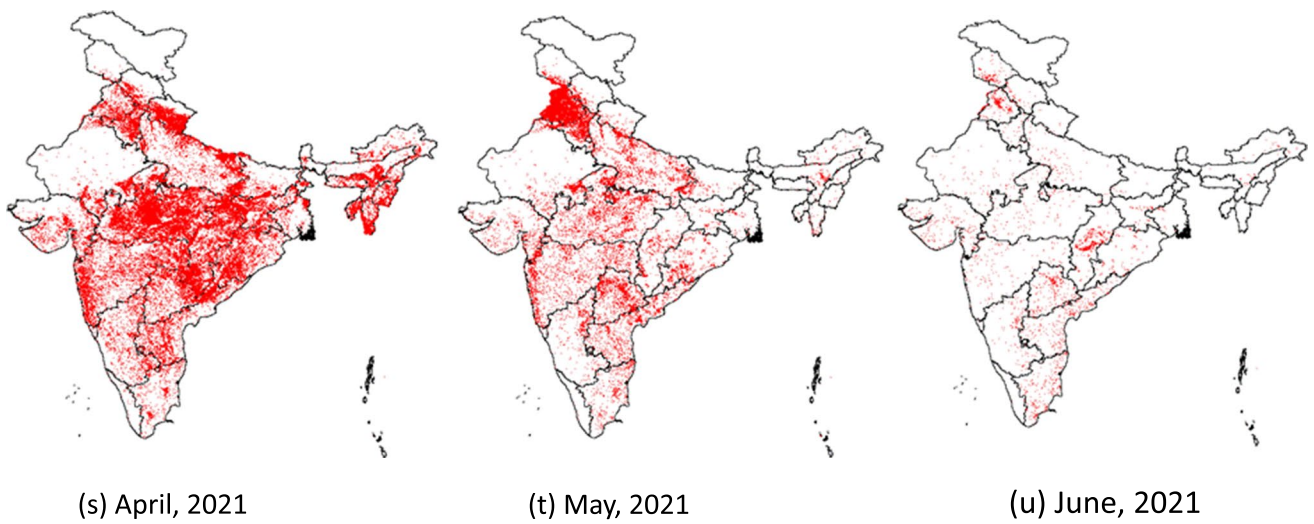


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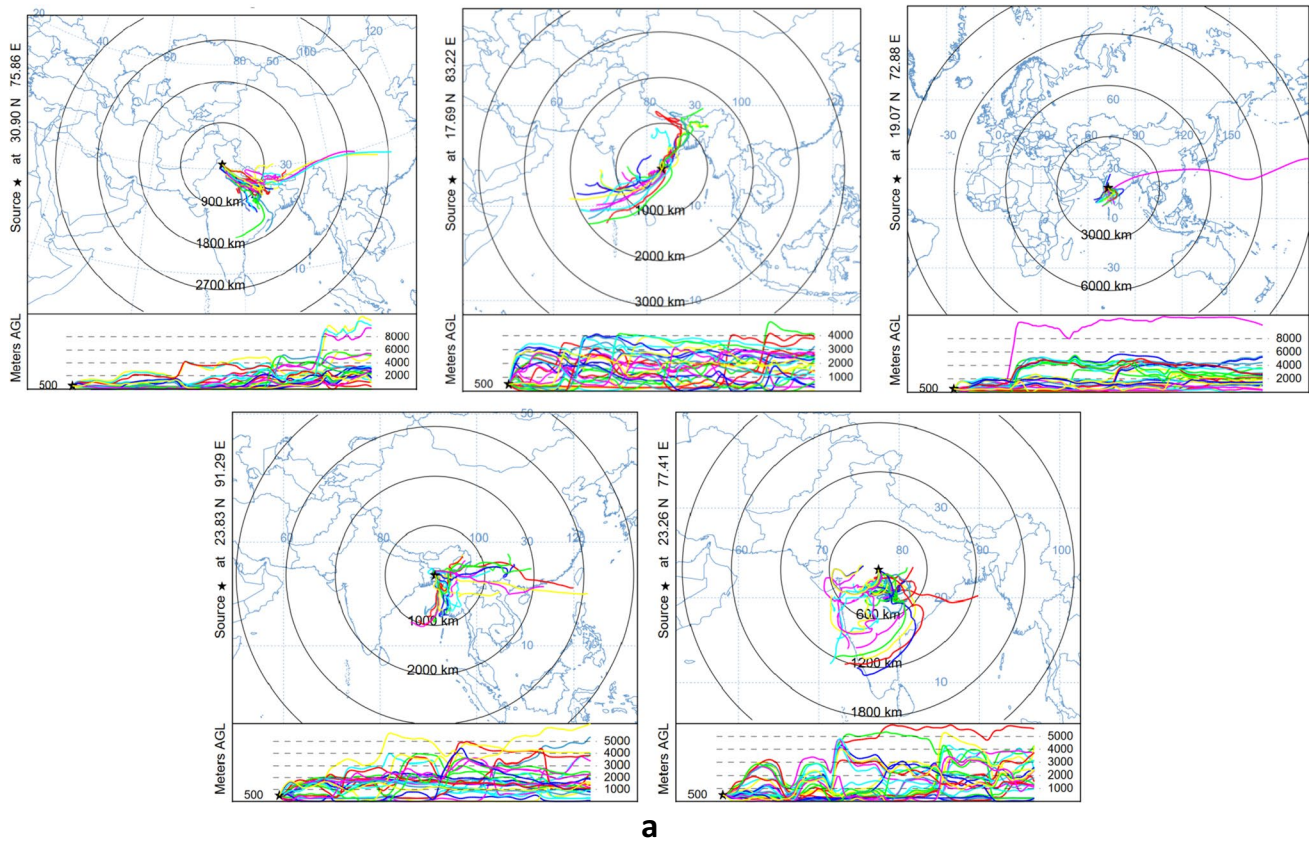


Fig. 2 **a** and **b** The 6-day forward trajectories of air masses from selected regions (Ludhiana, Vizag, Mumbai, Agartala and Bhopal) in **a** April 2021 and **b** May 2021

were observed that would have influenced airflow movements and smoke dispersal over these two months.

