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Impact of Biomass Burning on Ozone, Carbon Monoxide, and Nitrogen Dioxide in Northern Thailand

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The problem of smoke haze pollution in Northern Thailand affects both the environment and residents. The main sources of smoke are wildfires and open burning during the dry season, which release many pollutants, especially surface O_3, impacting health and causing an air pollution crisis. The aim of this research was to study the impact of biomass burning on the surface O_3, CO, and NO_2 levels in Northern Thailand using the Weather Research and Forecasting Model with Chemistry (WRF-Chem). The simulation domain was configured with two domains with a grid spacing of 50 and 10 km in March 2014. To elucidate the effect of biomass burning, the model simulation was conducted for two cases: 1) a simulation with anthropogenic, biogenic, and biomass burning emissions; and 2) a simulation excluding biomass burning emissions. Owing to the model performance, the diurnal temperature and precipitation were consistent with observations, as indicated by the index of agreement (IOA) ranges of 0.74–0.76, while those of O_3, CO, and NO_2 were in the ranges of 0.12–0.71. The results show that biomass burning increased O_3, CO, and NO_2 levels by 9, 51, and 96%, respectively.

Keywords: biomass burning, ozone, carbon monoxide, nitrogen dioxide, Southeast Asia

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INTRODUCTION

Biomass burning is a significant source of O_3 precursors in Southeast Asia, where peak biomass combustion typically occurs in February and March (Chang and Song, 2010; Sonkaew and Macatangay, 2015). Several chemical species liberated from biomass burning are related to air quality, such as O_3 and its precursors. Biomass burning considerably contributes to levels of O_3 and its precursors, making up to 30% of the total concentrations, particularly in March, when emissions from wildfires are highest (Amnuaylojaroen et al., 2014; Amnuaylojaroen et al., 2018; Amnuaylojaroen et al., 2019; Amnuaylojaroen et al., 2020). Moreover, a study by Pfister et al., 2006, who used the global chemical transport model to examine the ozone production from boreal forest fires in the summer of 2004 over Alaska and Canada, found that biomass burning emissions increased O_3 levels by approximately 7–9% and 2–3% over Alaska and Europe, respectively. Furthermore, a study on the tropospheric ozone distribution using the global chemical transport model, GEOS-Chem, and ground-based observations and satellite found a certain reduction in biomass burning emissions decreased tropospheric ozone by approximately 8% (Parrington et al., 2012).

O_3 is a secondary pollutant that is not directly released from both natural and anthropogenic sources, but rather is the result of photochemistry between volatile organic compounds (VOCs) and nitrogen oxides (NO_x). The chemistry in the troposphere involves the oxidation of organic molecules in the presence of nitrogen oxides. O_3 is considered to be the principal product of tropospheric chemistry. The source of ozone is nitrogen dioxide (NO_2). Ozone is formed as a product of NO_2 photolysis. Then, in the presence of NO, it is quickly destroyed (Seinfeld and Pandis, 1998). Carbon monoxide reacts rapidly with radical hydroxyl and hydrogen atoms, combining with O_2 to form the radical hydroperoxy (HO_2). When NO is present, the majority of atmospheric reactions are between it and the radical hydroperoxyl HO_2. A net formation of O_3 is caused by the radical conversion of NO to NO_2, rather than O_3 alone (Seinfeld and Pandis, 1998).

To understand the contribution of O_3 and its precursors to pollution, earlier studies have used models to predict their levels in Asia. For example, Amnuaylojaroen et al. (2014) used the Weather Research and Forecasting Model with Chemistry (WRF-Chem), inputting different anthropogenic emissions to predict surface O_3 and CO levels in Southeast Asia during periods of peak biomass burning (March). The results of this study indicated that none of the emission inventories were better than the others in predicting surface O_3 concentrations, but they differed in their ability to accurately predict CO concentrations. They also found that biomass burning enhances both O_3 and CO by 30 and 16%, respectively. Amnuaylojaroen et al., 2019 used the WRF-Chem to investigate the effect of volatile organic compounds from biomass burning on surface O_3 levels in Southeast Asia. Their results found that CO and VOCs such as BIGENE (lumped alkenes c > 3) play a key role in atmospheric oxidation to surface O_3. Xing et al., 2019 reported that biomass burning from Southeast Asia accounts for 51% of the increase in O_3 concentration in Yunnan Province. Sharma et al., 2017 employed three different emission inventories in WRF-Chem to evaluate the modeled surface O_3 over the South Asia. The diurnal variability of modeled ozone proved that the model was able to simulate clean, rural, and polluted urban conditions over this region. This work aimed to elucidate the contribution of biomass burning emissions to O_3, CO, and NO_2 levels in Northern Thailand.

