Carbonaceous aerosol from open burning and its impact on regional weather in South Asia

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Abstract
Seasonal open biomass burning contributes to significant carbonaceous aerosol loading over South Asia. This study analyzes long-term trends in emissions in two hotspot regions, Myanmar and Punjab, using data from the Global Fire Emissions Database (GFED4s) and Fire Inventory (FINN) from the National Center for Atmospheric Research (NCAR). Analysis of emissions during active fire seasons reveals that Punjab emissions increase by approximately 83-106% compared to anthropogenic emissions, while Myanmar emissions increase by 2338-3054% based on the FINN model results. We examine the impact of carbonaceous aerosol from open biomass burning on regional weather by Weather Research and Forecasting model coupled with the Chemistry (WRF-CHEM). We examine results from a year-long simulation during the post-monsoon and pre-monsoon periods when active fires are reported. Results show that carbonaceous aerosol from open biomass burning is lofted up to 3-5 km vertically; horizontally, these aerosol rises up to 850 hPa from the surface and disperse throughout South Asia. Radiative forcing calculations suggest changes up to -6.14 W/m² at the surface and -0.50 W/m² at the top of the atmosphere over Punjab and -42.76 W/m² at the surface and -1.91 W/m² at the top of the atmosphere over Myanmar. Our results indicate that carbonaceous aerosol (BC + OC together)

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also reduce surface temperature similar to black carbon (BC) despite the scattering effects of organic carbon. The results also show that surface temperature decreased by 2K, relative humidity changed by 8%, and planetary boundary layer changed up to 600m with open biomass burning. Changes in precipitation patterns and volume due to carbonaceous aerosol from open biomass burning were negligible when considering only the direct radiative feedback.

**Keywords:** South Asia; Biomass burning; Carbonaceous aerosol; WRF/Chem.
**Introduction**

Carbonaceous aerosol (CA) is generally denoted as black carbon (BC) and organic carbon (OC), and together OC and BC play an important role in weather and climate systems of the atmosphere (Penner, 1994; Vadrevu et al., 2015). Major components of carbonaceous aerosol come from anthropogenic activities or sources (Bond et al., 2007; Ramanathan and Carmichael, 2008; Sharma et al., 2014; Streets et al., 2003a). During specific months, open biomass burning becomes the source of loading of a significant amount of carbonaceous aerosol in the atmosphere (Duncan, 2003; Hoelzemann et al., 2004; Jain et al., 2014; Liu et al., 2014; Putero et al., 2014; Reid et al., 1998; Sahu et al., 2015; Song et al., 2010; Suresh Kumar Reddy et al., 2012; Zhang et al., 2015). Carbonaceous aerosol from open biomass burning are co-emitted along with both long and short lived climate forcers such as carbon dioxide (CO$_2$), carbon monoxide (CO), sulfur dioxide (SO$_2$), reactive nitrogen (NO$_x$, NO$_y$, PANs, and HNO$_3$) etc. (Chang and Song, 2010; Goldammer et al., 2008; Karl et al., 2007; Kondo et al., 2011; Potter et al., 2001). Emissions from biomass burning in South East Asia lift up to ~3 km (Lin et al., 2009). Similar uplifting of open biomass burning (OBB) emission was reported over Africa (Haywood et al., 2008) and Amazonia (Liu et al., 2014).

Hydrophobic BC strongly absorbs radiation and makes a direct impact by heating the atmospheric column, whereas hydrophilic BC contributes to ice nucleation (IC) in clouds (Bond et al., 2013; Chen and Bond, 2010; Guha et al., 2015). Hydrophobic OC mostly scatters solar radiation while a significant fraction of OC is also known to absorb a fraction of the radiation known as brown carbon and creating a surface cooling effect. Hydrophilic OC also acts as a cloud condensation nuclei (CCN) (Chen and Bond, 2010; Ellison et al., 1999; Penner, 1994). Climate forcing over snow and ice due to carbonaceous aerosol deposition have also been
reported in previous studies (Bond et al., 2013; Hansen and Nazarenko, 2004). In addition, the presence of absorbing aerosol such as BC near clouds can evaporate clouds by heating them (Conant et al., 2002; Koch and Del Genio, 2010). Results from the Precipitation Driver Response Model Inter-comparison Project (PDRMIP) suggest that climate forcing from BC affects precipitation patterns outside the emission source region of BC (Liu et al., 2018). Previous studies also indicate that ~1 K temperature change near to surface can alter the water vapor content by ~5% (Andrews et al., 2010; O’Gorman et al., 2012).