BC surface mass concentration and corresponding PBLH

The regions with highest surface BC levels during 2015–2021 covered parts of states like Uttar Pradesh (part of Indo-Gangetic Plain), Punjab and Haryana and also, Delhi National Capital Region (NCR) in Northern India; Bihar and West Bengal in Eastern India representing the Indo-Gangetic Plain; Tripura, Mizoram, Manipur, Meghalaya, and parts of Assam in north-eastern India. During the entire period of study, the concentration of surface BC was highest in April when fire spots were also most expansive whereas, in May and June, BC concentrations progressively declined along with declining fire incidents (Fig. 4a–u). Parts of a few states like Madhya Pradesh, Chhattisgarh, Odisha, and Andhra Pradesh in Central and South-Eastern India had lower levels of

BC while parts of Rajasthan, Ladakh, Jammu and Kashmir, and Gujarat witnessed lowest BC levels. The states involved in hosting prominent fire clusters during the study period or that became the primary recipients of air masses coming from major fire clusters, had high levels of surface BC.

The temporal variation in PBLH was studied in 2020 and 2021. Over April to June during this period, the average monthly PBLH decreased with time (Fig. 5a–f) along with decreasing monthly median and maximum but increasing monthly minimum, except in June 2021 (Fig. 6a, b). In 2020, the mean PBLH declined from 1628.84 m in April to 1035.25 m in June while in 2021, the decline was from 1865.34 to 1030.58 m. The maximum PBLH also had conspicuous decrease in 2020 and 2021 over April to June (2792.53 to 2045.39 m and 3218.27 to 2143.45 m, respectively). The zones of maximum PBLH shifted from Central Indian regions in April towards north-western parts over May to June as summer conditions progressed in India.

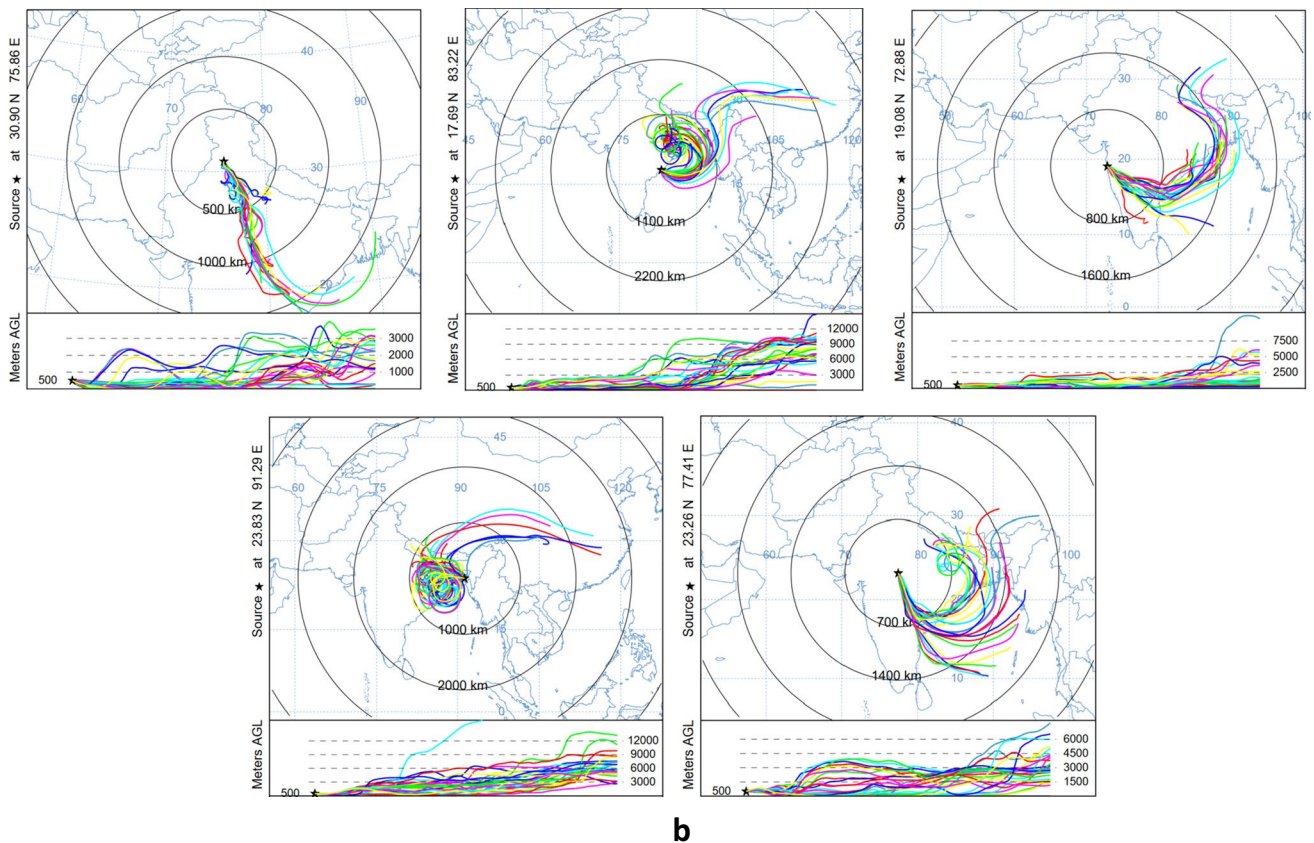


Fig. 2 (continued)

Discussion

A substantial share in the summer fires can be attributed to wheat stubble burning after analysing available information on concurrent agricultural practises. Some of the states hosting major fire clusters are also major paddy-producing ones viz. Punjab, Chhattisgarh, Bihar, Odisha, Andhra Pradesh, Uttar Pradesh, Tamil Nadu, and West Bengal, where wheat fields need to be cleared in summer starting from April, for Kharif (June–September) paddy cultivation. Maize, the third most important crop in India after rice and wheat, is also cultivated during Kharif season in states like Andhra Pradesh, Karnataka, Rajasthan, Maharashtra, Bihar, Uttar Pradesh, Madhya Pradesh, and Himachal Pradesh, most of which are also wheat growing states (https://farmer.gov.in/m_cropstaticsmaize.aspx). Also, the states of Gujarat, Haryana, Maharashtra, Andhra Pradesh, and Rajasthan, jointly accounted for 83.7% of the national acreage of Kharif groundnut in 2018 (Agricultural and Processed Food Products Export Development Authority, https://www.apeda.gov.in/apedawebsite/HACCP/2018_Groundnut_Survey_Report.pdf).