MATERIALS AND METHODS

Model Configuration

We used WRF-CHEM version 3.8.1 (Grell et al., 2005) to simulate the meteorological conditions and concentrations of air pollutants in March 2014. WRF-Chem is a regional model of air quality that shares a physical framework with the WRF model. The model was set up with two domains with a grid spacing of 50 and 10 km, respectively. In addition, the vertical level of the model was configured with 30 vertical levels up to 50 hPa. As shown in **Figure 1**, the outer domain (D1) covers the majority of the land area of Southeast Asia and some parts of East and South Asia, while the inner domain (D2) covers Northern Thailand. The initial and boundary meteorological conditions were generated from the final analysis data output with a grid spacing of 1°–1°. To reduce the impact of initial conditions, the spin-up of the model was performed between February 15 and 28. Biogenic emissions were estimated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006). Biomass burning emissions were obtained from the Fire INventory (FINN) (Wiedinmyer et al., 2011). Anthropogenic emissions were simulated by the global atmospheric research database Hemispheric Air Pollution Transport (EDGAR HTAP) (Janssens-Maenhout et al., 2015). The model configurations are listed in **Table 1**.

Data Used for Model Evaluation

The model predictions of the O_3, CO, and NO_2 levels from WRF-Chem were compared to observations from the Pollution Control Department (PCD) in Thailand during March 2014. The PCD provides ground-based air quality observations in Thailand. The Thai PCD monitors six chemical species' hourly surface concentrations: CO, O_3, SO_2, CO, $PM_{2.5}$, NO_2, and PM_{10}. In Thailand, the measurement sites were urban, and, therefore, urban (especially motor vehicle) emissions dominated. The reference method or equivalent methods were used to measure the data. Almost every O_3 observation was obtained using Model 400 (http:/www.teledyne-api.com/products/400e.asp) Teledyne Advant Policy Instrumentation. The detection limit of the instrument is lower by 0.6 ppbv and 1% accuracy. Nearly all of the CO observations were obtained using Teledyne Advanced Pollution Instrumentation Model 300, with a lower detection limit of 40 ppbv and a 0.5% detection precision (http:/www.teledyne-api.com/products/300e). There is regular missing information in PCD measurements, but only 15 percent of the time. In order to evaluate the model's performance, a range of statistical methods was used, including the mean absolute error (MB) and the index of agreement (IOA).

$$\text{Mean Bias} = \frac{1}{n}\sum_{1}^{n}(M - O), \tag{1}$$

$$\text{IOA} = 1 - \left[\frac{\sum_{1}^{n}(O - M)^2}{\sum_{1}^{n}\left(|M - \overline{O}| + |O - \overline{O}|\right)^2}\right], \tag{2}$$

$$\text{MAE} = \frac{\sum_{i=1}^{n}|\text{M} - \text{O}|}{\text{n}}, \tag{3}$$

where M = predicted concentration, O = observed concentration, and n = number of data.

RESULTS AND DISCUSSION

Model Evaluation

The output of the model from the inner domain, that is, the precipitation and 2 m temperature, and O_3, CO, and NO_2 output, was compared to the ground-based measurement from the Thai