Current understanding of emissions of carbonaceous aerosol from open burning shows two regional hot spots relevant to South Asia (Chang and Song, 2010; Jain et al., 2014; Venkataraman et al., 2006). They are the Indo Gangetic Plains (IGP), and in and around Myanmar in Southeast Asia. Among Asian countries, Myanmar is known as the biggest source of forest fires during the months of March and April (Biswas et al., 2015; Vadrevu et al., 2015). Emissions from agricultural residue (biomass) burning over Myanmar in both dry and wet seasons is much lower compared to forest fires (Chang and Song, 2010; Kim Oanh et al., 2018; Song et al., 2010). In contrast, crop residue burning during April-May and October-November over IGP causes a serious air quality problem, especially in October-November when the planetary boundary layer (PBL) is low (Rajput et al., 2014; Sharma et al., 2010; Singh and Kaskaoutis, 2014). Over South Asia (Bangladesh, Bhutan, India, Myanmar, Nepal, and Pakistan), BC emission from non-agricultural open fire is ~11.62 Gg/year whereas OC emission is estimated at ~106.17 Gg/year (Song et al., 2010). Total emission from open biomass burning (OBB) is estimated at BC ~150Gg and OC at ~1151Gg for South Asia (Streets et al., 2003b). Furthermore, BC emission from crop residue burning is estimated at ~68 Gg/year during 2008-09 over India (Jain et al., 2014) whereas it was ~14 Gg/year during 2010-2015 over Myanmar.
Over India, OBB contribute a total BC emission of 104-409 Gg/year and OC emission of 399-1529 Gg/year (Venkataraman et al., 2006). In contrast, in Myanmar, OBB contributes a total BC emission of ~59 Gg/year and OC emission of ~590 Gg/year (Kim Oanh et al., 2018).

Earlier studies have reported on local and regional pollution events due to forest fires and agricultural biomass burning (Goldammer et al., 2008; Reddington et al., 2014). But most of these have been limited to characterization and estimation of emission from OBB (forest and crop residue burning) (Song et al., 2010; Vadrevu et al., 2015; Venkataraman et al., 2006). Moreover, some studies on South East Asia were limited to transport of emissions from OBB which have implications for urban and regional air quality (Sahu et al., 2015; Zhou et al., 2018).

Menon et al., (2002) reported the impact of BC on regional precipitation over India and China. Recently Liu et al., (2018) and Andrews et al., (2010) have simulated the climatic effects of hypothetical 10x-BC (where anthropogenic BC emission was increased by a factor of 10) on regional weather and climate. The present study investigates a case of high carbonaceous aerosol (BC+OC) in the atmosphere emitted from OBB during the pre- and post-monsoon periods and its impact on the weather over South Asia. While the hypothetical high BC emission case studies were carried out using a global chemistry-climate model, we tried to understand the impact of high BC emission using a high resolution regional weather forecasting model coupled with chemistry (WRF-Chem) in this study. This study does not prescribe hypothetical carbonaceous aerosol emissions to understand the impact of carbonaceous aerosol on radiation like previous studies. Instead, we estimated an increase in carbonaceous aerosol emissions from OBB regardless of the magnitude in this study. We also analyzed results from two different OBB inventories over South Asia which indicate the difference in emission strength. We present the
vertical concentration of carbonaceous aerosol over South Asia as have been done in prior
studies (Chung et al., 2010; Ramanathan et al., 2001) in order to estimate the vertical profile of
CA from OBB and its impact on radiative forcing over South Asia. Further, we discuss in detail
the impact of carbonaceous aerosol on regional weather and meteorological.

Observation and Methodology:

Fire Observations:
We use information from the monthly gridded Global Fire Emissions Database (version 4.1)
(GFED4s), from 1997 to 2015, for analysis (Giglio et al., 2013). This data set is available at
0.25° resolution and was downloaded from https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1293.
This set of data provides total carbon (g C m⁻² month⁻¹) and dry matter (kg DM m⁻² month⁻¹)
emissions from open fires globally. It includes emissions from different sources such as
grassland and savanna, woodland, deforested and degraded areas, forests, agricultural waste
burning, and peat fires. MODIS (Moderate Resolution Imaging Spectroradiometer) burned area
map, along with TRMM (Tropical Rainfall Measuring Mission), VIRS (Visible and Infrared
Scanner) and ATSR (Along-Track Scanning Radiometer) data were used to generate this GFED
data set (Giglio et al., 2013).
The Fire Inventory from NCAR (version 1.0) (FINNv1) available at 1 km resolution was also
used in this study (Wiedinmyer et al., 2011). This dataset was downloaded from
http://bai.acom.ucar.edu/Data/fire/. The data contains trace gas and particle emissions from
various sources of open burning like wildfire, agricultural fires, and managed burnings
MODIS Rapid Response data was used to identify fire location and time for FINN data set.

