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Impacts of Biomass Burning Emission Inventories and Atmospheric Reanalyses on Simulated PM₁₀ over Indochina

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Received: 19 December 2019; Accepted: 24 January 2020; Published: 4 February 2020



Abstract: Biomass burning (BB) is a major source of atmospheric particles over Indochina during the dry season. Moreover, Indochina has convoluted meteorological scales, and regional meteorological conditions dominate the transport patterns of pollutants. This study focused on the impacts of BB emission inventories and atmospheric reanalyses on simulated PM_{10} over Indochina in 2014 using the Community Multiscale Air Quality (CMAQ) model. Meteorological fields to input to CMAQ were produced by using the Weather Research and Forecasting (WRF) model simulation with the United States National Centers for Environmental Prediction Final (NCEP FNL) Operational Global Analysis or European Centre for Medium Range Weather Forecasts Interim Reanalysis (ERA-interim). The Fire INventory from NCAR (FINN) v1.5 or the Global Fire Emissions Database including small fires (GFED v4.1s) was selected for BB emissions for the air quality simulation. The simulation case with NCEP FNL and FINN v1.5 (FNL + FINN) performed best throughout 2014, including the season when BB activities were intensified. The normalized percentage difference for maximum daily mean PM_{10} concentrations at Chiang Mai for FNL + FINN and the two simulation cases applying GFED v4.1s for BB emissions (-53% to -27%) was much larger than that between the FNL + FINN and ERA + FINN cases (10%). BB emission inventories more strongly impacted PM₁₀ simulation than atmospheric reanalyses in highly polluted areas by BB over Indochina in 2014.

Keywords: biomass burning; CMAQ; PM₁₀; atmospheric reanalysis

1. Introduction

Indochina, the peninsular region that includes Cambodia, Laos, Myanmar, Thailand, and Vietnam, has a monsoonal climate with a dry and wet season; the prevailing wind direction and the pattern of precipitation changes seasonally. During the dry season, particulate pollution degrades air quality over Indochina [1]. Outdoor exposure to particulate matter (PM) contributes to ill health, such as cardio- and cerebrovascular disease, respiratory illnesses, lung cancer, and possibly other diseases [2]. A major source of atmospheric particles over Indochina is biomass burning (BB), such as forest fires and agricultural burning. Thailand is surrounded by mountainous areas where BB frequently occurs in the dry season. Chiang Mai, the largest city in northern Thailand, has experienced severe air pollution caused by BB [3–5]. Furthermore, measurements of aerosol properties on Dongsha Island in the northeastern South China Sea revealed that smoke originating from BB in Indochina rises and is trapped within the free troposphere (3–4 km above the earth's surface) in some situations [5–7].

As part of NASA's 2006 Biomass Burning Aerosols in Southeast Asia: Smoke Impact Assessment (BASE-ASIA), regional modeling studies were conducted to assess the impacts of BB in Southeast



Asia on atmospheric composition over Asia in 2006 by using the Community Multiscale Air Quality (CMAQ) model [8]. The CMAQ simulations revealed that during two intense episodes in 2006, BB contributed to ground-level CO, O_3 , and $PM_{2.5}$ concentrations in the source region of Southeast Asia by as much as 400 ppbv, 20 ppbv, and 80 μ g m⁻³, respectively [9]. The emissions from BB could also be spread over the southeastern parts of East Asia via strong eastward transport in the free troposphere from 2 to 8 km above the earth's surface [9,10]. It should be noted that the model performance was evaluated using only observed CO concentrations in Thailand, and that discrepancy existed between simulations and measurements due to uncertainty in emission inventories. Amnuaylojaroen et al. [11] reported that BB emissions create a substantial increase for simulated O_3 and CO surface mixing ratios by up to 29% and 16%, respectively, for Southeast Asia in 2008. However, particulate matter was not evaluated in the simulations. Li et al. [12] reported that BB contributed 70%–80% of simulated PM_{2.5} in northern Myanmar, Laos, and Vietnam during March-April 2013.

Several BB emission inventories are available, such as the Fire INventory from NCAR (FINN) [13], the Global Fire Assimilation System (GFAS) [14], and the Global Fire Emissions Database (GFED) [15]. BB emission inventories have substantial uncertainties in their temporal and spatial variabilities because the data to estimate the emissions of BB, such as area, fuel loading, and emission factors, are limited [13,15]. Vongruang et al. [16] reported that PM_{10} was overestimated in air quality simulation with FINN, whereas PM_{10} was underestimated with GFAS in the source region of Northern Thailand in March 2012.