All the above states that need to clear their fields for either Kharif paddy or maize or groundnut after wheat harvest by March, hosted most of the fire clusters during April–June. The heavy fires witnessed in April in these states that diminished by May and June vindicates wheat stubble burning theory. Ravindra et al. (2022) have reported about 60% increase in paddy residue burning in Indo-Gangetic Plain in India during COVID-19 pandemic and linked this to declining income of farmers during the pandemic. In recent years (2020 and 2021), fire spots are observed to have substantially grown in expanse in parts of the North-Eastern Region (NER) of India, covering the states of Tripura, Meghalaya, Manipur, and Nagaland.

It is also important to note that many of the fire clusters are co-located with forested regions in the states of Odisha, Madhya Pradesh, Chhattisgarh and Maharashtra and North-Eastern states of Tripura, Meghalaya, Manipur, Mizoram, and Nagaland (<https://www.isro.gov.in/earth-observation/forest-environment>). These regions in NER are notable areas of shifting (Jhum) cultivation (Seitinthang 2014) and are conveniently co-located with the fire clusters. Therefore,

Fig. 3 **a** and **b** Wind vectors at 1000 mb showing resultant monthly wind direction and wind speed (m s^{-1}) contours over India in **a** April 2021 and **b** May 2021

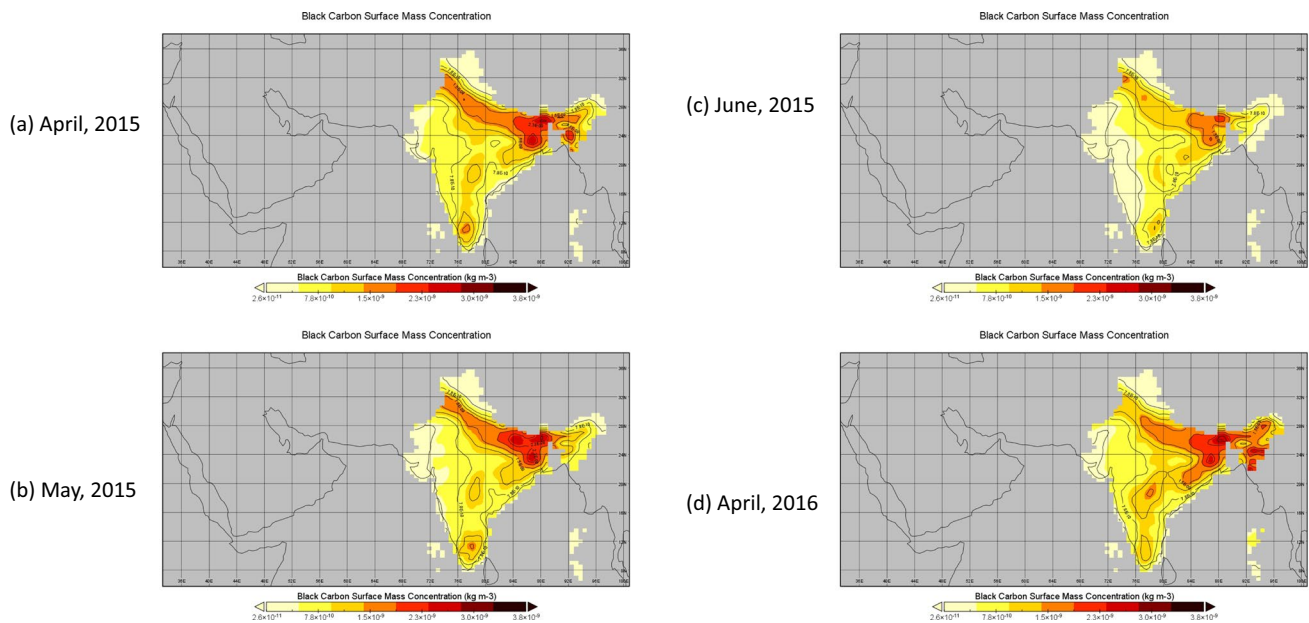
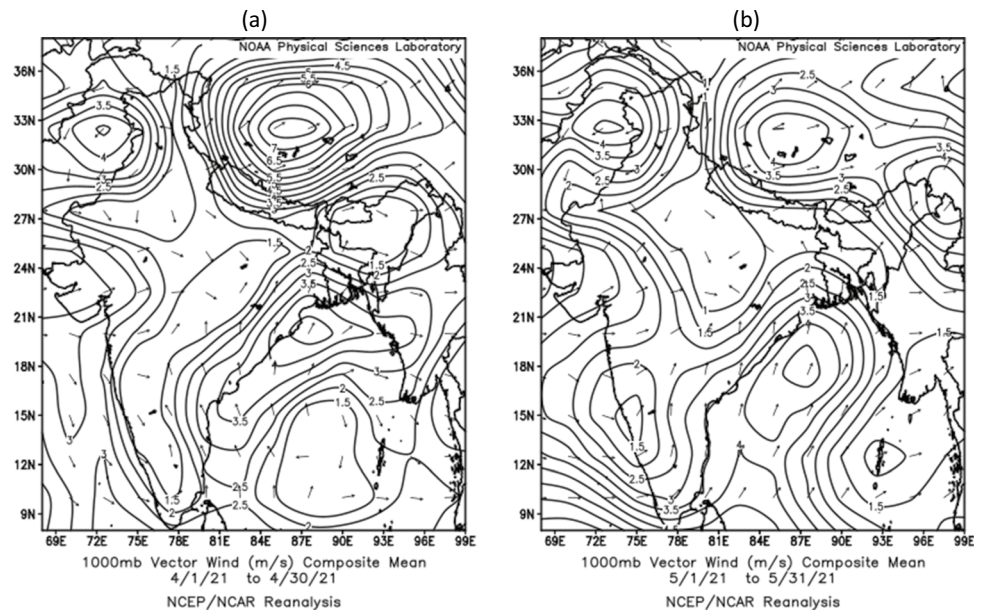


