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Assessing the contribution of open crop straw burning to ground-level ozone and associated health impacts in China and the effectiveness of straw burning bans

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ABSTRACT

In recent years, ozone pollution in China has been shown to increase in frequency and persistence despite the concentrations of fine particulate matter (PM_{2.5}) decreasing steadily. Open crop straw burning (OCSB) activities are extensive in China and emit large amounts of trace gases during a short period that could lead to elevated ozone concentrations. This study addresses the impacts of OCSB emissions on ground-level ozone concentration and the associated health impact in China. Total VOCs and NO_x emissions from OCSB in 2018 were 798.8 Gg and 80.6 Gg, respectively, with high emissions in Northeast China (31.7%) and North China (23.7%). Based on simulations conducted for 2018, OCSB emissions are estimated to contribute up to 0.95 µg/m³ increase in annual averaged maximum daily 8-hour (MDA8) ozone and up to 1.35 µg/m³ for the ozone season average. The significant impact of OCSB emissions on ozone is mainly characterized by localized and episodic (e.g., daily) changes in ozone concentration, up to 20 µg/m³ in North China and Yangtze River Delta region and even more in Northeast China during the burning season. With the implementation of straw burning bans, VOCs and NO_x emissions from OCSB dropped substantially by 46.9%, particularly over YRD (76%) and North China (60%). Consequently, reduced OCSB emissions result in an overall decrease in annual averaged MDA8 ozone, and reductions in monthly MDA8 ozone could be over 10 µg/m³ in North China. The number of avoided premature death due to reduced OCSB emissions (considering both PM_{2.5} and ozone) is estimated to be 6120 (95% Confidence Interval: 5320–6800), with most health benefits gained over east and central China. Our results illustrate the effectiveness of straw burning bans in reducing ozone concentrations at annual and national scales and the substantial ozone impacts from OCSB events at localized and episodic scales.

1. Introduction

Open biomass burning (OBB) could emit large amounts of trace gases and particulate matter during a short period, thereby exhibiting substantial impacts on air quality and public health at local and regional scales (Zha et al., 2013; Zhou et al., 2017; Zong et al., 2016). Emissions of primary aerosols directly result in elevated concentrations of fine particulate matter (PM_{2.5}). In contrast, emissions of gaseous species (e.

g., volatile organic compounds, VOCs) lead to the formation of secondary organic aerosols and ground-level ozone (O₃). The impacts of OBB on PM_{2.5} concentration over different regions have been evaluated in many studies (Bossioli et al., 2016; Cheng et al., 2014; Huang et al., 2021; Wilkins et al., 2018; Yang et al., 2020; Zhou et al., 2018). Being an important type of biomass burning, open crop straw burning (OCSB) is a common management practice in China, especially during the harvesting, post-harvest or pre-planting periods. According to Hong et al.

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(2016), the crop straw resources in China rank first in the world, accounting for 20% of global production. Numerous studies have demonstrated the important contribution of OCSB to atmospheric PM_{2.5} in China. For instance, Cheng et al. (2014) showed that OBB contributed 37% of the observed PM_{2.5} concentrations in the Yangtze River Delta (YRD) region of China. Zhou et al. (2018) investigated an intense biomass burning event in the North China Plain (NCP) and found that the contribution of OCSB to PM_{2.5} concentration reached 19% in China. During a harvest season (November 2015) in Northeast China, OCSB contributed more than 50% to PM_{2.5} concentration (Yang et al., 2020). To mitigate the PM_{2.5} pollution in China, prohibition on OCSB activities (referred to as “straw burning bans”) was proposed by the Chinese government, among many other control policies (Sun et al., 2019; Yang et al., 2020). According to our previous study (Huang et al., 2021), the national total PM_{2.5} emissions from OCSB reduced by 46.9% from 2013 to 2018, and annual averaged PM_{2.5} concentrations show widespread reductions over China with maximum decrease exceeding 2.0 μg/m³ in East China.

On the other hand, observed ozone concentrations in key regions of China have shown a generally increasing trend from 2013 to 2018 (Fan et al., 2020), and the frequency and persistence of ozone pollution episodes are rising (Gong & Liao, 2019; Gong et al., 2020). Elevated ozone concentration negatively impacts human health, vegetation, and ecosystem production (Fleming et al., 2018; Mills et al., 2018; Xu et al., 2020). Consequently, ozone is listed as a co-control air pollutant along with PM_{2.5} in China in the 14th Five-Year Plan for National Economic and Social Development of the People’s Republic of China and the Vision for 2035 (http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm, accessed on August 15th, 2022). Nevertheless, the control of ozone is much more complicated due to the nonlinearity of ozone chemistry to its precursors, namely nitrogen oxides (NO_x) and VOCs, both of which are emitted simultaneously from burning activities. So far, only a limited number of studies have addressed the impact of biomass burning on local or regional ozone formation (Lee et al., 2019; Tang et al., 2013; Zhu et al., 2016). For example, Tang et al. (2013) found that agricultural straw burning in June increased ozone concentrations by 27%–39% in the YRD region. Most existing studies are either limited to certain areas or focused on a certain period of the burning episode. A multi-regional and year-long study of the impacts of OCSB on ground-level ozone concentration is needed for a comprehensive evaluation in China. Whether implementing the straw burning bans has also effectively reduced surface ozone concentration needs to be addressed.

As a follow-up to our previous study (Huang et al. 2021), the present work aims to address the impacts of OCSB on surface ozone concentration and public health in China and further evaluate the effectiveness of straw burning bans based on a typical modeling approach. Three objectives are to be achieved by this work. Firstly, the ozone contribution from OCSB emissions is quantified over different regions and seasons. Secondly, the effectiveness of straw burning bans in reducing ozone concentration is assessed. Lastly, the impacts on human health associated with ozone exposure under different scenarios are quantified. This work represents the first comprehensive modeling study evaluating the effects of OCSB emissions on ground-level ozone concentrations in China. Findings from this study shall provide useful information on future ozone control policies regarding open biomass burning.