Indochina has convoluted meteorological scales, and regional meteorological conditions dominate the transport patterns of pollutants [1]. Atmospheric reanalyses, initial and boundary conditions for a mesoscale model, have great impacts on the simulated meteorological fields. Several atmospheric reanalyses have been developed by different organizations, for example, the European Centre for Medium Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-interim) [17], the Japanese 55-year Reanalysis (JRA-55) [18] from the Japan Meteorological Agency (JMA), and the United States National Centers for Environmental Prediction Final (NCEP FNL) [19] Operational Global Analysis. These reanalyses employ various forecast models and data assimilation approaches. ERA-Interim has the highest ability to reproduce climate variables of the East Asian summer monsoon, especially precipitation [20,21].

To the best of our knowledge, there are few studies simulating particulate pollution in Indochina for a period of one year that consider the uncertainties of BB emissions and the complexities of the regional meteorology. In one study, two BB emission inventories were assessed by simulating particulate matter using CMAQ during a specific pollution event [16]. This study focused on the impacts of BB emission inventories and atmospheric reanalyses on the simulation of PM_{10} over Indochina in 2014. From the end of February to early April in 2014, agricultural burning and forest fires in northern Thailand caused severe particulate pollution over the region [5].

2. Materials and Methods

2.1. Simulation Design

Air quality simulations for the year 2014 were conducted by CMAQ v5.0.2 with an initial spin up period of December 2013. The modeling domains covered regions from East Asia (D1) to Indochina (D2) (Figure 1). The horizontal resolutions were 72 km and 24 km, and the number of grid cells were 92×92 and 98×98 for D1 and D2, respectively. The domains consisted of 30 sigma-pressure coordinate vertical layers ranging from the surface to 100 hPa. Figure 2 shows the procedure of air quality simulation in this study.



Figure 1. Locations of observation sites for PM₁₀ and meteorology, and fire spots (MCD14DL) provided by Fire Information for Resource Management System (FIRMS) on 21 March 2014 in the modeling domains covering (**a**) East Asia (D1) and (**b**) Indochina (D2). Elevation and dominant United States Geological Survey (USGS) 24-category land use are provided in (**a**) and (**b**), respectively.



Figure 2. Procedure of air quality simulation by meteorological model and chemical transport model.

2.2. Meteorological Model

Meteorological fields to input to CMAQ were produced by using the Weather Research and Forecasting (WRF) model [22] v3.4. The WRF simulations were conducted using the high-resolution, real-time, global sea surface temperature analysis (RTG_SST_HR) of NCEP, and two atmospheric reanalyses: NCEP FNL or ERA-Interim. The physics options were as follows: Rapid Radiative Transfer Model for General Circulation Models Shortwave and Longwave Schemes [23], planetary boundary layer physics of Asymmetric Convection Model 2 Scheme [24], cumulus parameterization of the Kain–Fritsch Scheme [25], micro physics of Morrison 2-moment Scheme [26], and Pleim–Xiu Land Surface Model [27]. Grid nudging was applied to horizontal wind components at all the vertical layers with a coefficient of $3.0 \times 10^{-4} \text{ s}^{-1}$ in D1 and $1.0 \times 10^{-4} \text{ s}^{-1}$ in D2 for the entire period.

2.3. Chemical Transport Model

CMAQ was configured with the Carbon Bond chemical mechanism (CB05) [28] for gas-phase chemistry and the sixth generation CMAQ aerosol module for the aerosol process. The initial and lateral boundary conditions for D1 were obtained from the Model for Ozone and Related Chemical Tracers v4 (MOZART-4) [29]. Several datasets were used to produce emission data. In particular, the Fire INventory from NCAR (FINN) [11] v1.5 or the Global Fire Emissions Database including small fires (GFED v4.1s) [30] was selected for BB emissions. FINN v1.5 provided 1 km-resolution BB emissions estimated from the active fire observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua satellite. GFED v4.1s provided 0.25°-resolution BB emissions estimated from the 500 m Collection 5.1 MODIS direct broadcast burned area product plus additional burned area from small fires based on a revised version of the Randerson et al. [31] small-fire estimation approach. Anthropogenic emissions were obtained from the Task Force Hemispheric Transport of Air Pollution (HTAP) v2.2 inventory [32]. The other natural emissions were derived from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) [33] v2.04 for biogenic emissions and the Aerosol Comparisons between Observations and Models (AEROCOM) data [34] for baseline volcanic SO₂ emissions. There were differences between the periods of simulations and the reference years in the anthropogenic emission data available for the simulations, and the uncertainties associated with the differences may have affected model performance.

In order to evaluate the impacts of BB emission inventories and atmospheric reanalyses on simulated PM_{10} concentrations, four cases of simulations (FNL + FINN; FNL + GFED; ERA + FINN; and ERA + GFED) were executed. The first parts of cases' names indicate the applied reanalysis: FNL and ERA stand for NCEP FNL and ERA-Interim, respectively. The second parts indicate the selected BB emission inventories. Furthermore, simulations without BB emission inventories (FNL + exBB; ERA + exBB) were conducted. The difference between cases with BB emissions and those without BB emissions was calculated to estimate BB contributions to PM_{10} concentrations in the four simulation cases with BB emissions.