Fig. 4 **a–d** BC surface mass concentrations (kg m^{-3} , monthly time-averaged) at a resolution of 0.5×0.625 degrees over Indian landmass in April, May and June during 2015–2021

fire clusters appearing during April–June in NER could be dominated by forest fires resulting from shifting cultivation and other forms of forest fires. In past, about 50% of forest fires took place in NER of India (Bahuguna and Upadhyay 2002) and about 95% of that were caused by shifting cultivation. During January 2001 to April 2014, around 143,761 forest fire incidences occurred in NER (North Eastern Space Applications Centre 2014). In 2009, Mizoram and Meghalaya were amongst the prominent states in India in terms

of the number of detected fire spots (Sahu et al. 2015). The authors reported fire counts detected by the Along-Track Scanning Radiometer (ATSR) satellite sensors during 1998–2009 and the highest and lowest monthly fire counts were observed during March–May and July–September, respectively. Biomass fires were highest in Madhya Pradesh and Maharashtra, two central states of India which together had a share of about 25–45% of total annual fire counts in India. As per North Eastern Space Applications Centre

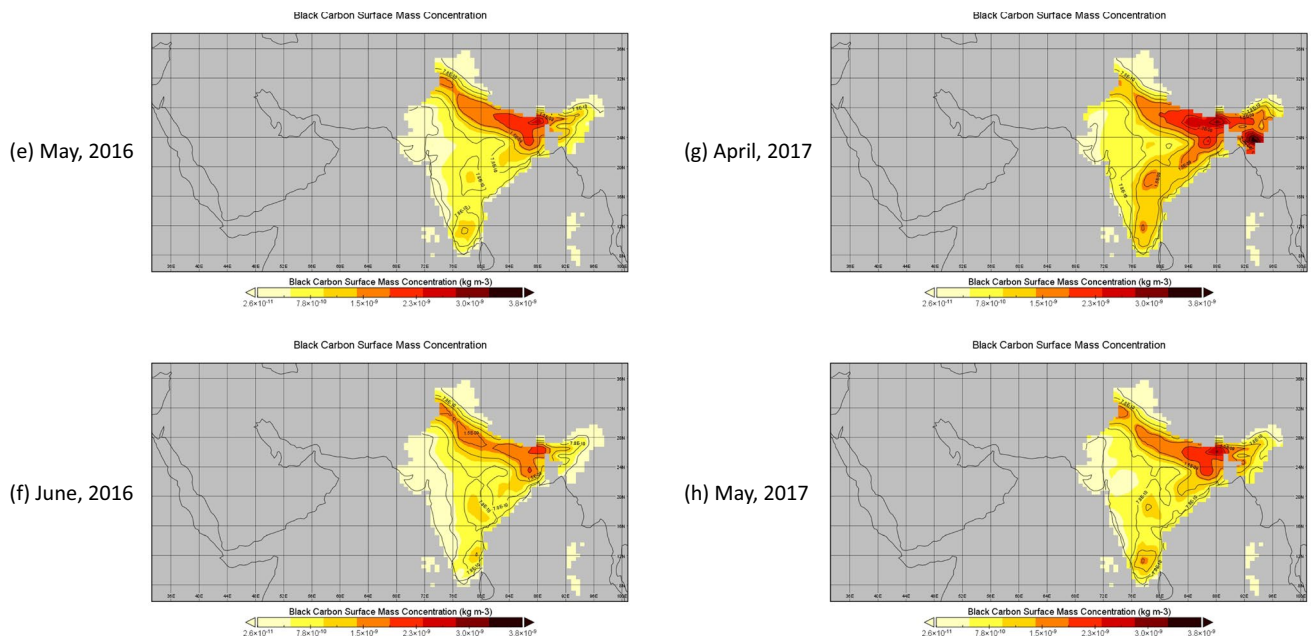


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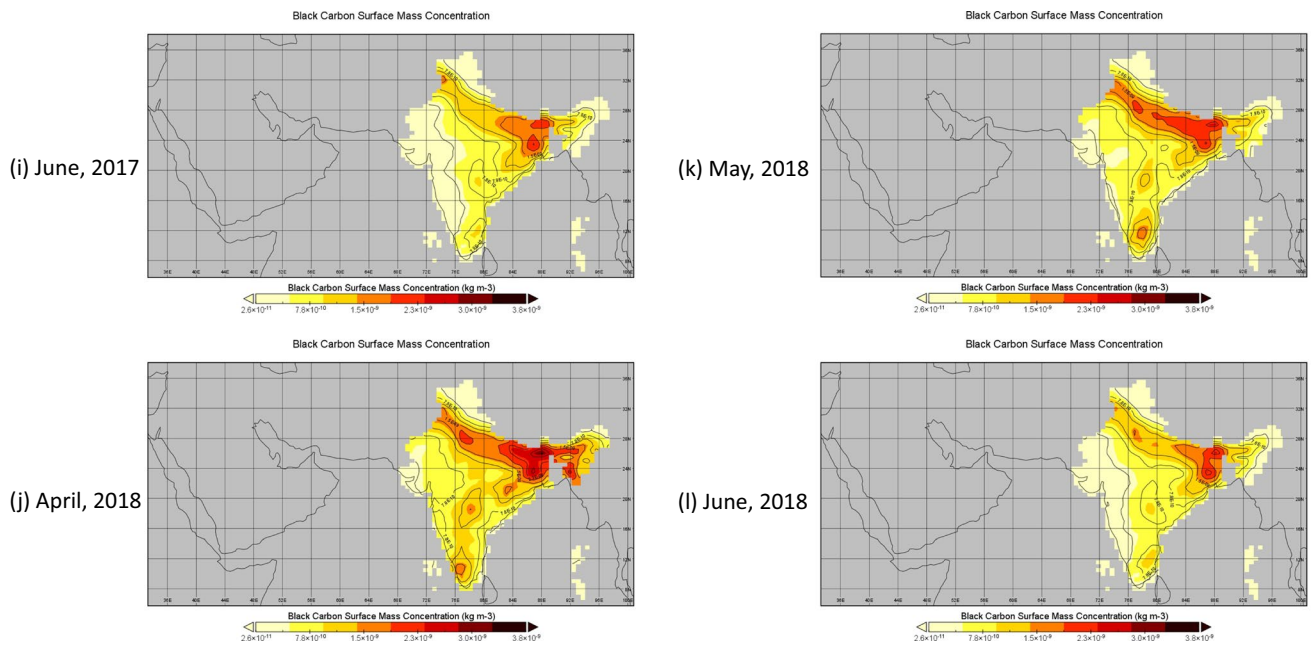