2. Methods

2.1. VOCs and NO_x emissions from open biomass burning

Ground-level ozone is formed via complicated photochemical reactions involving VOCs and NO_x, both of which are emitted from burning activities, although their relative abundance differs by the burning materials. The widely-used Fire INventory from NCAR version 1.5 (FINNv1.5) (Wiedinmyer et al., 2011; <https://www.acom.ucar.edu/Data/fire/>) was adopted in this study to analyze the VOCs and

NO_x emissions associated with different burning types. Based on satellite fire detection, FINN combines land cover data, emission factors, and fuel loadings to calculate emissions of various air pollutants from burning events in a bottom-up fashion (Wiedinmyer et al., 2006) with a high temporal (daily) and spatial resolution (~1km) (Wiedinmyer et al., 2011). The burning types in FINN are classified based on the MODIS land cover type and are further grouped into four types – forest, grassland, shrub, and cropland – for analyzing VOCs and NO_x emissions.

2.2. Model configurations

To quantify the impacts of OCSB on ground-level ozone concentrations, the Weather Research Forecasting (WRF) model for meteorology simulation, followed by the Comprehensive Air Quality Model with Extensions (CAMx) for air quality simulation, is utilized in this work. The model configuration and input data can be found in our previous study (Huang et al. 2021) and briefly summarized here. The National Centers for Environment Prediction/Final Operational Global Analysis (NCEP/FNL) data is used to drive the WRF simulation. The gaseous and aerosol modules used in CAMx include the CB05 chemical mechanism (Yarwood et al., 2010) and the CF module. The aqueous-phase chemistry is based on the updated mechanism of the Regional Acid Deposition Model (RADM)(Chang et al., 1987). Simulations were conducted with a horizontal resolution of 36 km covering entire China and 23 vertical layers up to 50 hPa. Anthropogenic emissions for China are based on the Multi-resolution Emission Inventory of China for 2017 (MEIC, <http://www.meicmodel.org>, accessed on December 1st, 2021) developed by Tsinghua University. Emissions outside China are based on the European Commission’s Emissions Database for Global Atmospheric Research (EDGAR, <http://edgar.jrc.ec.europa.eu/index.php>, accessed on December 1st, 2021) for 2010. Biogenic emissions are calculated by an updated version of the Model of Emissions of Gases and Aerosols from Nature (MEGAN, version 3.0, <http://aqrp.ceer.utexas.edu/projects.cfm>, accessed on November 10th, 2021). Open biomass burning emissions are based on FINN with MOZART speciation and converted to CAMx CB05 model species.

Annual simulations were conducted for 2018 with different OCSB emissions while keeping other model inputs and configurations unchanged (Table 1). In the base scenario, the FINN OCSB emissions for 2018 were used. In a second scenario, OCSB emissions were excluded, and the simulated ozone difference from the base scenario represents the contribution of OCSB emissions to ozone concentrations. In a third scenario, the OCSB emissions for 2018 in the base scenario were replaced by emissions from 2013. According to our previous study (Huang et al. 2021), 2013 was considered the beginning year for vigorously implementing the straw-burning bans. The changes in OCSB emissions between 2013 and 2018 reflect the control policy’s effectiveness. The differences in simulated ozone concentration between the base and third scenarios were used to evaluate the effects of straw burning bans on ozone concentrations. Simulated meteorological variables such as temperature, wind speed, and relative humidity were verified in our previous work (Huang et al. 2021). The model performance of the base case ozone simulation was evaluated against the observations at 74 monitoring sites across China (Fig. 1) with commonly used metrics, including the Pearson correlation coefficient (R), mean bias (MB), normalized mean bias (NMB), root mean square error

Table 1
Emission configurations of different scenarios.

Scenario	Emissions besides OCSB	OCSB emissions
Scenario 1 (base)	MEIC 2017 + EDGAR 2010 + MEGAN + FINN 2018 for vegetation types except croplands	FINN 2018
Scenario 2		–
Scenario 3		FINN 2013

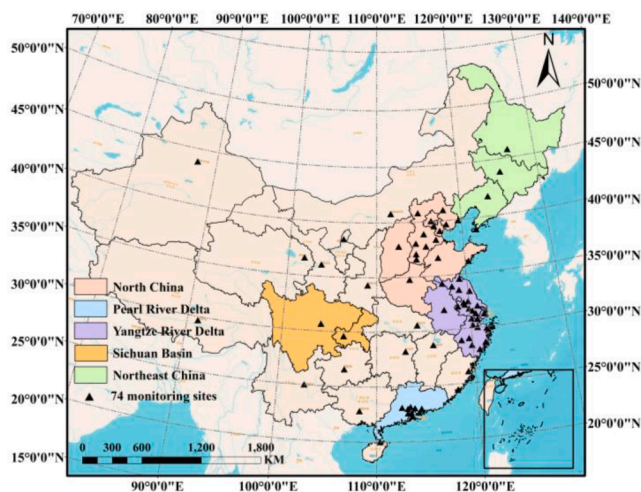


Fig. 1. Modeling domain with selected key regions.

(RMSE), and normalized mean error (NME) (see definitions in Table S1).

Five key regions were selected for further analysis of the impacts of biomass burning on ground-level ozone, including North China (including Beijing, Tianjin, province of Hebei, Shandong, Shanxi, and Henan), Yangtze River Delta (YRD) (Shanghai, province of Jiangsu, Anhui, and Zhejiang), Sichuan Basin (Chongqing, Sichuan province), Northeast China (province of Heilongjiang, Jilin, Liaoning) and Pearl River Delta and surrounding (i.e., Guangdong). These regions either have extensive burning activities (e.g., Northeast China) or suffer from elevated ozone concentration (e.g., YRD, Sichuan Basin) or both (North China) (Chen et al., 2017; Liu and Wang, 2020; Lu et al., 2019; Zhu et al., 2016).