Figure 3 shows spatial distributions of PM_{10} emissions from FINN v1.5 and GFED v4.1s in March and April 2014. During these two months, PM_{10} emissions in both BB emission inventories were concentrated in Indochina, especially the mountainous areas in Laos, Myanmar, and Thailand. FINN v1.5 estimated larger emissions in a wider area than GFED v4.1s. Figure 4 shows the variation of the amount of PM_{10} emissions over D2 and the relative contributions from BB. PM_{10} emissions from BB produced by FINN v1.5 and GFED v4.1s accounted for 244 mg s⁻¹ km⁻² and 91 mg s⁻¹ km⁻², respectively, which contributed 93% and 83%, respectively, of the total amount of PM_{10} emissions in March when burning activities were intensified.

The WRF performance was evaluated through comparison with ground-level air temperature, relative humidity, and wind speed data in Bangkok and Chiang Mai distributed by the University of Wyoming [35]. The CMAQ performance was evaluated through comparison with ground-level PM₁₀ concentration data in Bangkok and Chiang Mai distributed by the Acid Deposition Monitoring Network in East Asia (EANET) [36].



Figure 3. Spatial distributions of mean PM₁₀ emissions from biomass burning: (**a**) FINN v1.5 and (**b**) GFED v4.1s in March, and (**c**) FINN v1.5 and (**d**) GFED v4.1s in April.



Figure 4. Variation of mean PM₁₀ emissions over D2 and the relative contributions from biomass burning (BB): (**a**) FINN v1.5 and (**b**) GFED v4.1s.

3. Results

3.1. Daily Meteorological Factors at Observation Sites

The WRF performance was evaluated by using the normalized mean bias (NMB) and the index of agreement (IA) for ground-level air temperature, relative humidity, and wind speed for Bangkok and Chiang Mai (Table 1). More statistics were shown in supplementary data (Table S1). IA is a statistical measure to present the model performance and varies between 0 and 1, where 1 means model performance is perfect [37]. IA values for air temperature, relative humidity, and wind speed were relatively high in both WRF simulations: the models applying both NCEP FNL and ERA-interim simulated spatial and temporal variations of these parameters in the same level.

Site **FNL** ERA Observation Mar-Apr Mar-Apr Mar-Apr Year Year Year Temperature Mean Bangkok 27 30 27 30 29 30 $(^{\circ}C)$ Chiang Mai 26 31 26 31 26 28 NMB Bangkok -5 $^{-1}$ -5 $^{-1}$ (%) -2 8 $^{-2}$ 9 Chiang Mai IA 0.76 0.75 0.79 0.74 Bangkok Chiang Mai 0.86 0.62 0.85 0.60 **Relative Humidity** Mean Bangkok 78 70 77 70 70 70 (%) Chiang Mai 68 37 66 34 64 47 NMB Bangkok 11 0 9 0 2 (%) Chiang Mai 6 -21 -28IA Bangkok 0.65 0.57 0.67 0.56 Chiang Mai 0.78 0.60 0.79 0.54 Wind Speed Bangkok 2.4 2.9 2.5 2.9 3.2 3.7 Mean $(m s^{-1})$ 1.7 2.1 1.8 1.9 2.1 Chiang Mai 2.1 NMB -27-21-22-19 Bangkok -11 0 -80 (%) Chiang Mai IA 0.61 0.66 0.62 0.67 Bangkok

Table 1. Model performance for daily mean meteorological factors in the two simulation cases for the periods of one year and two months (from March to April) in 2014.

Note: Mean-mean value, NMB-normalized mean bias, IA-index of agreement.

0.64

0.59

0.70

3.2. Daily Concentrations of PM₁₀ at Observation Sites

Chiang Mai

0.58

The performance of daily mean PM_{10} concentration simulations in the four simulation cases with BB emissions was evaluated by using NMB and IA for the periods of both the entire year and the two month period from March to April 2014 (Table 2). More statistics were shown in supplementary data (Table S2). The highest PM_{10} concentrations in 2014 were observed on January 3 at Bangkok (123.9 µg m⁻³) and on March 21 at Chiang Mai (242.9 µg m⁻³), respectively. At Chiang Mai, maximum daily mean PM_{10} concentrations were simulated in all of the four simulation cases on the same day: March 21. The IA value for FNL + FINN was the highest for both the one-year and the two-month periods, indicating that FNL + FINN performed best throughout 2014, including the season when BB activities were intensified.

