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“Garbage Burning in South Asia – How Important Is It to the Regional Air Quality?”

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Abstract

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Growing air pollution in South Asia has severe consequences on air quality, health, and the climate within the region. In this project we assess the importance of garbage burning emissions on the regional air quality. We first use the newly-available emission factors (EF) from the recent field campaign—Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE), which took place in 2015 April to improve the existing emissions estimates for garbage burning in the region. Next, we use the "online" chemical transport model, Weather Research and Forecasting model coupled with Chemistry (WRF-Chem), to assess the impact of these emissions on regional air quality. In order achieve our goal, we created three different scenarios. Emission of baseline does not include garbage burning emissions. Scenario 2 includes garbage burning emissions estimated by Wiedinmyer et al. (2014) and Scenario 3 includes the garbage burning emissions estimated by this study. Through comparing model simulations among the three emission scenarios, the model results illustrate that including the improved garbage burning emissions has improved model simulation. Including garbage burning emissions increases the simulated concentrations of particulate matter of less than 10 micrometers in diameter (PM_{10}), elemental carbon (EC) and organic carbon (OC), and mixing ratio of carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC) in South Asia. The results of study are significant as it informs the garbage disposal management policy changes in the region and in other developing countries.

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1 Introduction

Tropospheric ozone (O_3) and particulate matter (PM) are air pollutants that not only affect air quality but also human health (WHO, 2005). In 2012, one out of every nine premature deaths was caused by air-pollution-related problems (WHO, 2016). Bangladesh's ambient air quality ranked as the worst followed by Nepal, and India is ranked as the fifth worst among 178 countries (Environmental Performance Index, 2017). Among the top ten countries with the worst air quality, five of them are in South Asia (Bangladesh, Nepal, Pakistan, India and Bhutan). According to the World Health Organization (WHO), ambient air pollution led to more than 620,000 premature mortality cases in India in 2012, and the total number of premature mortality is ranked as the second highest among all countries. In Nepal, 9,900 premature deaths were due to ambient air pollution. Besides health effects, air pollution also affects climate and agriculture. For example, surface O_3 is a greenhouse gas and also negatively affects agricultural crop yields, impacting welfare (Avnery et al., 2011).

Many studies have illustrated that the increase in these air pollutant concentrations since preindustrial period are due to anthropogenic sources (Akimoto et al., 2003). Emissions from power, industrial, and transportation sectors have contributed to air pollution at first in developed and increasingly so in developing countries, such as in India and Nepal. Total energy consumption in Asia has doubled from 1980 to 2003, and it caused a rapid growth in Asian anthropogenic emissions, by 28% for elemental carbon (EC), 30% for organic carbon (OC), 64% for carbon monoxide, 108% for volatile organic compounds (VOC), 119% for sulfur dioxide ($SO_{2)}$, and 176% for nitrogen oxides (NO_x) (Ohara et al., 2007).

In addition to the major sources, garbage burning in many parts of developing countries has led to deterioration of air quality. In developing countries, municipal solid waste management has been a serious environmental problem due to the rapid growth in waste production combined with the incessant growth of industrialization, urbanization and population (Gupta et al. 2015, Streets et al., 2004). Open burning of garbage is ubiquitous in South Asia as the lack of economic support for having an alternative solution to the waste disposal (Pokhrel and Viraraghavan, 2005). Every year, there is more than 150 million metric tons of garbage burned in South Asia and it accounts for 15.8% of total global garbage burned. More than 80 million metric tons of garbage are burned in India and the total amount of garbage burned in both India and Nepal combined accounts for 8.4% of global garbage burned (Wiedinmyer et al., 2014).

Garbage burning in South Asia contributes to a significant amount of regional air pollution. Garbage burning is estimated to account for 29% and 43% of global total anthropogenic $PM_{2.5}$ and OC emissions, respectively (Wiedinmyer et al., 2014). Even though open garbage burning is estimated to have contributed greatly to air pollution, only few studies estimate the amount of garbage burned in South Asia, as well as emissions from such garbage burning. Additionally, no study has quantified the impacts of garbage burning emissions on regional air quality (Wiedinmyer et al., 2014). The objective of this study is to assess the impact of garbage burning emissions on the regional air quality in South Asia, especially in India and Nepal. We first revise the existing garbage burning emissions estimates in South Asia by using the most recent emission factors (EF) taken in Nepal during the Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE) field campaign. We then use the newly updated emissions to assess the impact of garbage burning on regional air quality, using the Weather Research Forecasting Model coupled with Chemistry version 3.5 (WRF-Chem v3.5).

This paper is divided into five sections. Section 2 describes emissions inventories we used for the study, as well as the methodology to estimate garbage burning emissions in South Asia. Section 3 presents a chemical transport model and three scenarios that we used to assess the impact of garbage burning on regional air quality. Section 4 describes results and compares and assesses the regional air quality under three different scenarios. Section 5 presents a summary of results and suggestions for future research.

2 Emissions

2.1 Emission inventories

This study combines emissions from three sectors, including anthropogenic, biomass burning, and biogenic emissions. For anthropogenic emissions, we use the Hemispheric Transport of Air Pollution (HTAP) version 2.2 (Janssens-Maenhout et al., 2015). The HTAP inventory includes emissions from combustion/conversion (energy industry, manufacturing industry, transport and residential sector), industrial processes, solvents and other product use, agriculture, large scale biomass burning, waste and miscellaneous sources (Janssens-Maenhout et al., 2015). HTAP emissions for the year of 2008 are used in this study.

For all regions, we use the Fire Inventory from NCAR (FINN) for biomass burning. FINN estimates daily fire emissions of CO, NO_x, PM and EC (Wiedinmyer, et al. 2011). For biogenic emissions of CO, NO_x, methane (CH_4) and other 13 chemical species, we use the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1). MEGAN 2.1 is the estimation of fluxes of biogenic composites between continental and the atmosphere ecosystems (Guenther et al., 2012).

2.2 Calculating garbage burned emissions

2.2.1 Methodology

Garbage burning emissions of twenty-four species (e.g., CO, OC, EC, $PM_{2.5}$) are estimated by the following equation, as explained in Wiedinmyer et al. (2012):

$E_i = EF_i \times M$

E_i: emissions for species i (g)

EF_i: emission factor for species i (g kg^{-1})

M: amount of garbage burned (kg)

Table 4 presents the total emission for 7 species (CO, NO_x, $PM_{2.5}$, PM_{10}, EC, OC, SO_2 and ammonia (NH_3)) over the domain. In this study, we modify emissions of garbage burning in South Asia for 15 species, using newly available EF data from the recent fieldwork in Nepal. We replaced the EFs by Stockwell et al. (2016) with those used in Wiedinmyer et al. (2012). We explain EFs in more detail in the next section.