2.3. Evaluation of health impacts associated with ozone exposure

According to existing epidemiological studies, chronic ozone exposure is mainly associated with respiratory and cardiovascular diseases (Jerrett et al., 2009; Turner et al., 2016). A commonly used method for studying the ozone exposure–response relationship is the epidemiological research approach, which quantifies the correlation between the health status of the population and the concentration of air pollutants through epidemiological surveys. In this study, the number of premature deaths due to cardiovascular disease (CVD) and respiratory disease (RD) attributable to ozone exposure is used to represent the health impact of ground-level ozone, which is calculated using Eq. (1)–(2), following many existing studies (e.g., Malley et al., 2017; Seltzer et al., 2018; Wang et al., 2020):

$$RR(C) = \begin{cases} e^{\beta(C-C_0)}, & C > C_0 \\ 1, & C \leq C_0 \end{cases} \quad (1)$$

$$H = \sum B \times P \times \frac{RR - 1}{RR} \quad (2)$$

where RR is the relative risk, i.e. the probability of a particular health endpoint associated with a 10 ppb increase in ozone concentration (Cairncross et al., 2007; Liu et al., 2018); β is the observation-based concentration response factor, i.e., the slope of the log-linear relationship between exposure concentration and mortality; C represents the value of a specific ozone indicator, and C_0 is the threshold below which there is no adverse effect. In Eq. (3), H is the estimated number of premature deaths; B is the provincial incidence rate of a specific disease, obtained from the online GBD database (<https://vizhub.healthdata.org/gbd-compare/>, accessed on December 1st, 2021); P is the exposed population for each province in China, which is obtained from the 2019 statistical yearbook. We used the annual mean daily 8-hour maximum ozone concentration (AMDA8) as the ozone indicator and adopted a

threshold of 26.7 ppb following Turner et al. (2016).

3. Results and discussions

3.1. OCSB emissions of ozone precursors

According to FINN estimates, the annual total VOCs and NO_x emissions from OCSB activities for year 2018 in China are estimated to be 798.8 Gg and 80.6 Gg, respectively. In terms of the emitted VOCs species, oxygenated-VOCs (OVOCs) represents the dominant group (70%), followed by aromatics (15%) and alkenes (12%) (Table S2). The high VOCs/NO_x emission ratio range (~10) for OCSB suggests a NO_x-limited environment within the fire plume, yet the impacts on ozone formation could be different, especially when mixed with different background emissions downwind the fire plume. Spatially, OCSB activities occur frequently in Northeast China, North China, and northern YRD, which are the major agricultural regions in China (Fig. 2). With respect to the seasonal variations, OCSB emissions show huge peaks in March and April in Northeast China, whereas in North China and YRD, OCSB emissions are more evenly distributed from February to November. Although the annual total VOCs and NO_x emissions due to OCSB only account for 3.4% and 0.4% compared to the anthropogenic emissions (Table S3), the impact of OCSB emissions should not be ignored given the episodic and localized feature of the burning activities.

3.2. Impact of OCSB emissions on ground-level ozone concentrations

3.2.1. Base case evaluation

Fig. 3 shows the spatial distribution of the simulated seasonal daily maximum 8-hour average (MDA8) ozone concentration in 2018 against observations. Values of MB, RMSE, NMB, NME, and R of daily MDA8 ozone concentration by season and region are provided in Table S4. Results for other pollutants can be found in Huang et al. (2021). In general, the model well captures the spatial distribution and seasonal variations of the observed ozone concentration. The model tends to overestimate ozone concentrations for all regions except in Northeast China. The observed AMDA8 concentration averaged over 74 monitoring sites is 77.0 ppb, contrasted to the simulated value of 83.8 ppb. Sichuan Basin shows the highest overestimation, also found in other studies (Hu et al., 2016). In terms of the seasonal results, NMB is all within 15%, and summer shows the highest R value. According to Eq.1, premature mortality increases exponentially with the ozone concentration, with a steeper slope near the threshold and a milder slope at higher ozone concentrations. This indicates the same relative bias in the simulated ozone concentration would cause more deviation at low ozone concentration near the threshold. For those 74 monitoring sites, we estimated an overestimated premature mortality by 10.5% when simulated ozone concentrations were used.

3.2.2. Impact of OCSB emissions on ground-level ozone

As shown by Fig. 4, OCSB emissions lead to a widespread increase in annually averaged ozone concentrations and during ozone season (April–October) across China. Regions with high ozone impacts include North China, Northeast China, and northern YRD, which aligns with the high OCSB emission regions (Fig. 2). For AMDA8, the maximum increase due to OCSB emissions reaches 0.95 $\mu\text{g}/\text{m}^3$ in North China; for ozone season averages, OCSB emissions contribute up to 1.35 $\mu\text{g}/\text{m}^3$ of ozone enhancement over North China. Since OCSB emissions are characterized as intermittent and point emissions, it is reasonable to look at the impacts on daily ozone changes and grid-cell levels. As illustrated by Fig. 5, both positive and negative impacts were observed in terms of daily MDA8 ozone change at the grid cell level and the magnitudes and temporal variations closely follow that of OCSB emissions. For example, in Northeast China, while most grid cells showed increased ozone concentration due to OCSB emissions in March (up to 70 $\mu\text{g}/\text{m}^3$), a few grid cells showed decreased ozone concentration with the inclusion of OCSB