Additionally, the Copernicus Atmospheric Monitoring Service (CAMS) Global Fire Assimilation System (GFAS) data set is also used in this study. It was downloaded from https://apps.ecmwf.int/datasets/data/cams-gfas/. The CAMS-GFAS data set contains the wildfire flux of ~40 species at the 0.1° special resolution at a daily resolution. The MODIS generated fire radiative power is used in GFAS to generate the emission product (Di Giuseppe et al., 2018). We used CAMS-GFAS data for the months of March, April, October and November of 2013 in the analysis.

CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) uses active lidar and passive infrared sensors to measure the vertical profile of the atmosphere. We used CALIPSO images from https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/ to understand fire emissions, during the active biomass burning events in this study, from the available satellite overpass. Specifically, CALIPSO level 1 version 3.3 data with air pollution speciation (clean marine, dust, polluted continental, clean continental, polluted dust and smoke) was used in this study.

Chemical Transport Model:

The WRF-Chem (version 3.8.1) (Weather Research Forecasting model) is used in this study (Grell et al., 2005; Skamarock et al., 2008). Fig. 1 shows the model domain projected on Mercator projection centered at 22°N, 78°E which covers from 6.5°-36.0°N and 53.0°-103.0°E on a spatial resolution of 25 km. The model contains 40 vertical levels from surface to model top at
50 hPa. The heights of the first 10 levels are within 300 m each and all levels above are within 650 m each.

The Emission Database from Global Atmospheric Research- Hemispheric Transport of Air Pollution (EDGAR-HTAP) offers anthropogenic emission at 0.1°×0.1° spatial resolution for the year 2010 (Janssens-Maenhout et al., 2013). We used the EDGAR-HTAP emissions in this study using the preprocessor tool available from the NCAR website (Kumar et al., 2015). We have updated the initial and boundary condition in simulations for this study using the simulations from the Model for Ozone and Related chemical Tracers, version 4 (Mozart-4) (Emmons et al., 2010). O₂ and O₃ column densities from exo_coldens are used for photolysis processes in the MOZART/MOZCART option in the WRF-Chem simulation. The exo_coldens tools read O₂ and O₃ from the WRF input file and MOZART data is used to calculate column density and create a separate file. We use the monthly biogenic emission flux from the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1) in the WRF-Chem simulation for this study (Guenther et al., 2012). The daily sea surface temperature (SST) was updated in the model simulation using data from (http://polar.ncep.noaa.gov/mmab/translation.shtml).

We use the MOZCART based chemistry option in the WRF-Chem simulation for this study. MOZCART is a combination of the MOZART model (for trace gas chemistry) and the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (for bulk aerosols chemistry). Dust emission is selected as suggested in GOCART chemistry and provided with fractional erosion map. Dimethyl sulfide (DMS) emissions are kept active in all the simulations (Chin et al., 2000).

The simulations for this study incorporates the emission estimate from the Fire INventory from NCAR model version1 (FINNv1) which provides daily open burning emission at 1 km × 1 km
spatial resolution (https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar) (Wiedinmyer et al., 2011). Both smoldering and flaming emissions are included in the mapped data set. We use the MOZCART based biomass burning emission and plume rise calculation for FINNv1 data as mentioned above.

**Methodology:**

We used the FINN and GFED monthly biomass burning carbonaceous emissions from 1997 to 2015 to identify and analyze fire hot spots over South Asia (6.5°-36.0°N, 53.0°-103.0°E). On the basis of GFED and FINN, Punjab (28.83°-32.01°N, 72.91°-77.86°E) and Myanmar (13.86°-27.74°N, 90.28°-102.69°E) were identified as hot spots for biomass burning. Given the temporal and spatial similarity of the fires, this study only used FINN fire emissions for further analysis. We used the fire_emis source code from NCAR site is used to map FINN data set from 2002 to 2015 on hourly file.

We carry out two sets of year-long simulations with the WRF-Chem model for 2013. The first set of simulations are carried out with total emissions (anthropogenic + OBB) of all air pollutants including carbonaceous species while the second experiment is simulated by omitting only carbonaceous aerosol from OBB. In both the model simulations, we used data from National Centers for Environmental Prediction Final Analysis (NCEP FNL) to update initial and boundary meteorological condition. To preserve similar meteorology in both simulations and avoid divergence in meteorological parameters, simulations were reinitialized every day with NCEP FNL data. Whereas chemistry was carry forward from the last step of every previous day simulation to maintain consistency in the vertical and horizontal concentration of chemical species. The chemical boundary condition was updated using MOZART output for each time
step. This algorithm was followed in both simulations throughout the year in order to maintain meteorology and chemistry consistency. The WRF-Chem simulations of meteorology and chemistry have been compared in detail in several other studies (Adhikary et al., 2007; Kumar et al., 2015).