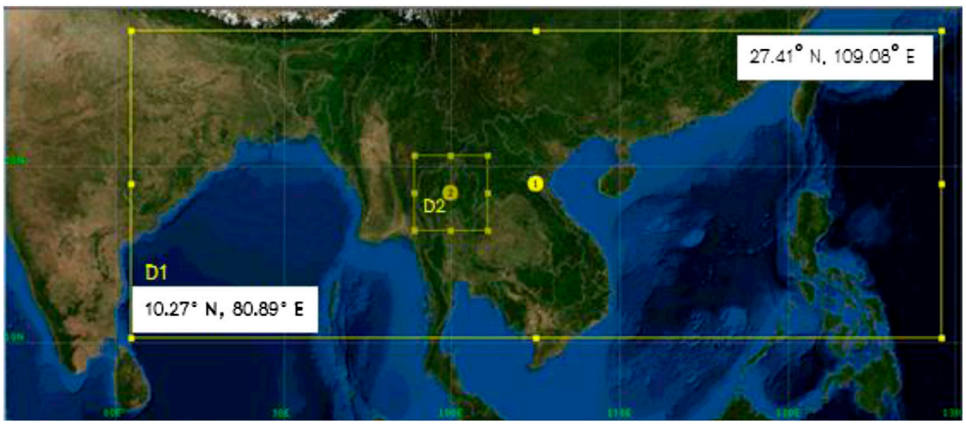

FIGURE 1 | Domain configuration.

TABLE 1 | Model configuration.

	Model configurations
Microphysics	Thompson Thompson et al. (2004)
Cumulus parameterization	Kain–Fritsch Kain (2004)
planetary boundary layer	Mellor Yamada–Janjic Janjic (2002)
Land surface model	NOAH land surface model Chen and Dudhia (2001)
Friction and wind speeds	Similarity theory Dyer and Hicks (1970), Paulson (1970), Zhang and Anthes (1982). Webb (1970)
Gas-phase chemistry	MOZART Emmons et al. (2010)
Photolysis rate	Rapid Tropospheric Ultraviolet and Visible (TUV) system Tie et al. (2003)
Dry and wet deposition	Wesely (1989) and Neu and Prather (2012) resistance methods

PCD. Statistical analyses such as index of agreement (IOA), mean absolute error (MAE), and mean bias (MB) were utilized to examine the model performance (**Table 2**). The simulations of WRF-Chem were fairly consistent with the observations from PCD. The monthly mean 2 m temperature and precipitation from the model were agreeable, with IOAs in the range of 0.354–0.726 for temperature and 0.47 to 0.966 for precipitation, while the mean bias and MAE, respectively, were (−0.05)°C to 0.04°C and 0.6 to 1.5°C for temperature, and (−0.03) to 0.02 and 0.2mm–1.4 mm for precipitation. In general, the chemical species from the model were in fair agreement with those in observations, with IOA values in the range of 0.128–0.713. In comparison with the observations, however, the modeled chemical species were underestimated. In addition, WRF-Chem predicted levels of chemical species (CO and NO_2) moderately well, with IOA values in the range of 0.445–0.713 for CO and 0.350–0.547 for NO_2. The mean bias and MAE, respectively, were (−0.2) to 0.1 ppmv and 5.8 to 14.1 ppmv for O_3; (−0.02) to 0.01 ppmv and 0.2 to 0.6 ppmv for CO; and (−0.4) to 0.04 ppmv and 2.6 to 12.9 ppmv for NO_2. The discrepancies likely occur due to calculating all chemical species through the plum-rised model in WRF-Chem from aggregated coarse-resolution data of biomass-burning emissions, which was discussed in Amnuaylojaroen et al. (2014). These calculations capture a significant portion of the fire thermal buoyancy, which transports these species to high altitudes. A limitation is that the model configuration in this work did not consider the effect of aerosol feedback on the meteorology, which likely causes changes in temperature, boundary layer height, and clouds. These factors are likely to affect the results of O_3 simulation (Forkel et al., 2012).

Impact of Biomass Burning on CO, NO_2, and O_3 Levels

The output from domain two was used to illustrate the difference between WRF-CHEM simulations, including biomass burning emissions and WRF-CHEM simulations, excluding biomass burning emissions for monthly O_3, CO, and NO_2 concentrations in March 2014 (**Figure 2**). Biomass burning contributed between approximately 3–7% to background O_3 (**Figure 2A**), where increases in the average monthly O_3 concentration of approximately 3–4 ppmv were mostly observed in Northern Thailand (**Figure 2D**). Furthermore, biomass burning emissions substantially contributed to both CO and NO_2 levels—approximately 60–90% (**Figures 2B,C**)—which increased the average monthly CO and NO_2 concentrations by approximately 400 to 500 ppmv and 9 to 11 ppmv, respectively (**Figures 2E,F**). The majority of significant biomass burning—contributing to more than 90% of surface NO_2—occurred in Northern Thailand (**Figure 2F**).