2.2.2 Emission Factors

Table 1 describes the sources of each EF for both scenario 2 and scenario 3. Garbage burning EFs in Wiedinmyer et al. (2012) mainly used EFs from Agaki et al. (2011) and only EF of PM_{10} is from Woodall et al. (2012). EFs presented in Agaki et al. (2011) were based on smoke measurements in Mexico by Christian et al. (2010). We replace these EFs with those from the recent NAMaSTE campaign (Stockwell et al., 2016). NAMaSTE took place in and around the Kathmandu Valley during April, 2015. It provided the EF for garbage burning for approximately

80 species including CO_2, CO, CH_4, NH_3, and NO_x (Stockwell et al., 2016). We use EF from the NAMaSTE campaign to update EF for two reasons. First, NAMaSTE campaign is conducted in Nepal while EF from Agaki et al. (2011) is collected by the field and laboratory work in Mexico, so we expect to have a better estimation of garbage burning emission by obtaining EF from NAMaSTE campaign. Second, the NAMaSTE campaign was conducted in 2015. With the most updated EFs from the NAMaSTE campaign in Nepal, we believe the estimation of emissions from garbage burning in South Asia might be more realistic than using the EF from Akagi et al. (2011). Using the more realistic emission might lead to better air quality simulation in the model.

3 Atmospheric Chemistry Transport Model

3.1 Model description

We used the fully-coupled “online” Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem) version 3.5 to simulate the regional air quality (Grell et al., 2005). The model domain, as shown in Figure 1, covers most of the South Asian region with 249 × 209 grid cells, using Mercator map projection. The horizontal resolution of the grid is 20km × 20km, with 31 vertical levels from the surface to 50 mb. The center of the map is on India at 21.2° latitude and 78.9° longitude, around Nagpur, India.

This study used 2008 meteorological data from North Center for Environmental Prediction (NCEP) Global Forecast System final gridded analysis datasets. The NCEP datasets take evaporation, humidity, temperature, pressure, u- and v- wind speed, and other parameters into account and provides data 8-times daily (Physical Sciences Division, 2017).

In this study, we use the Regional Acid Deposition version 2 (RADM2) atmospheric chemical mechanism for gas-phase chemistry (Stockwell et al., 1990). For aerosol chemistry including some aqueous reaction, we use the Model Aerosol Dynamics for Europe with the Secondary Organic Aerosol Model (MADE/SORGAM) (Ackermann et al., 1998; Schell et al., 2001). This model is able to predict the mass of seven aerosol species, including sulfate, ammonium, nitrate, sea salt, EC, OC and secondary organic aerosols.

This study uses the initial and lateral boundary conditions with the same time period with our study from a global chemical transport model, the Model for OZone and Related chemical Tracers (MOZART) version 4 (Emmons et al., 2010). The MOZART model has 28 vertical levels from the surface to about 2 hPa and it has horizontal resolution of 2.8° longitude x 2.8° latitude.

3.2 Description of scenarios

In order to simulate the impact of emissions from garbage burning on surface air quality in South Asia, we performed three sets of scenarios, summarized in Table 2. The first scenario is a baseline scenario without any garbage burning emissions included in the simulation. For this baseline scenario we include biogenic emissions, biomass burning emissions, and anthropogenic emissions (transportation, domestic, power plants and industries sectors), excluding garbage burning emissions. The second scenario includes the gridded emission from garbage burning in Wiedinmyer et al. (2012), in addition to all the emissions in the baseline scenario. In the third scenario, we use our updated garbage burning emissions that we create by using the most updated EFs from the NAMaSTE campaign (Stockwell et al., 2016), in addition to all the emissions in the baseline scenario. Conducting three air quality simulations with three different garbage burning emissions estimates, we aimed to estimate and evaluate the impact of garbage burning on local and regional air quality.

For each of the scenarios, we used WRF-Chem to model air quality for October, 2008. We chose October for two reasons. The first is because we have the largest number of observations available for this time period for SO_2, O_3 and CO. The second reason is that we want to avoid the monsoon season. Summer monsoon season, which is often called rainy season normally takes place in early June, and last for approximately three months as it ends at the beginning of September (Joseph et al., 2006; Wang et al., 2009). During the monsoon season, the intense precipitation affects the measurement of several sources, which leads to great variability in measurement data (Schuck et al., 2010). Moreover, the study aimed to pick a month which has general high pollution. O_3 reached the seasonal peak in October, 2008 in South Asia (Kumar et al. 2012). For each monthly simulation, the model was spun-up for fourteen days, which were not included in the analysis.

4. Observations

WRF-Chem simulation was evaluated by comparing with observational data, which are collected by both Maharashtra Pollution Control Board (MPCB) Ambient Air Quality Monitor (2008 MPCB annual report), Kumar et al. (2012) and Ram et al. (2011). We evaluate the model performance using the normalized mean error and the standard error of the estimate.

4.1. SO_2 and NO_x

MPCB has Central Laboratory at Navi Mumbai and has its Regional Laboratories at five cities, including Aurangabad, Pune, Nagpur, Nashilk, Thane and Chiplun. In 2008, MPCB had 65 air quality monitoring stations in total (MPCB annual report, 2008). Some of the observational sites do not have available data for October, 2008. In our study, we used observational data from 8 sites out of 65 that had data for the time period of our interest for SO_2: Amravati, Aurangabad, Chandrapur, Kolhapur, Latur, Sangli and Solapur.

4.2. CO and O_3

For CO and O_3, we compared WRF-Chem simulated data with ground-based and balloon-borne observations for India. The ground-based observational data is taken from Kumar et al. (2012). Longitude and Latitude of each of these sites is listed in the Table 3 and shown in Figure 1.

4.3. PM, EC and OC data

We collected model simulated results for $PM_{2.5}$ and PM_{10} from Ram et al. (2011). This study has recorded the PM, EC and OC daily concentration for 11 days in October 2008 and all the data are from Kanpur.

5. Results

5.1 Emissions

In Fig. 3 we illustrate the monthly average emissions for each scenario in October, 2008, for CO, NO_x, PM_{10}, SO_2 and NMVOC. For CO, PM_{10} and NMVOC, the total emissions are high in northern and southern India. For Nepal, the south eastern region has the highest emission level for all the species. In the domain, Sri Lanka shows a relatively higher total emission level for all the species comparing to rest of our domain.

Fig. 2 shows Indian states and union. From Fig. 3, for PM_{10}, CO, NMVOC and NO_x, high monthly average emissions occur in northern India within the Indo-Gangetic plain. Two southern provinces Herala and Tamil Nadu also have high emissions for $PM_{10,}$ CO, NMVOC, NO_x and SO_2.