**Results and Discussion:**

Fig. 1a shows the averaged total carbon emissions (g C m\(^{-2}\) month\(^{-1}\)) from biomass burning from 1997 to 2015 using GFED4. Burning over Myanmar shows the highest carbonaceous emission within the domain. Carbonaceous emissions due to biomass burning from Punjab (both Pakistan and India) to Bihar (India) also show elevated emissions. Apart from Myanmar and Punjab (IGP), Fig. 1(a) also shows biomass burning emission over the Western Ghats (WG), Eastern Ghats (EG) and Sri Lanka. Fig. 1(b) shows biomass burning carbonaceous aerosol emission (g C m\(^{-2}\) month\(^{-1}\)) from the FiNN data set averaged for the 2002 to 2015 period. Despite differences in input data sets (MODIS/VIIRS/TRMM etc.) both FiNN and GFED4 identify similar features within Myanmar and Punjab regions. The CAMS dataset for 2013 (Fig. 1c) shows similar features illustrating 2013 as a normal year at least in spatial emission patterns when compared to climatology datasets. All three data sets use similar kinds of satellite observation, but different algorithms to define the area of coverage and emissions from open biomass burning.

Myanmar biomass burning episodes mostly results from forest fires during the dry and hot days of the pre-monsoon season (Biswas et al., 2015; Liu et al., 2010; Vadrevu et al., 2015). In contrast, Punjab biomass burning is a result of agricultural crop residue burning in April-May when the wheat crop is harvested, and during October-November when the rice crop is harvested (Rajput et al., 2014; Tiwari et al., 2016; Venkataraman et al., 2006). October-November biomass burning in Punjab is often in the news and media reports because of the deteriorating air quality
situation in the IGP (Sharma et al., 2010; Singh and Kaskaoutis, 2014; Vadrevu and Lasko, 2018). Emissions during the months of March and April are under less scrutiny due to the convectively active season which transports the pollutants in the vertical layers unlike in the winter season (Vadrevu et al., 2015).

Further, area averaged OBB emissions from Punjab (28.83°-32.01°N, 72.91°-77.86°E) and Myanmar (13.86°-27.74°N, 90.28°-102.69°E), for the period of January 2012 to December 2015 is presented in Fig. 1d. It shows a single fire season over Myanmar starting in February and continuing till the onset of the monsoons. March is recorded as the highest OBB in Myanmar followed by April and February. Unlike Myanmar, Punjab shows two biomass burning seasons, the first in April-May and the second in October-November. Table 2 shows the emission strength from open burning within these two model subdomains compared to anthropogenic emissions. The results in the parenthesis show the lean burning seasons, which are March-April for Punjab and October-November for Myanmar. The analysis of the emissions during active fire seasons reveals that the Punjab emissions increase approximately 83-106% compared to anthropogenic emissions in the FINN model (~26-50% from CAMS) while the Myanmar emissions increase by 2338-3054% in the FINN model (476-735% from CAMS). These results show a real-world example of 10X BC climate simulations as carried out by the PDRMIP studies but applicable to current weather timescales.

Given the uncertainty of the emissions from biomass burning (Giglio et al., 2013; Di Giuseppe et al., 2018; Wiedinmyer et al., 2011), we proceed with further analysis using FINN model emissions to estimate the impact on weather. The simulations include biomass burning emissions and plume rise calculation for MOZCART (biomass_burn_opt=2). The model considers the fire emission as surface emission in the simulation whereas the injection height of OBB emission
depends on the stability of the atmosphere and vertical winds (Archer-Nicholls et al., 2015; Walter et al., 2016). Generally, injection height shows a strong diurnal cycle depending on PBL stability and varies 2-3 km in height which is usually above the PBL (Grell et al., 2011). As discussed in the model setup section the height of each vertical level (the first 10 levels) in the model simulations are less than 300m to capture the stability and mixing in PBL layers while the height of vertical levels above PBL (mostly the 11th level onwards) are below 650m. The injection height of OBB emission strongly depends on thermodynamic stability and PBL dynamics while uncertainty related to PBL height and thermal stability can affect the vertical distribution of BC. The GFED files are available on monthly time scales but are too coarse in terms of a temporal resolution for us to assess its impact on weather while the CAMS emissions were much lower than FINN to pick up significant alterations in weather variables. Hence, further results and discussions are limited to the period March-April for Myanmar, and October-November for the Punjab region.