Fig. 4 (continued)

(2014), month-wise fire incidences in NER were maximum in April in Arunachal Pradesh, Assam and Tripura and the minimum in February in all other states except Tripura, where no fire was observed. On the other hand, maximum fire incidences occurred in March in Nagaland, Manipur, Meghalaya, and Mizoram. It was concluded that man-made

forest fires perpetrated for shifting cultivation was the primary cause of fire incidences in NER. The evergreen/semi-evergreen forests had highest susceptibility to fire, followed by deciduous forests while alpine forests had least vulnerability. On the other hand, open forests had the highest vulnerability to fire.

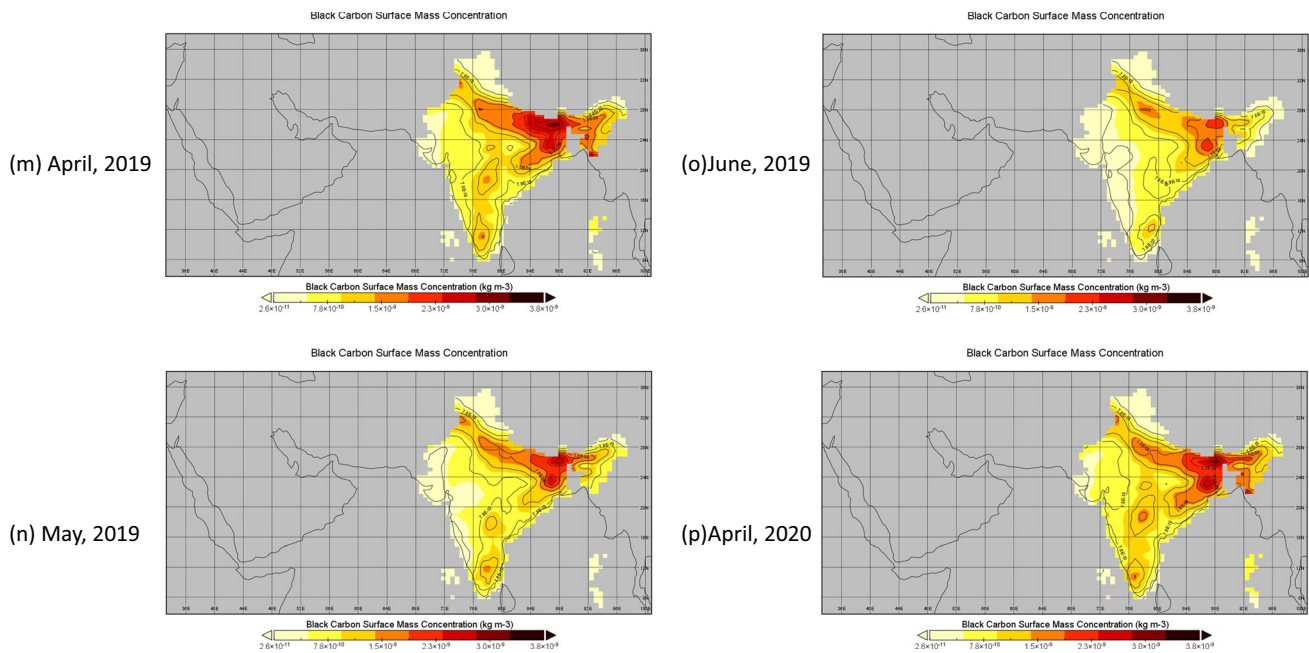


Fig. 4 (continued)

The observed trajectories of air masses moving out from five principal regions of India during April and May in 2021 suggest that a major part of Indian landmass can be potentially affected by particulates and gases emanating from the fires. It is known that during smouldering of biomass in wildfire incidents, larger combustion products like pyrometeors are suspended in fire front and smoke plume, subsequently depositing to ground within minutes to hours (McCarthy et al. 2019), whereas particulate matter (PM) and gases disperse much longer to local, regional, or continental scales and remain in atmosphere for days, months, and sometimes, even years (Guyot et al. 2021). Therefore, air movements over fire clusters are expected to affect local and regional air quality over India in terms of principal combustion products like particulates, BC, SO₂, NO_x, CO, and others. Earlier, Badrinath et al. (2009) used 5-day trajectory modelling to find that winds from North-Indian stubble fire clusters in October actually reached Hyderabad, a city in south-eastern India about 1500 km away.

In spite of the potential role of biomass fires on air quality, summer fires have received inadequate attention thus far, possibly due to the arrival of summer by March, triggering easy dispersion of air pollutants and sparing prominent urban centres of winter-like air quality. But, the scale of spatial expanse of summer fires definitely indicates likely perturbation in regional air quality in terms of BC, one of the major pollutants generated during biomass combustion. The Northern Indo-Gangetic Plain (IGP) hosted highest BC surface mass concentrations in summer, as this

zone is within the zone of influence of wind movements from several biomass fire clusters (viz. northern in April and May, south-eastern in April and May and western in May) as explained earlier. The Indo-Gangetic Plain (IGP) is known to have near stagnant wind conditions combined with shallow PBLH in winter and post-monsoon seasons so that air masses travelling to IGP are confined to a small volume (Vaishya et al. 2017), thereby having a possible build-up of air pollutants. In summer, however, IGP may witness better ventilation. As per a recent study, Sonbawne et al. (2021) found strong association of BC measured at ground level with fossil-fuel emissions, biomass smoke, and wood-burning activities at a rural station in Haryana in India. In Ontario (Canada), a significant contribution (35%) of seasonal biomass burning to ambient BC was observed in winter at a control site with low traffic contribution (Healy et al. 2017). BC being an important agent involved in triggering radiative forcing and climate change (Walsh 2014), biomass burning at such scale over India would surely accelerate radiative forcing over Indian landmass in summer. Furthermore, BC being an important component of PM_{2.5}, would play a key role in aggravating ambient PM_{2.5} levels. Stubble burning is known to have led to serious deterioration of air quality in terms of suspended particulate matter (SPM), SO₂ and NO₂ in selected areas in Haryana and Punjab in India (Singh et al. 2010; Grover and Chaudhry 2019).