5.1.1 Monthly average emission difference in baseline scenario and scenario 2

Fig. 4 shows the emissions difference between the baseline scenario and scenario 2 for PM_{10}, CO, OC and EC. Average monthly emissions have increased for the whole domain for all species from baseline scenario to scenario 2. For PM_{10}, EC and OC, the monthly average emissions in Delhi, Calcutta, Mumbai and Hyderabad have all increased by over 200 kg/km^2. Those four cities are the cities with the highest population in India (City Census, 2011). Monthly average PM_{10} emission is increased by over 40 kg/km^2 in Kathmandu, Nepal. For CO, we also see a relatively higher increase in Delhi, Calcutta, Mumbai and Hyderabad cities, compared to the rest of the region since those cities are very dense in population. CO emissions in those cities increased by over 1350 kg/km^2 and on average, in Indo-Gangetic Plain in the Northern India at the border between India and Nepal, we see an increase of over 200 kg/km^2. Monthly average CO emission increased by over 100 kg/km^2 in Kathmandu, Nepal.

5.1.2 Monthly average emission differences between the second scenario and the third scenario

Comparing the differences between baseline and the second scenario, the difference between the second scenario and the third scenario is greater for all species, based on Fig. 5. The monthly average PM_{10} emissions have increased by over 140 kg/km^2 in most areas. For Nepal, PM_{10} emission has increased by 40 kg/km^2.

For CO, the emission level has increased by 150-300 kg/km^2 in the Indo-Gangetic Plain. The emissions in Delhi, Calcutta and Mumbai areas have increased by over 1200 kg/km^2. We observed an increase of over 800 kg/km^2 in Delhi, Calcutta, Mumbai and Hyderabad.

For OC and EC, we observed that the increase is more significant in Delhi, Calcutta, Mumbai and Hyderabad than in other area of India.

5.2 Regional air quality

In Fig. 6, we present monthly average surface O_3 and CO mixing ratio and PM_{10}, OC and EC concentrations as calculated by WRF-Chem for the three different scenarios. For CO, EC, OC and PM_{10}, the difference between the second and the third scenarios is much larger than the difference between baseline and the second scenario.

Fig. 7 shows the impact of the existing garbage burning emissions by Wiedinmyer et al. (2012) on regional air quality. For PM_{10}, CO and OC, including their garbage burning emissions in scenario 2 mainly affected Indo-Gangetic Plain. After updating the exiting garbage burning emission in scenario 3 by using EF from study by Stockwell et al. (2016), for those three species, the area influenced extended geographically in general, than that of O_3 and CO.

For PM_{10} concentrations, we find an increase of over 40 $\mu g/m^3$ and for OC, we observe an over 20 $\mu g/m^3$ increase in the Indo-Gangetic plain in Scenario 3, compared to the baseline. For PM_{10}, long-term WHO daily standard value for PM_{10} is 20 $\mu g/m^3$. These levels are associated with approximately a 15% higher long-term mortality risk relative to the Air Quality Guideline level (WHO, 2000). The increase in concentration after including our garbage burning emission already exceeds this level. This illustrates that our garbage burning emissions result in

PM concentration levels that have serious adverse health impacts. The total emissions for OC in October in our domain have increased by 1.2 Tg between scenarios 2 and 3, which explains this large increase in monthly average OC concentrations from scenario 2 to scenario 3.

For surface O_3, WHO Air quality guidelines for Europe (WHO, 2000) sets the guideline value at 120 µg/m^3 (60 ppb) for an 8-hour daily average for health purposes. Our Scenario 3 simulation resulted in over 50 ppb O_3 in north India and over 100 ppb for most days in Delhi. Comparing scenario 3 to the O_3 mixing ratio in the scenario 2, we find decrease in Tamil Nadu and Kerala states in India. NO_x, CO and VOC react in the atmosphere in the present of sunlight forms O_3 and the process is non-linear (Finlayson-Pitts and Pitts, 1993). Since the O_3 formation process is non-linear, it is possible to see a decrease in concentration even if we add NO_x and volatile organic compounds (VOCs) emission in our model. However, one possible cause for O_3 concentration could be the decrease in EF of NO_x, which led to decrease in its emissions for scenario 3, compared to scenario 2.

In summary, the mixing ratio and concentration has an overall increased for all, species comparing scenario 3 to scenario 2. After updating the EF from scenario 2 to scenario 3, we see an overall increase in mixing ratio and concentration in most regions for PM_{10}, CO, EC and OC.

5.3 Comparison with observation

5.3.1 CO

Fig. 8 shows the comparison between simulated CO mixing ratios and the observation from three sites. Observations are collected from the study by Kumar et al. (2008) for Ahmedabad, Gadanki and Mt-Abu sites. All three simulations underestimate CO mixing ratio compared to the observational data for all three sites. For Ahmedabad and Mt-Abu, observational data is twice as much as that of the closest simulated mixing ratio, which is for scenario 3. Additionally, the monthly average CO mixing ratio from the baseline is the lowest among the three scenarios and that of the second scenario is the second lowest for all three sites. The scenario 3 using the updated EFs for garbage burning are the closest to the observational data at three sites, indicating that updating EF helped improve the model simulation.

5.3.2 O_3

Fig. 9 demonstrates the comparison between simulated mixing ratio of O_3 and the observations from seven different observational sites (Ahmedabad, Pune, Ananatpur, Gadanki, Mt-Abu, Nantital and Thumba). O_3 mixing ratios from model simulations are close to observational values in Ananatpur and Mt-Abu. Mt-Abu is located in the Indo-Gangetic plain, where we see high average monthly garbage burning emissions. O_3 mixing ratios from scenario 3 have less than 5% ppb difference than the observational data for those two sites. O_3 mixing ratios calculated under the baseline are the lowest among all three scenarios in all the regions.

5.3.3 SO_2

Fig.10 illustrates the comparison between simulated mixing ratio of SO_2 and the observational data for eight different observational sites (Amravati, Aurangabad, Chandrapur, Kolhapur, Latur, Sangli and Thumba). We find that our model simulation underestimates the SO_2 mixing ratio in 5 out of 7 regions. We did not see a large difference in mixing ratio changes among three scenarios. However, in Chandrapur, the mixing ratio from the third scenario is quite different from other scenarios, which is most likely caused by the boundary effect since the Chandrapur observational site is located in the southern tip of India and is close to our domain boundary.

5.3.4 PM_{10}

Fig. 12 shows that the model simulated values for Kanpur site. PM_{10} concentrations from scenario 3 are closest to the observed data for all days. The normalized mean error from observed daily mean with baseline and scenario 2 are 72% and 70%, respectively. After we include the newly estimated garbage burning emissions, the normalized mean error has decreased by 13% to 57%. Additionally, the standard error of the estimate from baseline to observed data is 222 $\mu g/m^3$ while it is 216 $\mu g/m^3$ from observed data to scenario 2. It has further decreased to188 $\mu g/m^3$ from observation to scenario 3. The standard error for baseline and scenario 2 are 201 $\mu g/m^3$ and 195 $\mu g/m^3$, respectively; while for scenario 3, the number decreased to 170 $\mu g/m^3$.