Fig. 2 shows a vertical BC concentration area average for Myanmar (March-April 2013) and Punjab (October-November 2013). Fig. 2a shows model simulations of BC concentration over Myanmar from the control run which includes biomass burning while Fig. 2b shows the concentration without biomass burning emissions. Similarly, Figs. 2(c and d) shows BC concentration from the control run and simulation without biomass burning emissions for the Punjab region. Fig.2a shows significantly higher surface and boundary layer BC concentrations when compared to Fig. 2b. Similar results are present in Figs. 2c-d. Fig. 2d shows that BC concentrations are very high (black color scale) for a few days in mid-October to mid-November indicating that significant-emissions from the Punjab region are limited to few days and not spread throughout the post-monsoon period. Moreover, CALIPSO passes over Myanmar shows
that most days of March and April consist of smoke up to 5 km (supporting Fig. 1) whereas
passes over Punjab during October-November shows the presence of smoke below 3 km
(supporting Fig. 2). A similar smoke plume height is reported over India and South East Asia in
another study (Lee et al., 2016; Vadrevu et al., 2015). Organic Carbon concentration over
Myanmar and Punjab show similar trends and spatial distribution albeit at higher concentration
than BC.

While Fig. 2 shows sub-domain (Punjab and Myanmar) averaged vertical profile of BC, Fig. 3
shows differences in plots of monthly averaged BC concentration between the control and no
OBB simulations at different vertical layers indicating the horizontal spread of BC aerosol. Rows
illustrate concentration differences over several months while columns report vertical levels. At
the surface, during March and April, differences in BC concentration in and around Myanmar
show a north-south gradient. Elevated concentration differences are also seen along the eastern
India shoreline in the Bay of Bengal. At 850 hPa which is near PBL, results show similar
features as the surface. Surface and 850 hPa results show that BC emitted from OBB during the
March and April fires affect mostly the eastern and the southern part of the domain. Further, at
500 and 300 hPa differences in BC concentration are still shown by the model, although
diminishing over the Bay of Bengal at the 300 hPa.

Similarly, the third and fourth rows in Fig. 3 show monthly averaged differences in BC
concentration for October and November respectively. At the surface, the results show prominent
features around the Punjab region with a sharp north to south gradient. The difference in
concentration between the two simulations is not as strong over the entire domain as that for fires
from the Myanmar region. The 850 hPa subplot shows similar features as the surface with lower
magnitude. The weak northerly winds (figure not shown) over the surface and the 850 hPa
prevent dispersal of BC concentration towards the northern portion of the modeling domain. A small amount of BC concentration from OBB is observed over the Tibetan Plateau (TP) at 500 hPa whereas 300 hPa remains clean. Similar trends are observed for OC at surface, 850 hPa, 500 hPa and 300 hPa for all the four months (supporting Fig. 5), although the observed OC concentration is much higher (~4×) than that for BC. Such amount of BC and OC at surface and column levels can affect the incoming shortwave and outgoing longwave radiation budget, which may feedback into local meteorology (Ramanathan and Carmichael, 2008).

Table 3 shows the area-averaged impact of carbonaceous aerosol from OBB on incoming shortwave and outgoing longwave flux over the entire modeling domain and within the source regions. Our results show that the outgoing longwave radiation (OLR) flux reduces by 0.28 W/m² over the entire modeling domain while it further reduce by 1.91 W/m² over the source region. Ramanathan et al., (2005) reported top of the atmosphere (TOA) BC forcing to be ±1 W/m² for South Asia. Although Chung et al., (2010) have reported -4.2 W/m² TOA radiative forcing due to anthropogenic aerosol, the BC radiative forcing reported is +2.1 W/m² for Asia which is similar to our results. Similar observation-based results from India suggest surface forcing -23 W/m² and TOA forcing of 5 W/m² by enhanced BC over the urban environment (Babu et al., 2002). Variation within the two months shows the sensitivity of forcing based on the emissions and subsequent concentrations.