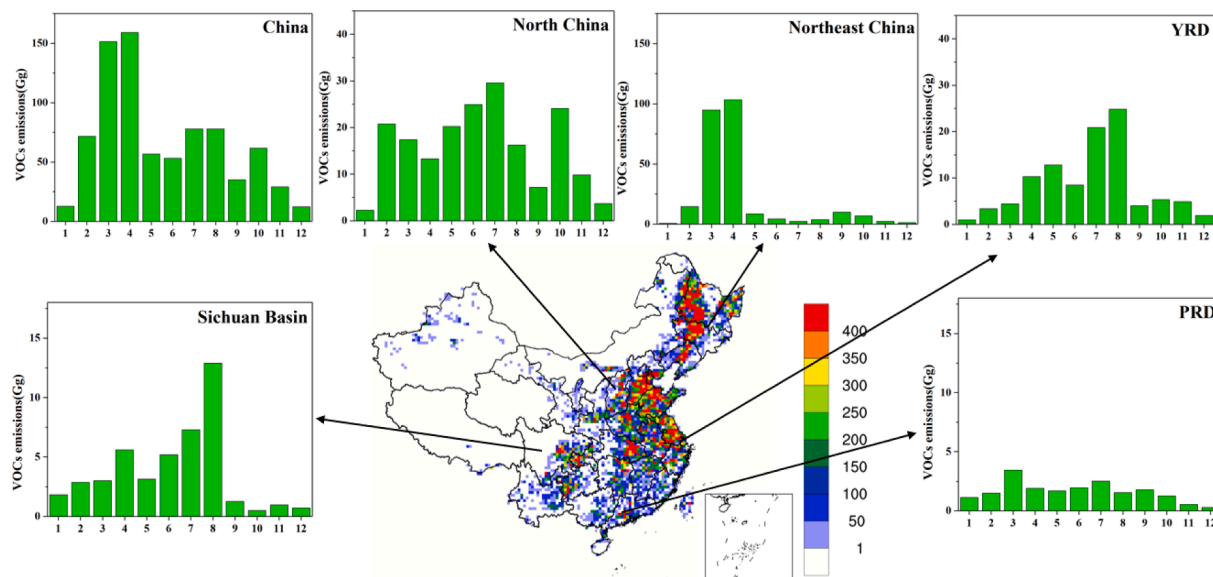


Fig. 2. Spatial distribution of annual VOCs emissions from OCSB ($\times 10^3$ Gg) with monthly variations for selected regions (Corresponding plots for NO_x are presented in Fig. S1).

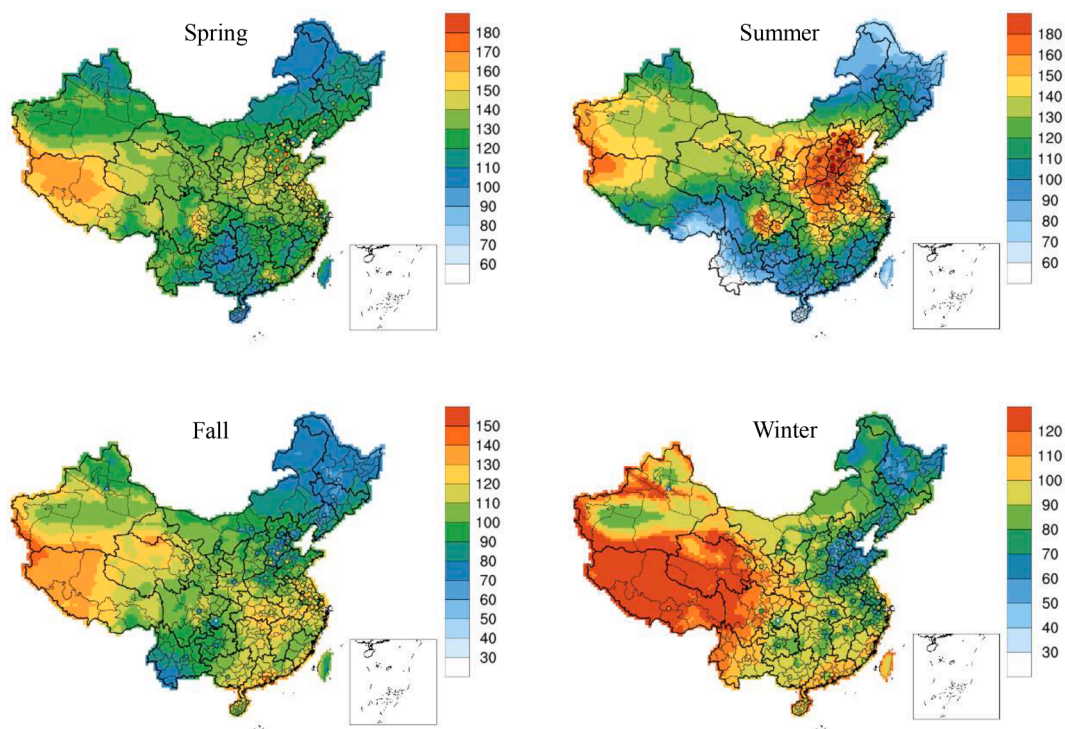


Fig. 3. Spatial distribution of simulated versus observed seasonal MDA8 ozone concentrations ($\mu\text{g}/\text{m}^3$) in 2018 (observed values shown by dots).

emissions. In North China and YRD, OCSB emissions exhibit substantial impacts from April to October, with more ozone increase (by as much as $20 \mu\text{g}/\text{m}^3$) than ozone reduction. The effects of OCSB emissions on daily ozone changes over the Sichuan Basin, PRD, and surrounding regions are within $\pm 10 \mu\text{g}/\text{m}^3$. The different ozone response to OCSB activities in localized areas reflects the non-linearity of the ozone formation chemistry, where reduced NO_x emissions do not always lead to ozone reduction, usually under a VOC-limited regime. The changes in ozone concentrations are determined by the local ozone formation regime as well as influenced by the transport of NO_x and VOC emissions from upwind crop burning activities. Further studies are needed to investigate

the underlying mechanism of the ozone response to representative burning events over different regions and under different meteorological conditions.