5.3.5 $PM_{2.5}$

Fig. 13 illustrates the comparison between observed and simulated data for $PM_{2.5}$ in Kanpur. The normalized mean error between observed and baseline $PM_{2.5}$ is 57%, and it is 52% between observed and scenario 2. Normalized mean error between observed and scenario 3 decreased to 30%. On October 27th, the difference is only 13% between observed and scenario 3. Moreover, for all days, scenario 3 is closest to the simulated data. The standard error of the estimate for baseline is 117$\mu g/m^3$ and for scenario 2 is 112 $\mu g/m^3$. For scenario 3, the standard error of estimation decreased to 91.7 $\mu g/m^3$.

5.3.6 EC

Fig. 14 presents the comparison between observed and simulated results for EC concentration. The normalized mean error from observational data to baseline, scenario 2 and scenario 3 are 65%, 62% and 51%, respectively. Even though the difference between observed and scenario 3 is over 50%, scenario 3 is still the closet to the observed data for all days. EC observed data has great variable among available days. For the 11 days for which we have the observed data, the mean EC concentration is 7.24 μg/m^{3}with the standard deviation of 2.40 μg/m^3.

5.3.7 OC

Fig. 15 presents the comparison between observed and simulated results for OC concentration for Kanpur site. Observed OC daily average has great variability with the minimum of 21.4 μg/ m^3 and the maximum of 77.2 μg/ m^3. The normalized mean error from observed to baseline and scenario 2 are 80% and 73%, respectively. After we update the emissions from garbage burning with the EF from Stockwell et al. (2016), the normalized mean error decreased to 45%. For October 19th and 30th, the daily concentration differences between observed and scenario 3 are less than 20%. The standard error of estimation is 65.3 μg/ m^3 between observed and baseline, while it is 63.9 μg/kg between observed and scenario 2.For scenario 3, it decreased to 44.9 μg/ m^3. This result indicates that model result from scenario 3 is closest to the observed data. OC model simulation for scenario 3 on Oct 19th is 24.7 μg/kg and comparing it with the observation which is 25.1 μg/ m^3, there is only 1.5% difference. The Fig. 15 also illustrates that there is less than 3% difference between the observed and the scenario 3 simulation on Oct 26th.

6 Summary and future work

In this study, we first created a new emissions inventory for garbage burning in South Asia for October, 2008. Then we developed two scenarios for garbage burning emissions with different EFs and examined the impact of emissions from garbage burning on regional air quality in South Asia, focusing on India and Nepal. Through comparing concentration and mixing ratio between the baseline and three scenario cases, we find that garbage burning emissions of $PM_{2.5}$, PM_{10} and OC are large contributor to the regional air pollution.

Garbage generated in South Asia has contributed significantly to the total amount of global garbage generated (Wiedinmyer et al., 2014). With poor waste management, garbage burning is ubiquitous and it contributes to local and regional air pollution. In this study, we quantified the impact of garbage burning and analyzed its contribution to the regional air quality. In order to reach this goal, we developed three scenarios. In the first scenario, we modeled the regional air quality by using WRF-Chem and excluded emissions from garbage burning. Then we included emissions from garbage burning estimated by Wiedinmyer et al. (2014). In the third scenario, we update EF from study by Akagi et al (2006) by using the EF in the study of Stockwell et al. (2016). By comparing the differences in simulated air quality under these three scenarios, we are able to assess and qualify the impact of garbage burning on regional air quality in South Asia.

There is a large discrepancy between the EF from Wiedinmyer et al. (2014) and Stockwell et al. (2016). EF of EC and OC increased tremendously: EF of EC has increased by almost four times and EF of OC has increased by approximately twelve times. Based on Table 1, there are some species' EFs that have decreased, such as NO_x, $PM_{2.5}$ and NH_3, but they do not decrease significantly. EFs of NO_x, $PM_{2.5}$ and NH_3 only decreased by 9.3%, 14.7% and 32%, respectively.

From the Fig. 7, it is evident to see the increase in concentration and mixing ratio for PM_{10}, CO, OC and EC in the Indo-Gangetic Plain. When comparing the scenario 2 with scenario

3, the mixing ratio and concentration has increased more significantly than comparing baseline with scenario 2. PM_{10} concentration under scenario 3 has exceeded 40 $\mu g/m^3$ in most areas in India, and Nepal has exceeded 20 $\mu g/m^3$. The simulated values in these simulations are higher than the WHO standard, indicating the potentially large impact of garbage burning on local and regional air quality. Based on the standard error and mean average difference between observed and simulated results, model simulations including our garbage burning emissions for $PM_{2.5}$, PM_{10}, EC and OC reproduce observations the best.

Discrepancies between observational and model-simulated results are evident with all the species in all regions. One possible explanation is that there is a quality control issue over observational data. Different studies have different observational data over the same time period (Beig et al., 2007, Renuka et al., 2014). The air quality in South Asia is understudied and this study collected as many observed data as possible in order to evaluate the model. The other possibility could be that we didn't add enough garbage burning emission into the model. Based on Fig. 11, Ahmedabad is located in the Ahmedabad city and the city itself generates over 1000 ton per day of municipal solid waste (MSW). For CO in Ahmedabad site, the observed data is around twice as much as simulated data. It's the same case for CO in Gadanki site. Gadanki site is located in the city of Chennai and the city produces over 1000 ton per day of MSW. Since we used total amount of garbage burned from Wiedinmyer et al. (2014) to estimate the emission from garbage burning, the total amount of garbage burned might be underestimated.

There are limitations associated with our study. First, we find that the greatest difference in emissions and concentrations of species are found in the Indo-Gangetic Plain among the three scenarios. However, only two observational sites are located in this region. In order to evaluate the model better, we need to obtain more observational data from various parts of South Asia, especially the Indo-Gangetic Plain. Secondly, in this study we revised garbage burning emissions using different EF from Wiedinmyer et al. (2011), assuming that their estimation of the amount of garbage burned was correct. However, we see the discrepancies between observed and simulated data for all species. The discrepancies can be caused by many different factors, including modeling error, meteorology data bias and observation measurement error, etc. One of the possibilities, however, is the underestimation of amount of garbage burned. For the future study, we plan to evaluate the amount of garbage burned by using the most updated population and other factors, which might affect the amount of garbage burned.

Garbage burning emissions have significantly negative impact on air quality in South Asia. We estimate that 15% of CO, 81% of OC and 27% of EC are due to garbage burning, on average, in this region. Although we find discrepancies between model simulations and observations, in most cases, we further observed that Scenario 3 simulation was the closest to observations. The results of this study are important for informing policy changes in regard to the garbage disposal management in the region and in other developing countries.