TABLE 2 | Statistical analysis of ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), temperature, and precipitation between the weather research and forecasting (WRF) model and ground-based measurements.

Stations	MB					MAE					IOA				
	O_3	CO	NO_2	Temp (°C)	Precipitation (mm.)	O_3	CO	NO_2	Temp (°C)	Precipitation (mm.)	O_3	CO	NO_2	Temp (°C)	Precipitation (mm.)
Lampang	−0.292	−0.025	0.048	−0.010	0.001	9.289	0.663	2.678	1.389	0.264	0.290	0.445	0.471	0.665	0.470
Mae Hong Son	−0.161	−0.023	–	−0.037	0.027	8.872	0.610	—	1.242	1.166	0.431	0.575	—	0.682	0.067
Lamphun	0.106	−0.009	−0.062	−0.002	−0.035	5.822	0.254	3.623	0.646	1.407	0.217	0.554	0.547	0.688	0.966
Phrae	−0.143	0.010	−0.130	0.046	−0.023	6.282	0.329	4.913	1.616	0.153	0.339	0.363	0.423	0.354	0.937
Phayao	−0.457	−0.009	0.090	−0.053	0.010	14.409	0.358	4.456	1.727	1.224	0.350	0.633	0.350	0.534	0.323
Chiang Mai	−0.016	−0.015	−0.479	−0.029	−0.006	5.899	0.449	12.921	1.022	0.747	0.208	0.505	0.358	0.531	0.887
Chiang Rai	0.021	−0.016	–	−0.048	−0.018	9.477	0.433	—	1.503	0.727	0.128	0.713	—	0.457	0.924
Nan	−0.121	−0.012	0.209	0.011	−0.015	7.538	0.333	5.827	1.142	0.499	0.262	0.613	0.453	0.726	0.953

According to the model simulation, biomass burning emissions have a small effect on the increase in O_3 concentration, but a significant one on the increase in CO and NO_2 concentrations in Northern Thailand. These results are similar to those of the previous study; for example, Galanter et al., 2000 found that biomass burning is a major source of NO_x and CO in the tropical region, which contributes >50% of atmospheric CO and NO_x. In addition, Granier et al., 2000 argued that biomass burning emissions make a significant contribution to the tropospheric O_3 budget, particularly in the tropical region. Because biomass burning emissions directly add to NO_2 and CO levels, the resulting impact on O_3 is buffered by the nonlinear response of ozone chemistry and transport (Galanter et al., 2000); processes controlling surface O_3 production are likely due to another factor in its chemistry. As discussed in the study by Amnuaylojaroen et al., 2019, the net O_3 production in upper Southeast Asia is NO_x-limited, which is insensitive to both constant NO_x and VOC decreases—the production of BIGENE (note that BIGENE represents lumped alkenes, Emmons et al., 2010) and CO peroxy radicals mainly dominates the reaction rate for O_3 production. In addition, biomass burning emissions slightly increase the BIGENE and CO reaction rates. However, this research does not consider the impact of the transport of biomass burning plumes that also play an important role in increasing the O_3 mixing ratios. As discussed by Kondo et al., 2004, the increase in the mixing ratios of O_3 and its precursors in the western Pacific due to biomass burning in Southeast Asia was estimated using the tracers. Additionally, Brocchi et al., 2018 found that the intercontinental transport of biomass burning from Siberia and Canada qualitatively reproduced CO and O_3 concentration variations in the Mediterranean Basin.