Sharma et al., (2010) have reported a total surface radiative flux of -134 W/m² to -212 W/m² and TOA radiative flux -41 W/m² to -47 W/m² over Punjab for the month of October (2006-2007). Our study estimates changes in OLR flux over Punjab to be ~0.48 W/m² for the entire region. The model reports area averaged surface forcing to be 0.008 to -78.21 W/m² and OLR at TOA to be -4.96 to 2.48 W/m² over Punjab which is comparable with the observations. The
regional BC radiative forcing at the surface in the 1990s was estimated to be between -30 W/m² to -20 W/m² over northern BoB (Krishnan and Ramanathan, 2002; Ramanathan et al., 2001, 2005) while a total aerosol forcing of ~75 W/m² was reported for the same time period by Lelieveld et al., (2001). The surface radiative forcing reported by Chung et al., (2010) due to anthropogenic aerosol is -8.6 W/m² and -5.2 W/m² by BC over Asia. Our results provide insight into the contribution of carbonaceous aerosol which has similar emission sources and patterns, unlike the previous studies that either focus on a single aerosol or total aerosol effect. Our results show that carbonaceous aerosols from open biomass burning strongly alter radiation balance in the atmosphere at a local and regional level.

Carbonaceous aerosols from OBB shows a strong influence on surface incoming shortwave flux over Myanmar and Punjab (Table 3), which indicates less radiation is reaching to surface. Such a strong reduction in radiation at the surface, make a negative change in temperature, which is further justified in Fig. 4, where the temperature drops significantly even as other factors also change. Similar results are presented by Ding et al., (2013) for China where the drops in temperature up to 10K is reported during OBB and high pollution events.

Fig. 4 depicts the domain averaged OBB carbonaceous aerosol impact on surface weather parameters over Punjab and Myanmar. Figs. 4a-b shows the time series of OBB- carbonaceous aerosol concentration while the rest show changes in meteorological parameters. The results show that changes are proportional to surface concentration. Lower concentration of carbonaceous aerosol from fire over both Myanmar and Punjab do not make significant impacts on the meteorological parameters. Wind speed (Figs. 4c-d) shows both positive and negative changes, RH (Figs. 4e-f) shows an increase in values while temperature (Figs. 4g-h) and PBL (Figs. 4i-j) height show a decrease in magnitude. The magnitude of the surface temperature
change is up to 2K. RH values change by up to 8%. The increase in relative humidity (RH) is
due to high moist static energy during biomass burning events as, during this period, high
evaporation rate (MA et al., 2015) and shallow PBL height result in higher RH (Ding et al.,
2013). The magnitude of wind speed is change between -0.6 to 0.3 m/s with decreasing wind
speed most of the time. The PBL height significantly changes in 200-600 m.

Krishnan and Ramanathan, (2002) suggest that a 10-15% increase in BC concentration can block
up to 10% solar radiation which leads to 0.3° C cooling at surface. They further note that the
observed cooling may lead to warming elsewhere. Wilcox et al., (2016) suggested up to 8%
increase in relative humidity during polluted period. In Balachandran et al., (2017), fire PM$_{2.5}$
had an inverse relationship with variables like PBL and wind speed similar to our results.

Fig. 5 shows a temperature difference (monthly average) due to OBB emitted carbonaceous
aerosol at different vertical layers. Given the higher difference in OBB carbonaceous aerosol
concentration over Myanmar compared to Punjab, the changes in surface and 850 hPa
temperature is stronger over Myanmar than Punjab. Small rises in temperature are seen over the
northwestern domain during the month of April and over the Eastern portion of the domain in
November possibly due to changed circulation. Smaller temperature changes are simulated over
the entire domain during the month of April at 500 hPa and 300 hPa, while other months show
very little or localized change at these altitudes. Balachandran et al., (2017) and Saha et al.,
(2014) have also reported changes in PBL and other meteorological variables due to aerosol
radiative feedback which could lead to warming elsewhere. Finally, our study suggests that
carbonaceous aerosol (BC + OC) also reduces surface temperature similar to BC despite the
scattering effects of organic carbon.
We also examined the impact of OBB carbonaceous aerosol on precipitation amount and pattern over South Asia. OBB occurs during pre-monsoon and post-monsoon in south Asia, a period when there is no significant precipitation over the subcontinent. Previous studies have reported on the impact of aerosols, especially BC on changes in monsoon precipitation later on during the season (Manoj et al., 2011). In this study, we analyzed fast response to precipitation amount and pattern. Our results indicate that there is no significant change in either amount or pattern of precipitation over the modeling domain; a ~2-5% change is simulated near Myanmar, which is limited to a few grids (supporting Fig 4.). We wish to point out that the study only considered direct effects through radiative forcing and did not examine the aerosol cloud interaction and pathways for changes in precipitation. The PDRMIP multi-model study also suggested that the effect of 10×BC on Asian precipitation is very small (~1.4%) (Liu et al., 2018) similar to the results of this study.