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Table 1. List of Emission Factors for Garbage Burning (g/kg)

Emission Factor for Garbage Burning				
	Scenario 2		Scenario 3	
Species	EF	Sources	EF	Sources
CO	38	Akagi et. al	84.7	Stockwell et. al
NO_x	3.74	Akagi et. al	3.39	Stockwell et. al
$PM_{2.5}$	9.8	Akagi et. al	7.37	Stockwell et. al
PM_{10}	11.9	Woodall et al.	11.9	Stockwell et. al
EC	0.65	Akagi et. al	2.59	Stockwell et. al
OC	5.27	Akagi et. al	77.3	Stockwell et. al
SO_2	0.5	Akagi et. al	0.50	Stockwell et. al
NH_3	1.12	Akagi et. al	0.76	Stockwell et. al

Table 2. List of WRF/Chem scenarios

Scenario	Emissions	Garbage Burning Emissions
WRF baseline	Anthropogenic (no garbage burning) Biomass Burning Biogenic Emission	N/A
WRF scenario 2	Anthropogenic (with garbage burning) Biomass Burning Biogenic Emission	Wiedinmyer et al. (2012)
WRF scenario 3	Anthropogenic (with garbage burning) Biomass Burning Biogenic Emission	This Study

Table 3. Description of observational sites

Name	Latitude (°N)	Longitude(°E)	Sources	Species
Ahmedabad	23.00	72.60	Kurmar et al.	CO,O_3
Amravatl	20.92	77.75	MPCB	SO_2
Aurangabad	19.88	75.33	Kurmar et al.	O_3
Chandrapur	19.92	79.23	MPCB	SO_2
Gandaki	13.50	79.20	Kurmar et al.	CO
Kanpur	26.50	80.3	Ram et al.	PM_{10}, $PM_{2.5}$, OC, EC
Kolhapur	16.69	74.40	MPCB	SO_2
Latur	18.41	76.57	MPCB	SO_2
Mt-Abu	24.60	72.70	Kurmar et al.	CO, O_3
Nanital	29.40	79.50	Kurmar et al.	O_3
Pune	18.30	73.60	Kurmar et al.	O_3
Sangli	16.86	74.60	MPCB	SO_2
Solapur	17.67	75.91	MPCB	SO_2
Thane	19.20	72.98	MPCB	SO_2
Thumba	8.60	77.00	Kurmar et al.	O_3

Table 4. Total emission (Tg) for 7 species over the domain

Total Emission (Tg)			
Species	Baseline Scenario	Scenario 2	Scenario 3
CO	7.78	8.41	9.17
NO_x	1.32	1.38	1.37
$PM_{2.5}$	0.25	0.32	0.30
PM_{10}	0.21	0.31	0.31
EC	0.11	0.11	0.15
OC	0.29	0.38	1.56
SO_2	0.99	1.00	1.00
NH_3	1.18	1.20	1.19

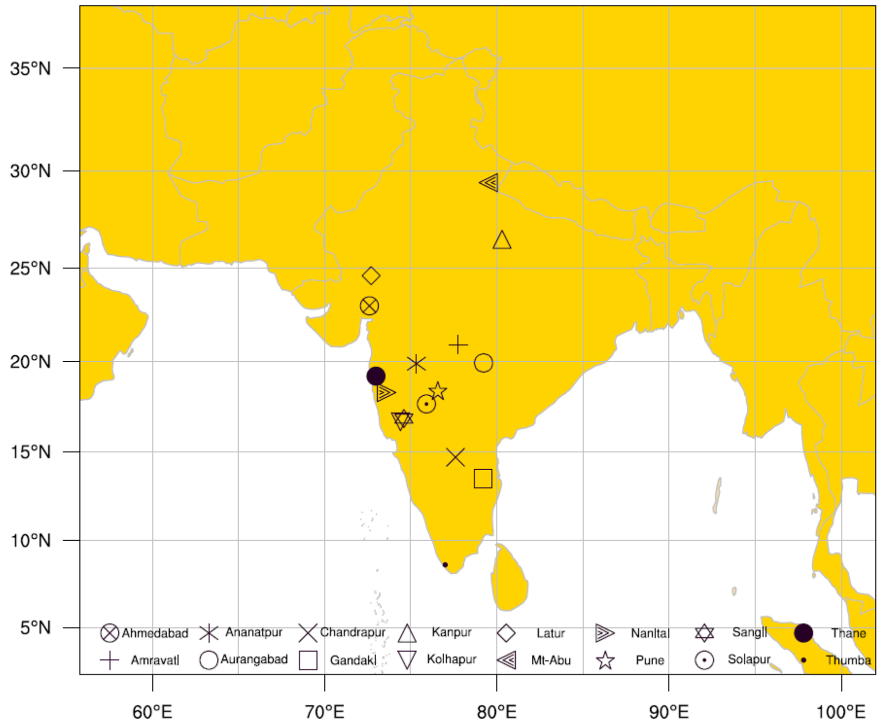

Fig. 1. WRF/Chem model domain with observational sites

Fig.2. Indian state and union map. (http://www.nationsonline.org/oneworld/india_map.html)

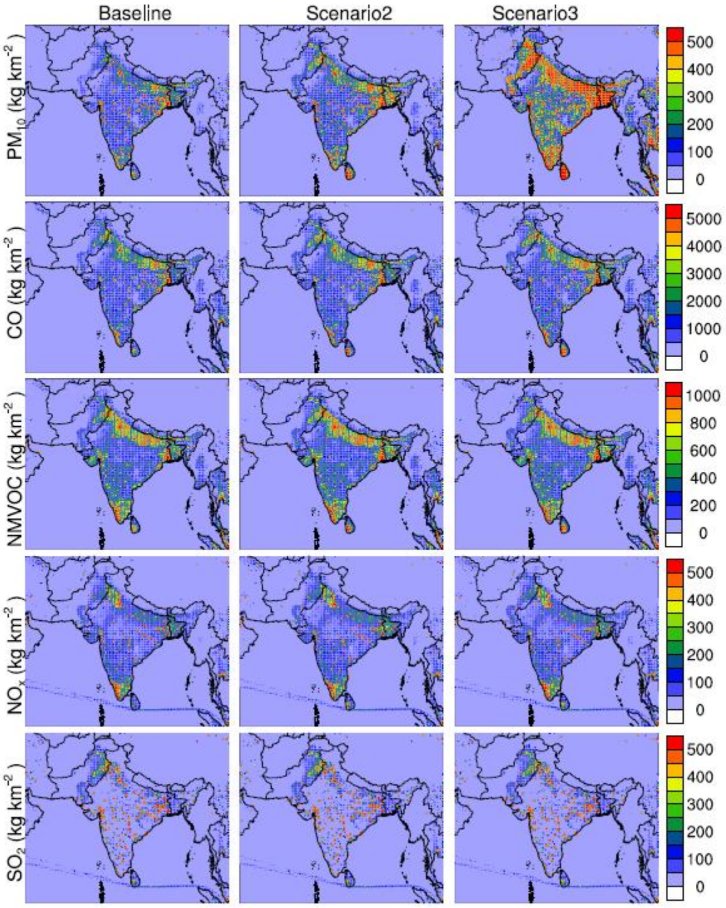

Fig. 3. Monthly average emission (kg/km^2) for PM_{10}, CO, NMVOC, NO_x, and SO_2