Urban air pollution is influenced by the depth and structure of the planetary boundary layer (PBL) (Garratt 1994; Xu et al.

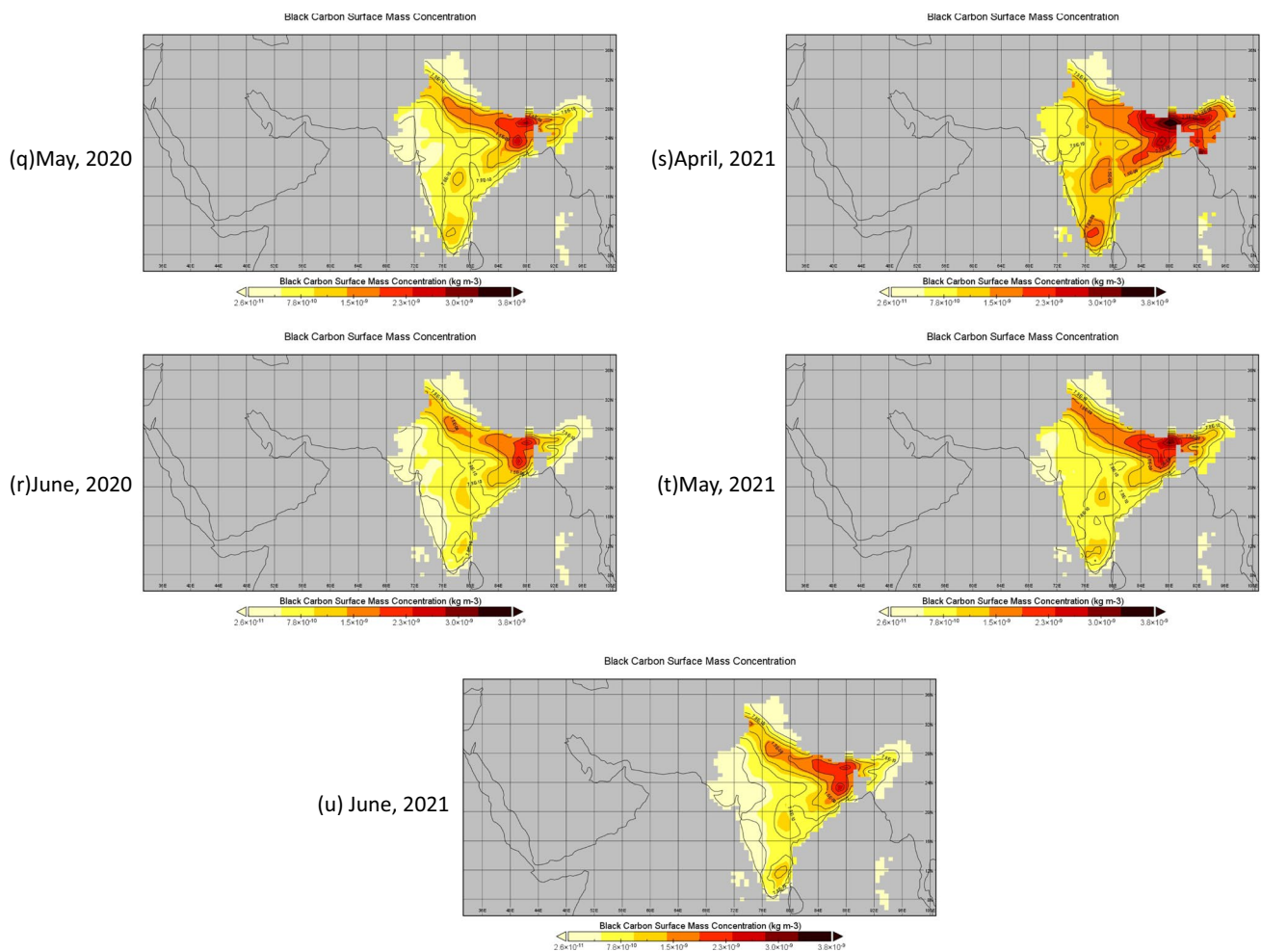


Fig. 4 (continued)

2018). The upward dispersion, mixing, transport, transformation, deposition of air pollutants, and exchange of cleaner air from above are strongly dependent on the PBL height (PBLH) and characteristics (Baklanov et al. 2011; Xu et al. 2018; Miao and Liu 2019). As BLH increases, vertical mixing height in the atmosphere also increases, helping dissipation and dilution of ground-level air pollutants and vice versa (Xiang et al. 2018). The PBLH undergoes large spatiotemporal variations vis a vis geographical location, land cover, soil characteristics, topography, season, and weather conditions (Sathyanadh et al. 2017). PBLH can have substantial diurnal variation also. In a year-long ground-based lidar measurement study on PBL over New Delhi in India, it was found that in the pre-monsoon season, PBLH grew by 100–300 m h⁻¹ (mean: 206 ± 134 m h⁻¹) (Nakoudi et al. 2019). In the study period, PBLH remained lower in many parts of IGP than central and many other parts of India, potentially supporting a build-up of BC in the former. Decreasing monthly average height of PBL over April to June ensured progressively declining vertical

mixing and lower dilution of air but, in spite of that, the concurrent decline in BC surface mass concentrations along with declining fire counts over April to June was clearly witnessed, implying the influence of biomass burning on BC surface mass concentrations.