**Summary and Conclusion:**

Climatology from GFED4, CAMS and FINN fire products shows Punjab and Myanmar as major contributors of carbonaceous aerosol emissions from open biomass burning along with some smaller emissions sources from the rest of South Asia. The major contribution to open biomass burning emissions in South Asia comes from the Myanmar forest fires, which occurs during March-April when the weather is dry and hot. Myanmar forest fire emit ~0.80 g/m²/month of total CA while total carbon emission is ~12.71 g/m²/month. On the other hand April-May and October-November are observed as the agricultural residue burning periods over the Punjab. However, both GFED4 and FINN show more CA (~ 0.12 g/m²/month) and carbon (~5.59 g/m²/month) emission over the Punjab during the October-November time period. While the
Myanmar CA emissions elevate up to 30 times during forest fire, Punjab emission go up 2-3 times in comparison to anthropogenic emissions in that region.

The area averaged, time series vertical profile of carbonaceous aerosol concentration shows that the bulk of the aerosol is lofted to 3-5 km. Specific events transport plumes higher, and concentrations are simulated to reach up to 300 hPa. Plume vertical transport depends completely on PBL mixing and thermodynamic stability in the atmosphere. During the Myanmar fires (March-April), PBL is high and more vertical transport is visible due to active convection in that region. In contrast, PBL is shallower over Punjab in October-November than during the rest of the season and the atmosphere is stable; very less vertical transport is evident. Uncertainty in PBL height and thermodynamic parameterization may affect the vertical plume height of OBB emission and transport. PBL aerosol feedback can also affect the concentration at the lower levels. Shallower PBL may reduce dispersion which would lead to higher aerosol concentration whereas high PBL helps in mixing aerosol so that more dispersion is possible which may reduce significant concentrations in PBL. Radiative forcing calculations show that carbonaceous aerosol over Punjab contributed to -6.14 W/m² at the surface and -0.50 W/m² at TOA while the results show -42.76 W/m² at the surface and -1.91 W/m² at TOA over Myanmar. The results are similar to estimates previous studies when compared with BC and total aerosol forcing. This is the first reporting of radiative forcing with combined effects of carbonaceous aerosol (BC +OC) from open fires which contributing to significant loading in the atmosphere during active burning. BC and OC interact with radiation differently. Thus, quantifying the effect of BC and OC separately on incoming and outgoing radiation flux is required in a future study. The effect of Carbonaceous aerosols on incoming and outgoing radiation flux results in changes in weather parameters such as surface temperature decreased by 2 K, RH changed by 8%, and PBL changed
up to 600m. Changes in meteorological parameters are proportional to concentrations of carbonaceous aerosol emitted during biomass burning events. Changes in precipitation pattern and amount were negligible due to carbonaceous aerosol from open biomass burning when considering only the direct radiative feedback. Since we had kept anthropogenic emissions and other emissions from fire the same as in the control run, precipitation changes due to carbonaceous aerosols from open biomass burning are not that evident.

Our study shows a similar radiative impact from carbonaceous aerosol generated from open biomass burning as the impacts from total (anthropogenic + biomass) BC aerosol. The study is limited to impacts of meteorology. It shows the strong effect of carbonaceous aerosol on local meteorological parameters in a sense which allows less dispersion of pollutants. Such negative feedback from carbonaceous aerosol on PBL and temperature leads to positive feedback on aerosol concentration. During winter, this effect leads to bad pollution events in the IGP region.

Future studies could explore the impact on circulation patterns and atmospheric composition. Further, the results are based on the year-long study and the results could vary intra-annually. There is also room to further explore the impacts of CA from OBB on precipitation patterns with aerosol-cloud interaction schemes in the model.

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References:


Venkataraman, C., Habib, G., Kadamba, D., Shrivastava, M., Leon, J.F., Crouzille, B., Boucher, O., and...


Table Captions

Table 1. WRF-chem Model Parameterization option used in this study.

Table 2. Comparison of carbonaceous aerosol emission with anthropogenic emissions and different fire emission model estimates.

Table 3. Radiative forcing from OBB carbonaceous aerosol over Myanmar and Punjab.
Table 1: WRF-chem Model Parameterization option used in this study.