We further evaluate the impact of OCSB emissions on the cumulative number of ozone exceedance days (defined as days with MDA8 ozone concentration higher than $160 \mu\text{g}/\text{m}^3$ according to China's Ambient Air Quality Standards) for cities in the selected five regions. The ozone exceedance days range from a total of 323 days in PRD and surrounding (~ 36 days per city) to as many as 4544 days in North China (~ 65 days per city) in 2018 (Table 2 and Table S5). For all regions except PRD, ozone exceedance days mainly occur in April-August, and June has the

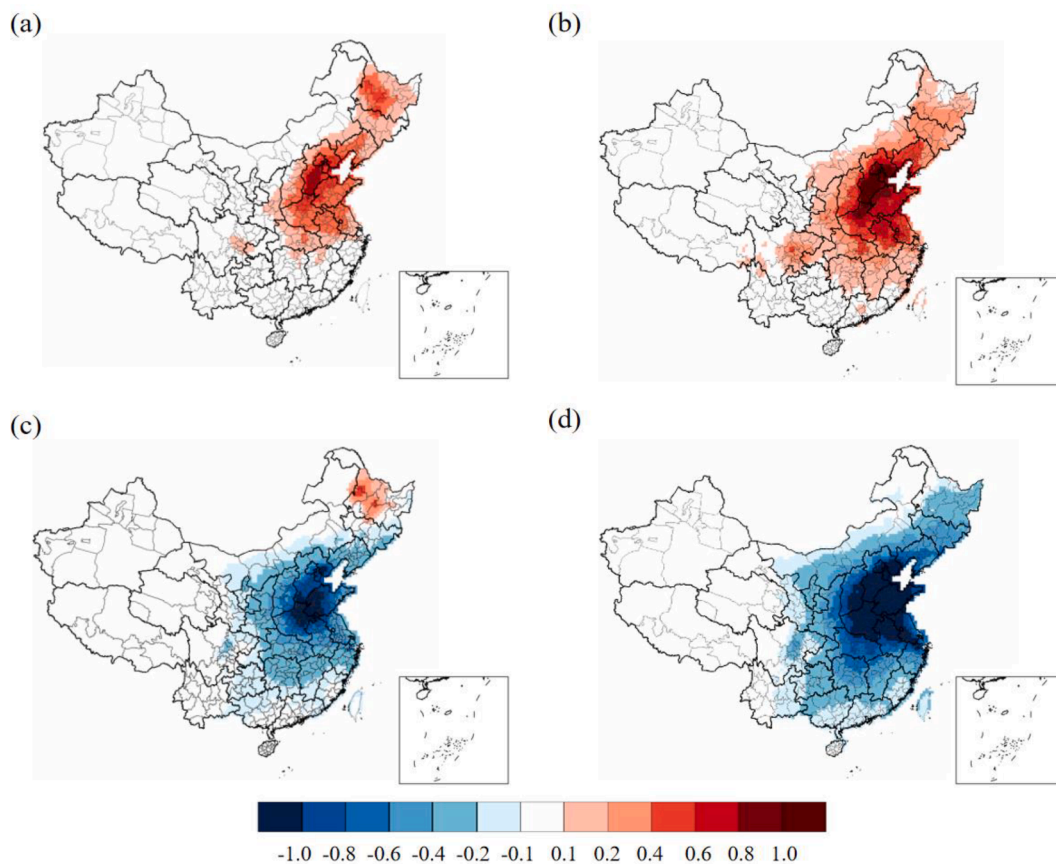


Fig. 4. Spatial distribution of changes in AMDA8 ozone and MDA8 ozone during ozone season (April-October) due to OCSB emissions (a, b) and straw burning bans (c, d) Unit: $\mu\text{g}/\text{m}^3$.