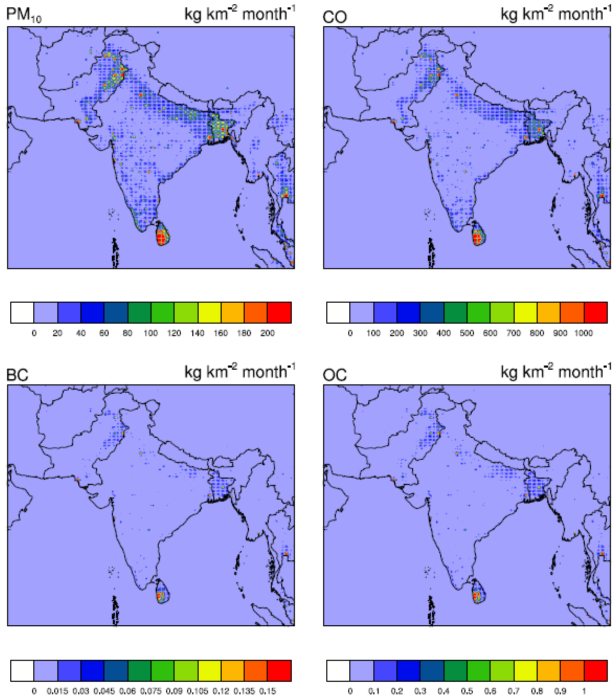

Fig. 4. Differences in monthly emissions of PM_{10}, CO, EC, and OC between baseline and scenario 2

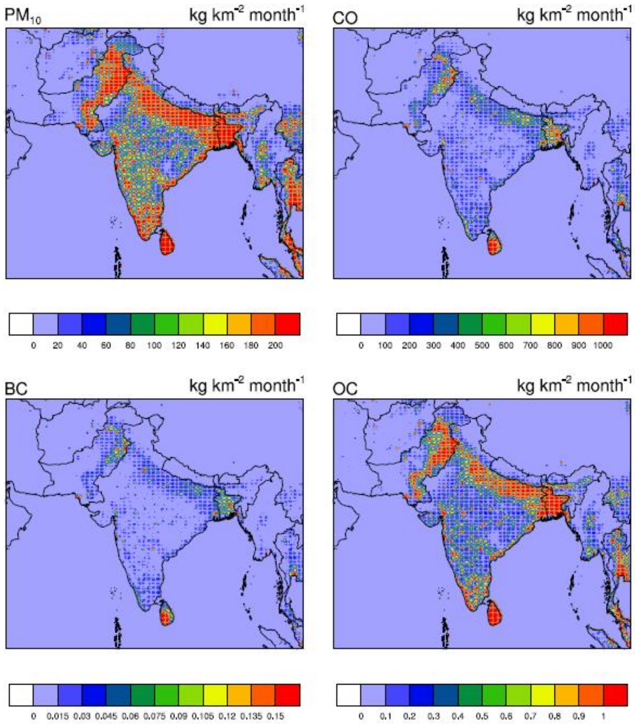

Fig. 5. Differences in monthly average emissions of PM$_{10}$, CO, EC, and OC between scenarios 2 and 3

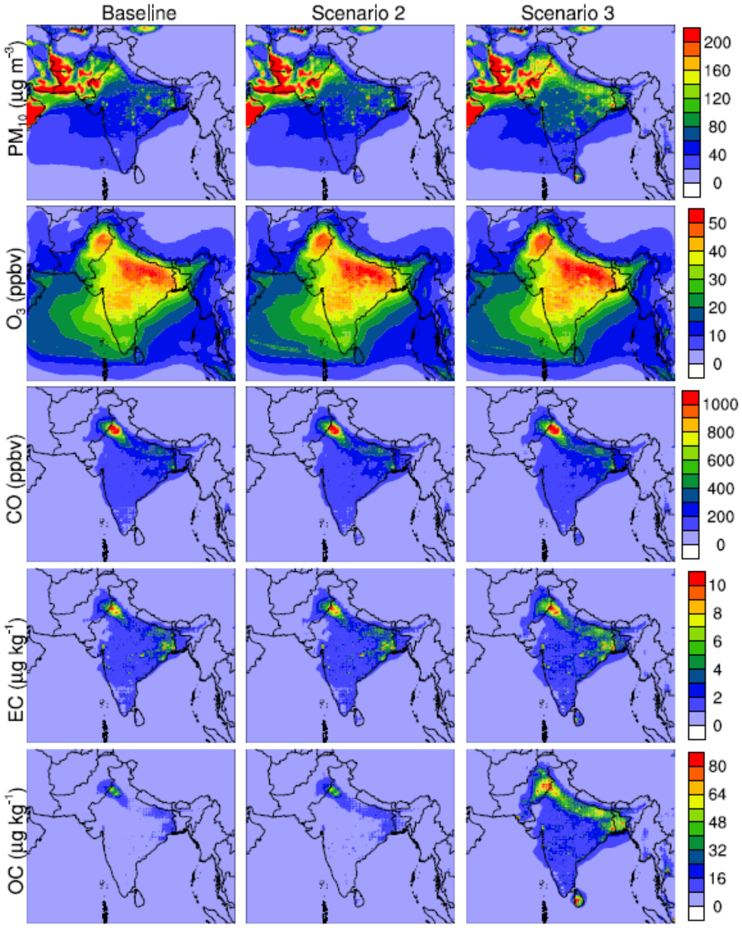

Fig. 6. Monthly average concentrations of PM$_{10}$, EC, and OC and mixing-ratio of O$_3$ and CO for three scenarios

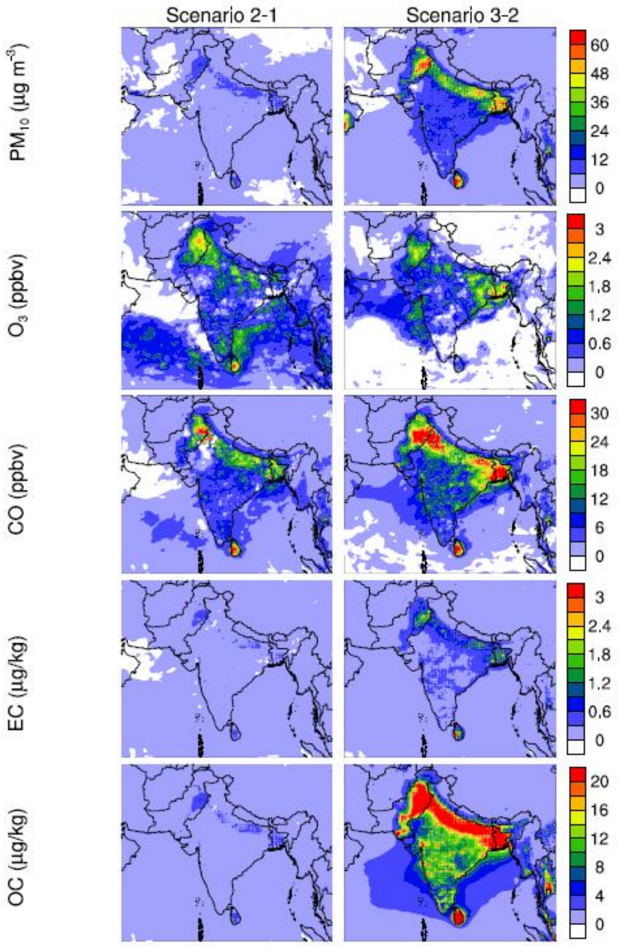

Fig. 7. Differences in monthly average concentrations of PM$_{10}$, EC, and OC and mixing-ratio of O$_3$ and CO between baseline and Scenario 2 (left) and scenarios 2 and 3 (right)