<table>
<thead>
<tr>
<th>Parameterization</th>
<th>Scheme</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk microphysical parameterization</td>
<td>Thompson scheme</td>
<td>(Thompson et al., 2008)</td>
</tr>
<tr>
<td>Convective parameterization</td>
<td>Kain–Fritsch Scheme</td>
<td>(Kain, 2004)</td>
</tr>
<tr>
<td>Planetary boundary layer(PBL)</td>
<td>Yonsei University Scheme</td>
<td>(Hong et al., 2006)</td>
</tr>
<tr>
<td>Shortwave radiation physics</td>
<td>Dudhia Shortwave Scheme</td>
<td>(Dudhia, 1989)</td>
</tr>
<tr>
<td>Longwave radiation physics</td>
<td>RRTM Longwave Scheme</td>
<td>(Mlawer et al., 1997)</td>
</tr>
<tr>
<td>Land-atmosphere interaction</td>
<td>Unified Noah Land Surface Model scheme</td>
<td>(Tewari et al., 2004)</td>
</tr>
<tr>
<td>Surface layer option</td>
<td>MM5</td>
<td>(Paulson, 1970)</td>
</tr>
<tr>
<td>Photolysis</td>
<td>Madronich fast-Ultraviolet-Visible Model (F-TUV)</td>
<td>(Madronich and Weller, 1990)</td>
</tr>
</tbody>
</table>

Table 2: Comparison of carbonaceous aerosol emission with anthropogenic emissions and different fire emission model estimates.

<table>
<thead>
<tr>
<th>Region</th>
<th>Anthropogenic (g/m²/month) (BC+OC)</th>
<th>FINN Emission (g/m²/month) (BC+OC)</th>
<th>CAMS (g/m²/month) (BC+OC)</th>
<th>GFED Emission (g/m²/month) (carbon emissions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myanmar</td>
<td>0.03</td>
<td>0.62-0.81 (0.0011-0.0019)</td>
<td>0.13-0.19 (0.0002-0.0005)</td>
<td>9.91-12.71 (0.0319-0.0775)</td>
</tr>
<tr>
<td>Punjab</td>
<td>0.11</td>
<td>0.091-0.12 (0.0019-0.0038)</td>
<td>0.03-0.05 (0.0001-0.0013)</td>
<td>1.59-5.59 (0.044-0.2250)</td>
</tr>
</tbody>
</table>
Table 3: Radiative forcing from OBB carbonaceous aerosol over Myanmar and Punjab.

<table>
<thead>
<tr>
<th>Region</th>
<th>Month</th>
<th>Domain area average effect</th>
<th>Local area average effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Surface incoming short wave flux(W/m²)</td>
<td>TOA outgoing longwave wave flux(W/m²)</td>
</tr>
<tr>
<td>Myanmar (13.86°-27.74°N, 90.28°-102.69°E)</td>
<td>March</td>
<td>-8.05</td>
<td>-0.28</td>
</tr>
<tr>
<td></td>
<td>April</td>
<td>-6.78</td>
<td>-0.1</td>
</tr>
<tr>
<td>Punjab (28.83°-32.04°N, 72.91°-77.86°E)</td>
<td>October</td>
<td>-0.45</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>-1.34</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 1. Long term average of carbonaceous aerosol emission from open biomass burning (OBB): (a) GFED monthly average total carbon emission from 1997-2015, (b) FINN average carbonaceous (Black + Organic) aerosol emission rates from 2002-2015, (c) Area averaged carbonaceous (Black + Organic) aerosol emission from CAMS and (d) Climatology of carbonaceous aerosol (Black + Organic) from FINN model for Punjab and Myanmar regions.

Fig. 2. Area averaged BC concentration (a) Myanmar control run (b) Myanmar without OBB BC (c) Punjab control run and (d) Punjab without OBB BC.

Fig. 3. Atmospheric loading of BC from OBB (a) at the Surface, (b) 850 hPa, (c) 500 hPa, (d) 300 hPa.

Fig. 4. Effect of OBB carbonaceous aerosol concentration (a-b), impact on 2m relative humidity (c-d), 2m-Temperature (e-f), PBL height (g-h) and 10m wind speed (i-j) for Myanmar and Punjab respectively.

Fig. 5. Effect carbonaceous aerosol from OBB on temperature at different pressure level (a) Surface (b) 850 hPa (c) 500 hPa and (d) 300 hPa.
**Fig. 1.**

(a) GFED: carbon emission
(b) FINN: BC + OC
(c) CAMS-GFAS: BC + OC
(d) g(BC+OC)/m²/Month

- 
- 
- 
- Year
Fig. 2.
Fig. 3.
Fig. 4.
Supplement Material:

Supporting Fig. 1. CALIPSO pass over Myanmar region during OBB period.

Supporting Fig. 2. CALIPSO pass over Punjab region during OBB period.
Supporting Fig. 3. Domain average BC concentration and change in temperature over Myanmar and Punjab region.
Supporting Fig. 4. Precipitation rate during OBB period with control run and experiment run and difference in precipitation rate in respective months.
Supporting Fig. 5. Atmospheric loading of OC from OBB at the Surface, 850 hPa, 500 hPa, 300 hPa.

Supporting Fig. 6. Model domain with terrain height used for the simulation in this study.