Conclusions

Fire spots detected by VIIRS over India in the summer months (April to June) during 2015–2021 suggest the prevalence of wheat stubble burning in some regions, corroborated by co-locating fire clusters with wheat growing areas, coinciding with harvesting season and confirming the significant decrease in number of fires after April when majority of wheat is harvested. In forested regions, the majority of fire incidents are expected to have been caused by shifting cultivation (in NE hilly region) and other types of forest fires. The potential distribution of polluted air moving from five principal fire

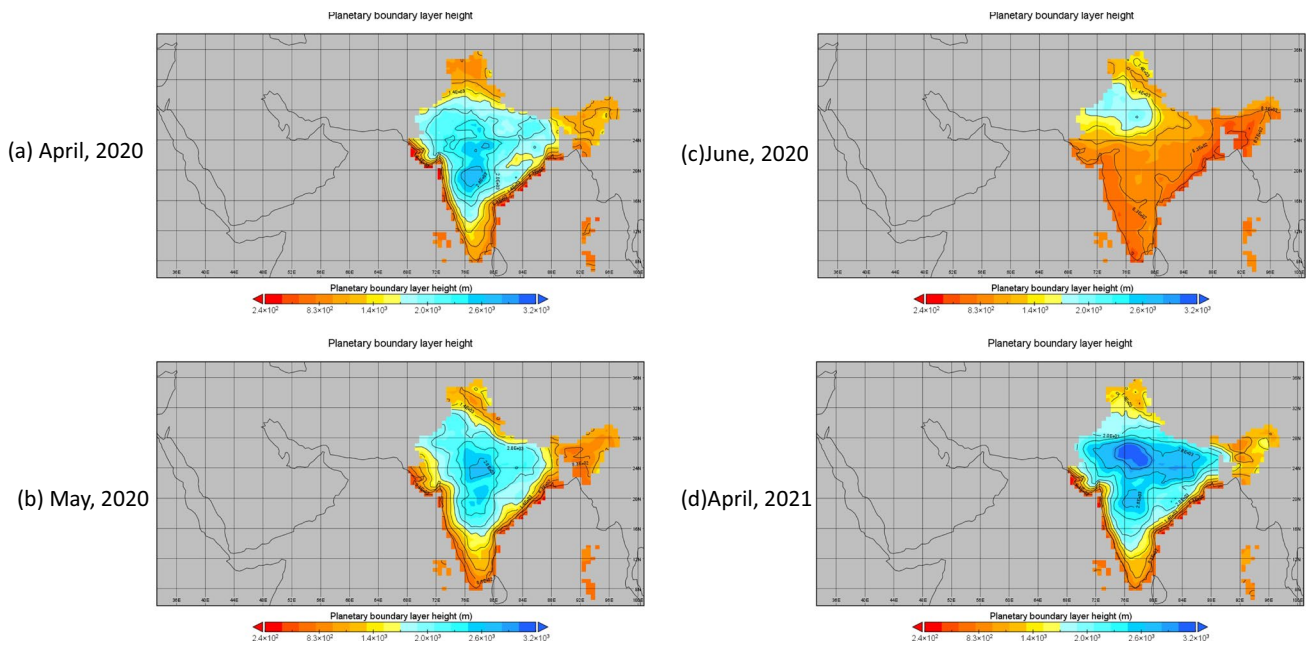


Fig. 5 Overlay maps of planetary boundary layer height (m, monthly time-averaged) at a resolution of 0.5×0.625 degrees over Indian landmass in April, May and June of 2020 and 2021

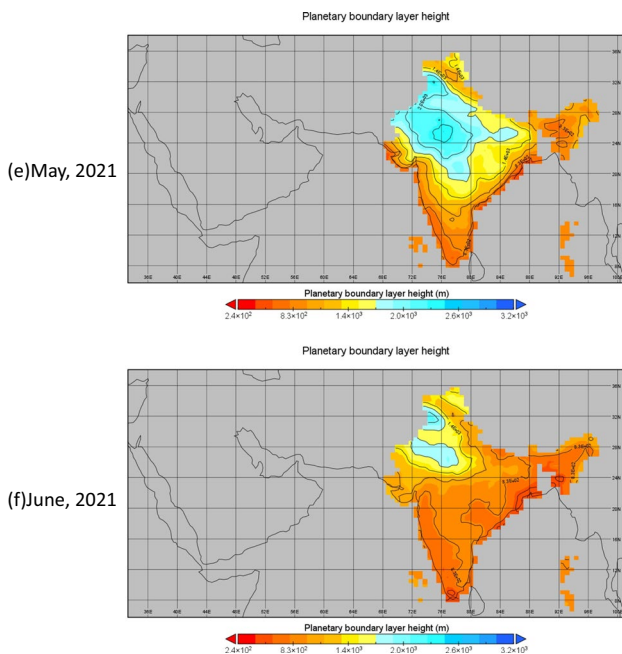


Fig. 5 (continued)

cluster locations in northern, south-eastern, western, north-eastern, and central locations via wind movements during April–June may be a key contributor to air pollution in summer over India. The strongest connection of surface BC with biomass burning is the reduction in BC surface mass concentrations simultaneously with decreasing number of forest fires

even as PBLH decreased, which must have helped increase stagnation of regional atmosphere in several areas. The IGP had higher levels of BC than other regions at any given time within the study period, possibly prompted by lower PBLH and influx of BC through air masses entering IGP from fire clusters in northern, central, and south-eastern regions.