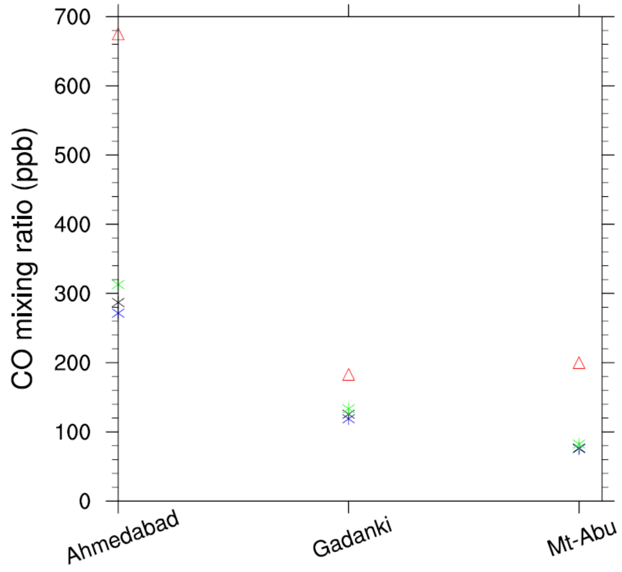

Fig. 8. Comparison of observed and simulated monthly mean mixing ratio of CO in Ahmedabad, Gadanki, and Mt-Abu. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.

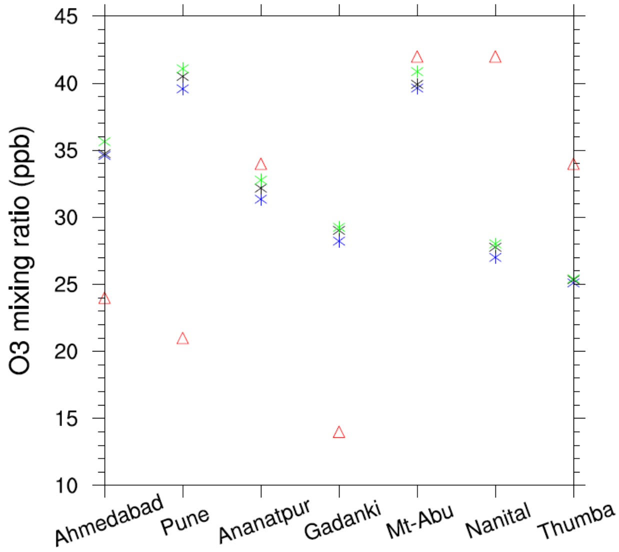

Fig. 9. Comparison of observed and simulated monthly mean mixing ratio of O_3 at eight observational sites. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.

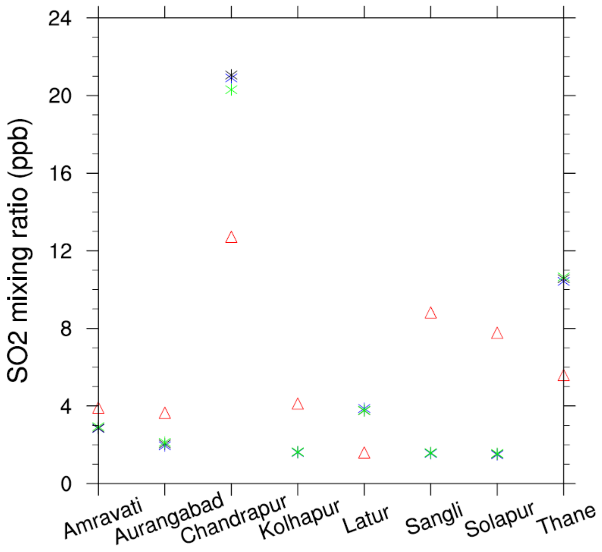

Fig. 10. Comparison of observed and simulated monthly mean mixing ratio of SO_2 at eight observational sites. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.

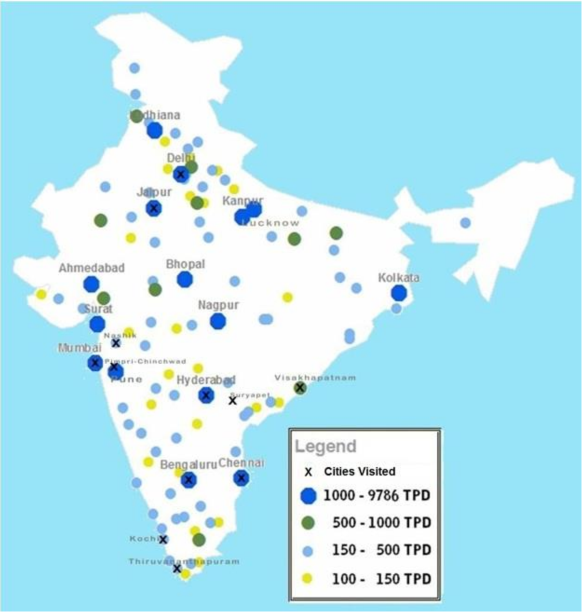

Fig. 11. Map of cities generating different quantities of municipal solid waste (tons per day) in 2001 (Annepu, 2012)

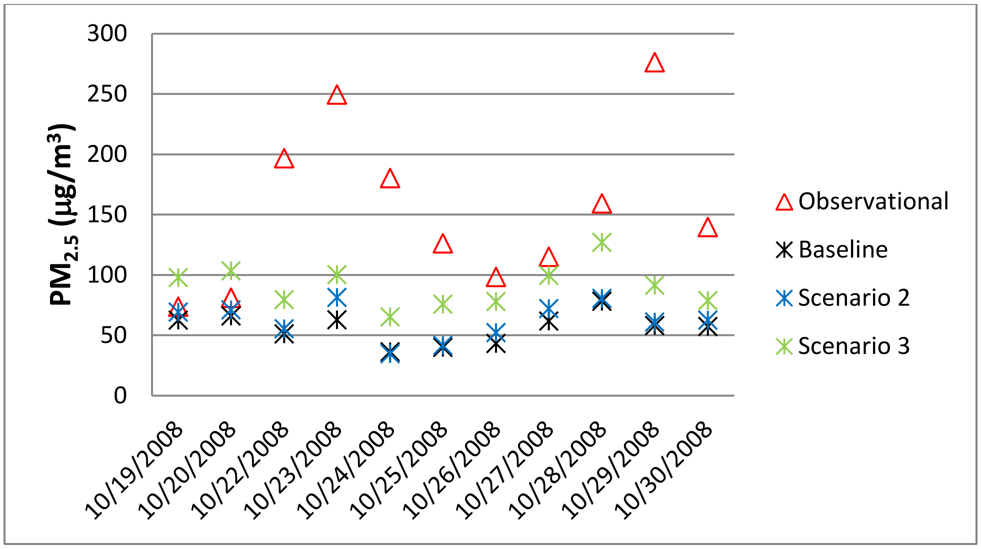

Fig. 12. Comparison of observed and simulated daily mean concentrations of PM$_{2.5}$. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.