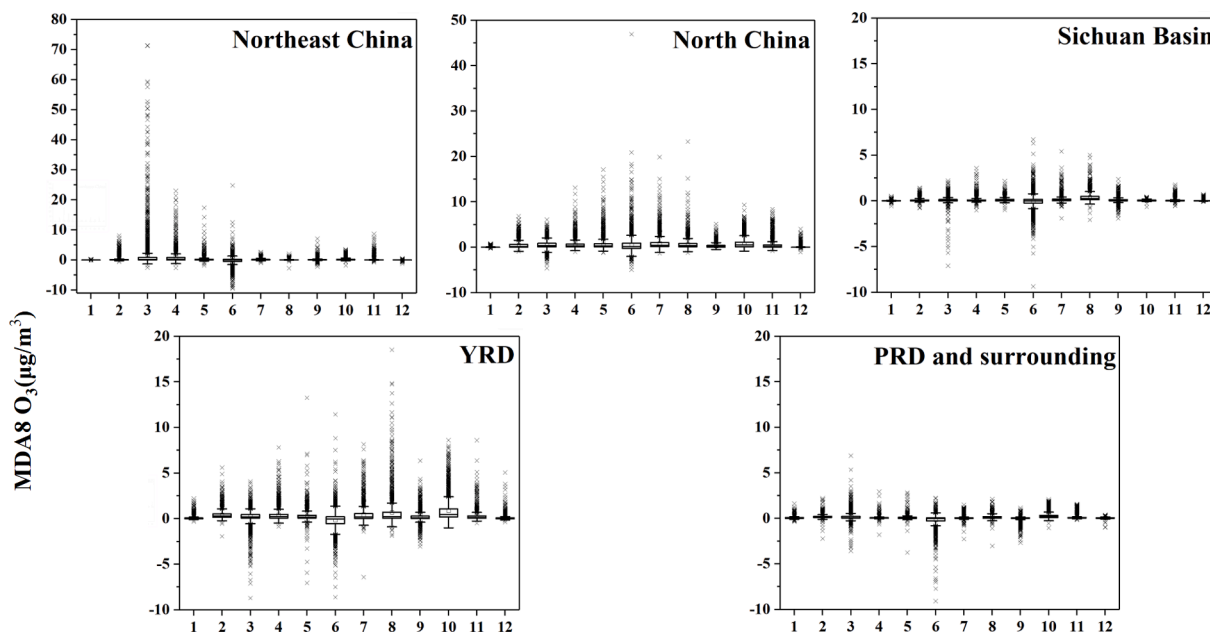


Fig. 5. Changes of monthly averaged MDA8 ozone concentration ($\mu\text{g}/\text{m}^3$) due to OCSB emissions.

most ozone exceedance days (except Sichuan Basin) (Fig. S2). We applied the method of relative response factor (RRF, calculated as the ratio of simulated ozone concentration from Scenario 2 to simulated ozone concentration from base scenario) to obtain the adjusted ozone concentration when OCSB emissions are removed. Results show that

OCSB emissions increase the number of ozone exceedances days by 2 to 106 days. North China shows the most significant increase in ozone exceedance days (+106 days) due to the OCSB emissions. The maximum increase in ozone exceedance days reaches four days at the city level. In YRD and Northeast China, ozone exceedances increased by 33 days and

Table 2
Changes in the number of ozone exceedances days for selected regions in 2018.

Region (No. of cities)	Number of ozone exceedances days	Δ ozone exceedances days due to OCSB emissions	Δ ozone exceedances days due to straw burning bans
North China (70)	4,544	+106	-138
YRD (56)	2,447	+33	-103
Sichuan Basin (22)	479	+5	-13
Northeast China (36)	746	+18	-31
PRD (9)	323	+2	-2

18 days due to OCSB emissions, whereas changes in Sichuan Basin and PRD are relatively small given that the OCSB emissions are comparatively lower in these two regions.

3.2.3. Impact of the straw burning bans

Consistent with the trends of PM_{2.5} emissions described in our previous study (Huang et al., 2021), the total VOC emissions from OCSB exhibit an overall downward trend from 2010 to 2018, with two distinct peaks in 2013 and 2017 (Fig. 6). The first peak in 2013 was mainly contributed by emissions from North China (32%) and YRD (29%), exhibiting a sharp decreasing trend after 2013. The 2017 peak is predominantly contributed by Northeast China, which showed a continuous increase in OCSB emissions during 2010–2017, followed by a drastic drop in 2018. Compared with 2013, VOCs and NO_x emissions from OCSB in 2018 decreased by 703 Gg and 71 Gg (both decreased by 47%), with a maximum reduction in June by 87%. YRD (by 76%) and North China (by 60%) show a significant decline in OCSB emissions, whereas Northeast China was the only region with increased OCSB emissions in 2018, especially in February–April (Fig. S3). The implementation of straw burning bans in Northeast China lagged relatively behind other regions (most policies were announced in 2017). During 2013–2017, Northeast China witnessed a continuous increase in OCSB activities, with a relative increase of VOC emissions by 235% in 2017 compared to 2013. Although a sharp reduction in OCSB emissions was observed in 2018 (reduced by 66% compared to 2017), it did not entirely offset the increased emissions from 2013 to 2017. Based on the existing results, the impacts on ozone concentration are proportional to the magnitude of OCSB emissions. Thus it is expected the impacts of OCSB emissions on ozone concentration would be the most significant in 2017, especially during March–April.

To assess the impact of straw burning bans on ground-level ozone concentration, we replaced 2018 OCSB emissions in the base scenario with 2013 OCSB emissions (i.e., Scenario 3) while keeping all the other emissions and model configurations unchanged. Fig. 6c–d shows the spatial distribution of the annual average and ozone season averaged change of MDA8 ozone before and after implementing straw burning bans. Except for Northeast China where OCSB emissions increased in 2018 compared to 2013, AMDA8 ozone concentrations generally decreased, with North China and YRD showing the most significant declines. Regional averaged ozone decreased by 0.69 μg/m³ and 0.49 μg/m³ for North China and YRD, with the largest localized decrease up to 1.3 μg/m³. Regarding the ozone season change (Fig. 4d), the maximum MDA8 ozone concentration decreased by up to 1.30 μg/m³ in North China and up to 0.94 μg/m³ in YRD.

Fig. 7 shows the changes in monthly average MDA8 ozone due to the implementation of straw burning bans. North China and YRD show overall reductions in monthly average MDA8 ozone, with the most reductions in June, which is also the month with the highest number of ozone exceedances days. Regional averaged MDA8 ozone decreased by 5.4 μg/m³ and 2.8 μg/m³ in June in North China and YRD, with a maximum decrease exceeding 10 μg/m³ at specific locations. This large decrease corresponds to the significant reduction of OCSB emissions in June (86% in North China and 95% in YRD). Northeast China exhibits increases in monthly MDA8 ozone concentrations during the burning seasons (March–April), with an average increase of 1.6 μg/m³ in March and a maximum increase of 7.2 μg/m³ due to increased OCSB emissions. The implementation of straw burning bans reduces the cumulative number of ozone exceedances days by 2 to 138 days for different regions (Table 2). Again, North China shows the largest decrease in ozone exceedance days by 138 days, followed by YRD (103 days) and Northeast China (31 days).