Summer stubble burning and ensuing air pollution in India have rarely been discussed, possibly due to easy dissipation of air pollutants under favourable meteorological conditions with the advent of summer, but nevertheless, stubble burning potentially has a key role to play in perturbing air quality during summer over India. Furthermore, prominent regional fire clusters in forested regions were also observed during this study which has a confirmation from Roy (2022), who reported the appearance of big summer fire hotspots in the forested regions hosting national parks and wildlife sanctuaries in Chhattisgarh, Andhra Pradesh, Odisha, and parts of Telangana states in India. The significant escalation in fire spots in recent years is a cause of grave concern in terms of air pollution, radiative forcing and global warming, climate change, reduction in bioclimatic comfort in and around fire-affected areas, loss of forest cover, animal habitats and biodiversity and therefore, CRB and wildfires in India need urgent attention. The priorities in socially relevant environmental sustainability are long-term sustainable landscape management, sustainable human settlements based on bioclimatic comfort, clean agriculture and food production, all of which will be severely impacted by continual occurrence of crop and biomass fires. Therefore, policy intervention to

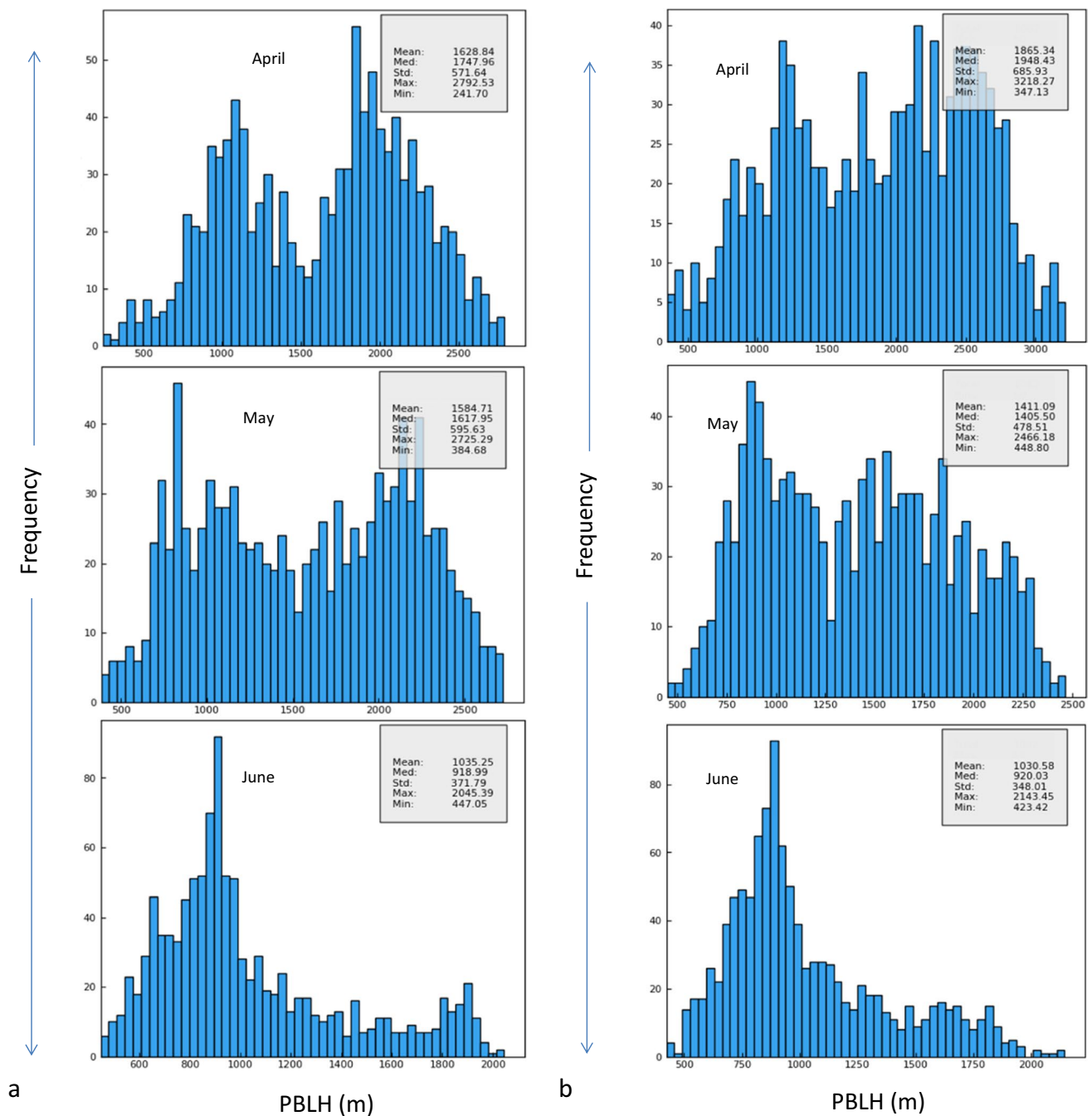


Fig. 6 a and b Histogram with descriptive statistical summary of planetary boundary layer height (m, monthly time-averaged) at a resolution of 0.5×0.625 degrees over Indian landmass in April, May and June during a 2020 and b 2021

ensure socially and economically acceptable means of clean agriculture *vis a vis* stubble management, shifting cultivation and sustainable biomass and forest management are necessary in de-escalation of biomass fire incidents in India.

This study underlines the fact that summer biomass burning incidences in India are too large in number and widespread spatially to be either downplayed or disregarded. But, unfortunately, such incidences and their

potential implications on summer air quality are under-reported and less discussed in the scientific community so far. Akin to paddy residue burning, wheat residue burning also needs to be recognised as an evolving problem in crop management and ambient air quality. This along with forest fires needs to be fixed urgently and early, considering them as means of resource destruction and deteriorating local and regional air quality in summer. The future course

of scientific research and deliberation on this subject area can be the following: (i) To assess the impacts of biomass fires on likely perturbations in regional meteorology and wind movements in summer, (ii) to estimate regional emission loads of principal air pollutants from summer fires, (iii) to decode the causes of increasing forest fires in summer in India and streamline management of the same to improve regional air quality, and (iv) to find suitable ways to minimise wheat residue burning and prioritise alternate ways of residue utilisation.

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Author contribution The author contributed to the study conception and design, material preparation, data collection and analysis, modelling, first draft preparation, and all revisions. The author read and approved the final manuscript [Deepanjan Majumdar].

Data availability The datasets generated during and/or analysed during the current study are available with the corresponding author on reasonable request.

Declarations

Consent to participate Not applicable.

Consent for publication Not applicable.

Informed consent Not applicable.

Competing interests The authors declare no competing interests.

Research involving human participants and/or animals This research did not involve any human participants and/or animals.

Disclaimer All authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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