CONCLUSION

During the peak period of biomass burning, we applied a regional model of atmospheric chemistry to study the effect of biomass burning on O_3, CO, and NO_2 concentrations in Northern Thailand. The model can be used to analyze, with acceptable precision, the contributions of biomass burning to surface O_3, CO, and NO_2 levels. By comparing the model results with ground-based measurements in Thailand, we found that the model was generally consistent with precipitation, the temperature at 2 m, and O_3, CO, and NO_x levels. However, in most areas of Northern Thailand, the model generally underestimated the magnitude of all chemical species. A comparison of WRF-CHEM simulations with and without burning biomass emissions showed an increase in O_3, CO, and NO_x levels due to biomass burning. Biomass combustion, however, contributed directly to over 60% of CO and NO_2 levels and indirectly to the concentration of O_3 in Northern Thailand. Compared to CO and O_3, biomass burning had the greatest impact on the NO_2 distribution, contributing to over 90% of total NO_2 background levels, while biomass burning slightly contributed to surface O_3 levels, by approximately 7%.

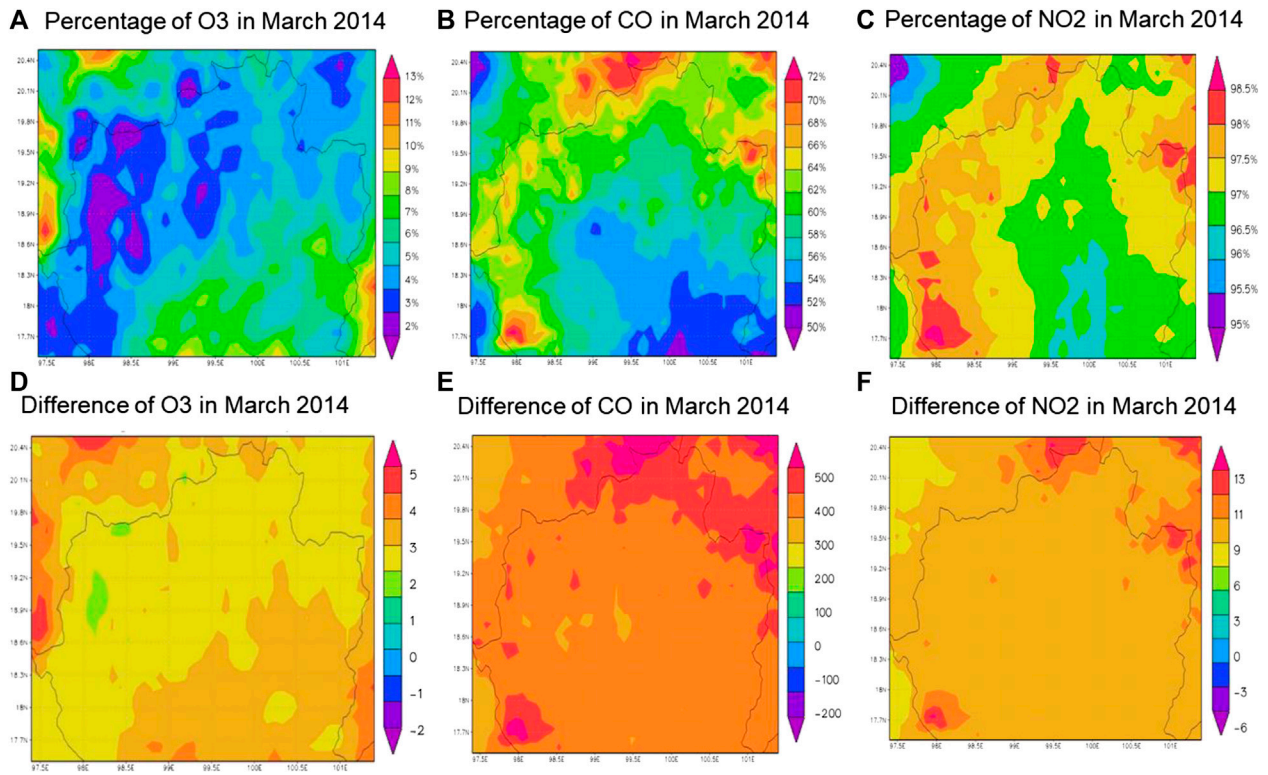

FIGURE 2 | Percentage **(upper panel)** and absolute **(bottom panel)** differences in O_3 **(A and D)**, CO **(B and E)**, and NO_2 **(C and F)** concentrations between the two WRF-Chem simulations with and without biomass burning emissions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

TA: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools, or data; and wrote the article. SK: contributed reagents, materials, analysis tools, or data.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.