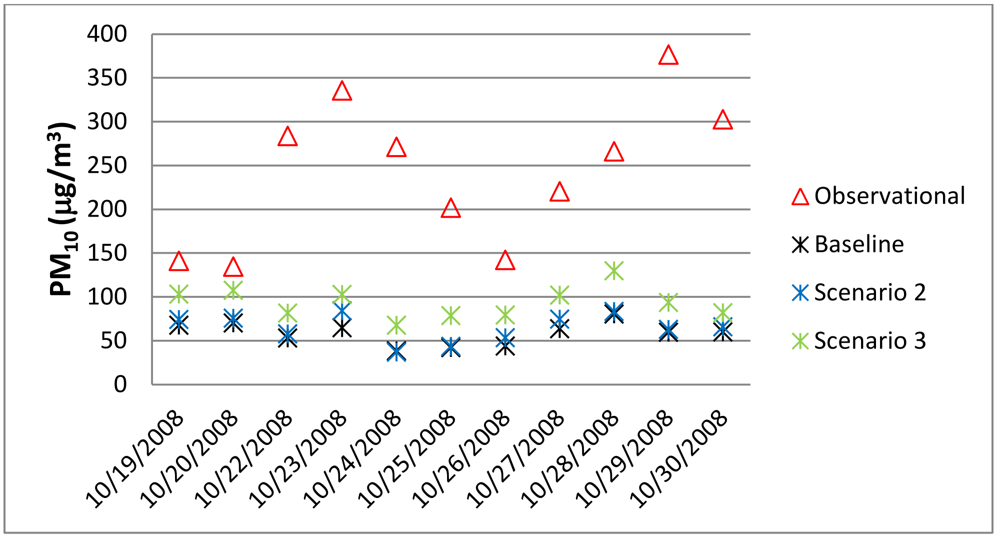

Fig. 13. Comparison of observed and simulated daily mean concentrations of PM$_{10}$. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.

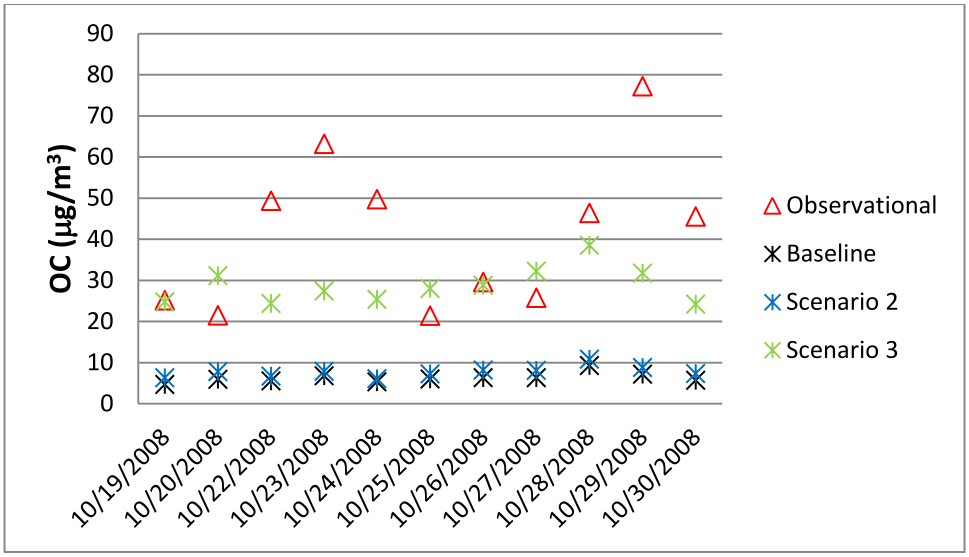

Fig. 14. Comparison of observed and simulated daily mean concentrations of OC. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.

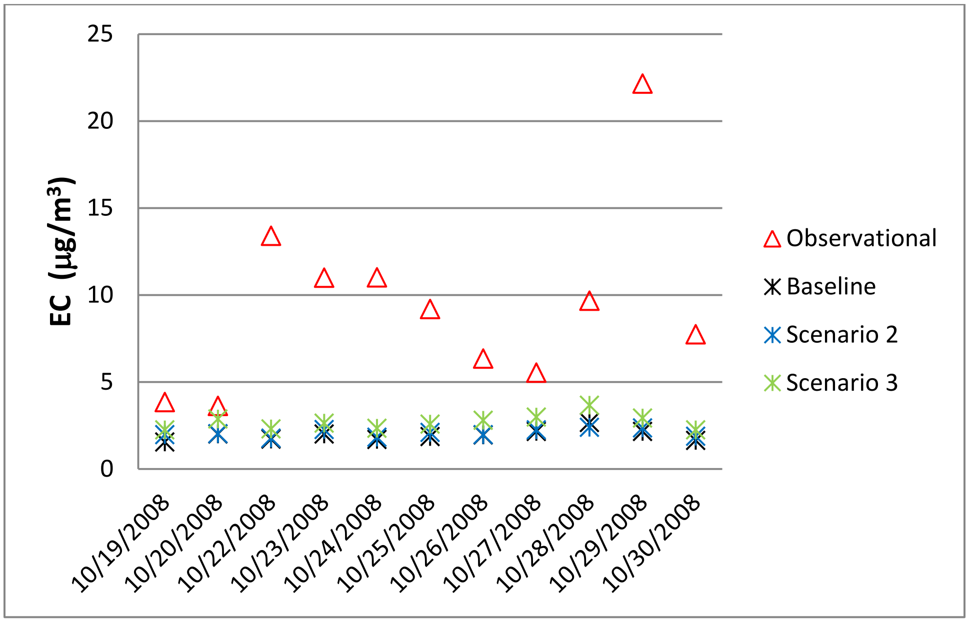

Fig. 15. Comparison of observed and simulated daily mean concentrations of EC. Red triangle represents observations, while blue, black, and green stars represent simulations from baseline, scenario 2 and scenario 3, respectively.