3.3. Health impact associated with OCSB

Based on the method described in Section 2.3, the number of premature deaths due to cardiovascular disease (CVD) and respiratory disease (RD) under different scenarios was estimated (Table S6). Under the base scenario, the national total number of premature deaths due to ozone exposure in 2018 was estimated to be 288,000 (95% Confidence Interval (CI): 164,000–401,000), which is relatively consistent with the values estimated by previous studies (e.g., Wang et al., 2020). As calculated in our previous study, this value is around 70% lower than that due to PM_{2.5} exposure in 2018. RD and CVD account for 61% and 39% of the total premature deaths, respectively. The spatial distribution of premature mortality due to ozone exposure concentrated over North China which has both high population density and high ozone concentrations (Fig. S4). The top five provinces that have the highest premature mortality due to ozone exposure include Shandong (23,980, 95% CI:13,640–33,390), Sichuan (23,650, 95% CI:13,510–32,820), Henan

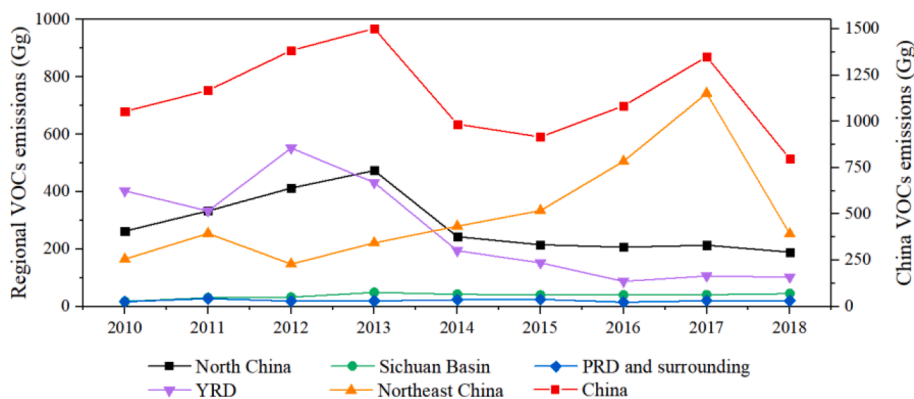


Fig. 6. Emissions of VOCs from OCSB in China by region from 2010 to 2018.

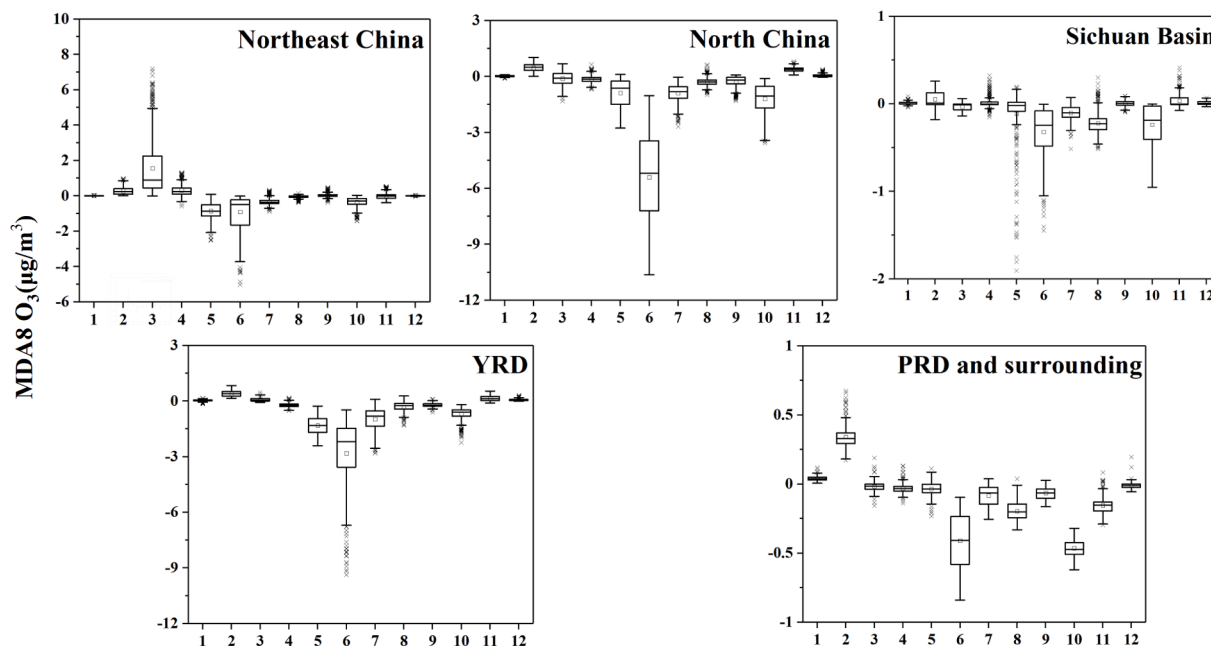


Fig. 7. Change of monthly MDA8 O₃ due to OCSB emission changes between 2013 and 2018 by region and month.

(22,050, 95% CI:12,580–30,610), Jiangsu (19,030, 95% CI:10,830–26,510), and Guangdong (17,420, 95% CI: 9900–24,310).

The total number of premature deaths due to ozone exposure attributable to OCSB emissions in 2018 was estimated to be 1550 (95% CI: 880–2010), accounting for 0.54% of ozone-related premature mortality. As expected, regions with evident health impacts are regions with high OCSB emissions and high populations (Fig. 8). The five provinces that have the highest OCSB related health impacts are Shandong (230, 95% CI: 120–300), Hebei(220, 95% CI: 140–310), Henan (180, 95% CI: 100–240), Jiangsu (120, 95% CI: 70–160), and Anhui (110, 95% CI:

60–140). If OCSB emissions were kept at 2013 levels, the total number of premature deaths associated with ozone exposure would increase by 1870 (95% CI: 1070–2550) (a relative increase of 0.65%). Shandong (360, 95% CI: 210–490), Henan (280, 95% CI: 170–390), Hebei (270, 95% CI: 160–260), Jiangsu (170, 95% CI: 100–230), and Anhui (140, 95% CI: 90–200) are the top five provinces that have the highest number of avoided premature mortality as the result of straw burning bans. When summed with our previous results of premature mortality associated with PM_{2.5} exposure (Huang et al. 2021), the total number of premature deaths attributed to OCSB emissions (considering both ozone

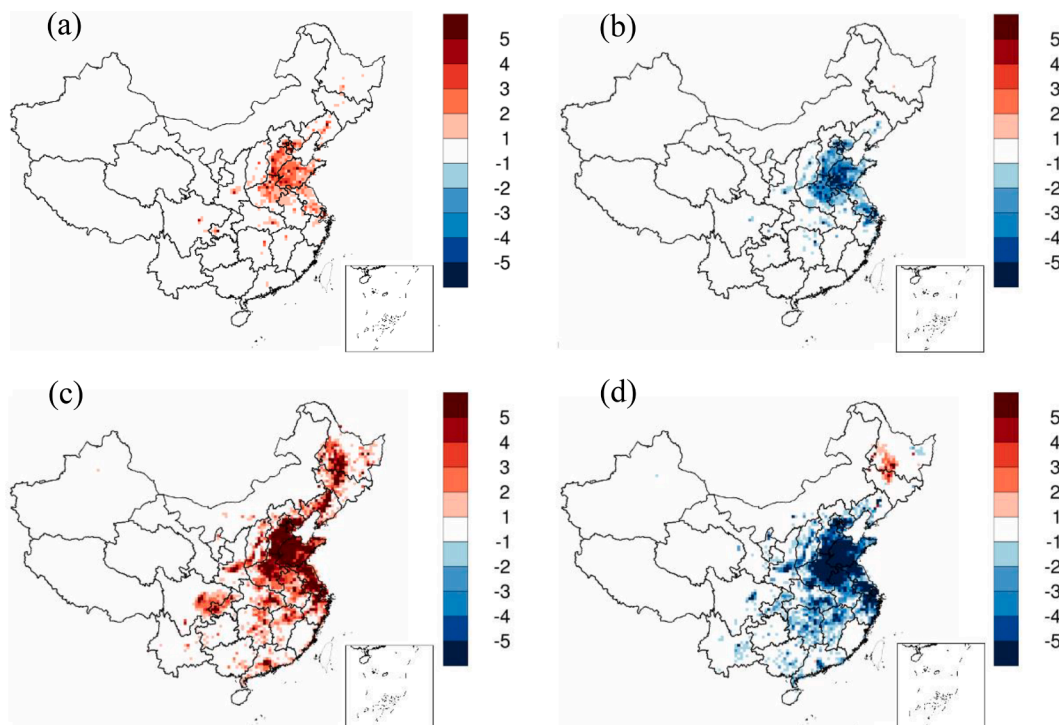


Fig. 8. Spatial distribution of premature mortality associated with ozone exposure (upper row) and associated with both PM_{2.5} and ozone exposure (bottom row) due to OCSB emissions (left) and straw burning bans (right) (No data for Taiwan, Hong Kong, and Macau) Unit: person/grid.

and PM_{2.5} exposure) in 2018 was 6290 (95% CI: 5620–6750). The implementation of the straw burning bans reduced the total number of premature death by 6120 (95% CI: 5320–6800), suggesting substantial health benefits of the control policy. The top five provinces that gained the most health benefits from the straw burning bans are Shandong (880, 95% CI: 730–1010), Henan (760, 95% CI: 650–870), and Anhui (590, 95% CI: 540–650).

4. Conclusions

Open crop straw burning (OCSB) represents an important source of VOCs and NO_x emissions in China that could affect ground-level ozone formation. In 2018, the total annual VOCs and NO_x emissions from OCSB activities were 798.8 Gg and 80.6 Gg, respectively, with high emissions located in North China, Northeast China, and northern YRD and distinct monthly variations across different regions. Our model simulation results show that OCSB emissions resulted in a widespread increase in annual average (up to 0.95 µg/m³) and ozone season average (up to 1.35 µg/m³) MDA8 in 2018, with North China exhibiting the strongest ozone impacts where the burning season coincides with the most severe ozone pollution month (i.e., June). OCSB emissions significantly impact daily and localized ozone concentrations, which could be up to 20 µg/m³ in North China and YRD region and even more in Northeast China during the burning season.

In addition, we show that the implementation of straw burning bans substantially reduces the overall VOCs and NO_x emissions from OCSB activities by 47% when comparing 2018 to 2013, although Northeast China is an exception. Regional averaged MDA8 ozone decreased by 5.4 µg/m³ and 2.8 µg/m³ in June in North China and YRD, with a maximum decrease exceeding 10 µg/m³ at specific locations. Due to the straw burning bans, the cumulative number of ozone exceedance days was reduced by 4 to 138 days for selected regions. Based on a concentration–response function, the total number of premature deaths attributed to OCSB emissions (considering both PM_{2.5} and ozone exposure) in 2018 was estimated to be 6290 (95% CI: 5620–6750), and the implementing the straw burning bans reduced the number of premature death by 6120 (95% CI: 5320–6800), suggesting substantial health benefits from the control policy.

CRediT authorship contribution statement

Ling Huang: Conceptualization, Formal analysis, Writing – original draft. **Yonghui Zhu:** Data curation, Formal analysis, Visualization. **Hanqing Liu:** . **Yangjun Wang:** Resources. **David T. Allen:** Writing – review & editing. **Maggie Chel Gee Ooi:** Writing – review & editing. **Kasemsan Manomaiphiboon:** Writing – review & editing. **Mohd Talib Latif:** Writing – review & editing. **Andy Chan:** Writing – review & editing. **Li Li:** Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2022.107710>.

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