	Site	FNL	+ FINN	FNL ·	+ GFED	ERA	+ FINN	ERA	+ GFED	Obse	ervation
		Year	Mar–Apr								
Mean	Bangkok	32.2	32.2	30.7	27.3	31.0	35.1	29.3	29.3	37.2	38.8
(µg m ⁻³)	Chiang Mai	37.2	94.1	30.1	57.6	40.1	107.3	32.3	66.7	46.6	87.9
Maximum	Bangkok	107.2	93.9	101.7	65.7	104.9	104.9	91.2	73.9	123.9	77.1
$(\mu g m^{-3})$	Chiang Mai	309.5	309.5	145.8	145.8	339.5	339.5	225.4	225.4	242.9	242.9
NMB	Bangkok	-13	-17	-17	-30	-17	-9	-21	-24		
(%)	Chiang Mai	-20	7	-35	-34	-14	22	-31	-24		
IA	Bangkok	0.88	0.84	0.85	0.78	0.85	0.83	0.82	0.78		
	Chiang Mai	0.84	0.77	0.75	0.67	0.83	0.73	0.80	0.74		

Table 2. Model performance for daily mean PM_{10} concentrations in the four simulation cases for the periods of one full year (2014) and two months (from March to April 2014).

Note: Mean—mean value, Maximum—maximum daily mean value, NMB—normalized mean bias, IA—index of agreement.

Figure 5 shows simulated and observed daily concentrations at Bangkok and Chiang Mai. All of the four simulation cases simulated the day-to-day variation patterns well at both sites for the year 2014. Cases applying FINN v1.5 for BB emissions (FNL + FINN; ERA + FINN) showed higher trends of simulated PM₁₀ concentrations at both observation sites compared to those applying GFED v4.1s (FNL + GFED; ERA + GFED), regardless of the atmospheric reanalysis. In particular, the former two cases clearly presented higher trends of PM_{10} concentrations than the latter cases at Chiang Mai from the end of February to early April, when high PM₁₀ concentrations were observed. Table 3 shows the normalized percentage difference for FNL + FINN and the other three cases for annual mean and maximum daily mean PM_{10} concentrations in 2014 at the two observation sites. The percentage difference at Bangkok (-9% to -4% for annual mean; -15% to -2% for maximum) was less than that at Chiang Mai (-19%-8%) for annual mean; -53%-10% for maximum). At both of the two sites, the percentage difference between the FNL + FINN and ERA + FINN cases was the smallest for annual mean and maximum daily mean PM₁₀ concentrations in 2014. In particular, the difference for maximum daily mean PM₁₀ concentrations at Chiang Mai for FNL + FINN and the two cases applying GFED v4.1s for BB emissions (-53% to -27%) was much larger than that between the FNL + FINN and ERA + FINN cases (10%). Consequently, BB emission inventories more strongly impacted the PM_{10} simulation than atmospheric reanalyses at the two sites in Indochina.



Figure 5. Time series of simulated and observed daily mean concentrations of PM₁₀ at (**a**) Bangkok and (**b**) Chiang Mai and estimated daily mean relative contributions of BB at (**c**) Bangkok and (**d**) Chiang Mai.

	Site	FNL + GFED	ERA + FINN	ERA + GFED
FNL + FINN				
Mean (%)	Bangkok	-5	-4	-9
	Chiang Mai	-19	8	-13
Maximum (%)	Bangkok	-5	-2	-15
	Chiang Mai	-53	10	-27

Table 3. Normalized percentage difference for FNL + FINN and the other three cases for daily mean PM_{10} concentrations for the year 2014.

Note: Mean—annual mean value, Maximum—maximum daily mean value.

BB contributions were estimated by the difference between cases with and without BB emissions (Figure 5). The BB contributions to PM_{10} concentrations of the four simulation cases were 2%–12% at Bangkok and 75%–89% at Chiang Mai for each day that the maximum concentrations were observed. Li et al. [12] reported that BB contributions to simulated $PM_{2.5}$ was 70%–80% in the BB source regions during March-April 2013 and the contributions were close to 75%–89% at Chiang Mai on 21 March 2014.

Figure 6 shows simulated and observed wind speed, planetary boundary layer (PBL) height, and daily concentrations at Bangkok and Chiang Mai from March to April. At Bangkok, these parameters were on the similar trends among the four simulation cases. At Chiang Mai, the maximum PM_{10} concentration was observed in weak-wind condition. On the other hand, there was little relationship between PBL height and PM_{10} concentrations. The simulated spatial distributions on January 3 and March 21 are analyzed in detail in the next subsection.



Figure 6. Time series of simulated and observed daily mean wind speed at (**a**) Bangkok and (**b**) Chiang Mai, and simulated daily mean planetary boundary layer (PBL) height at (**c**) Bangkok and (**d**) Chiang Mai. The simulated and observed daily mean concentrations of PM_{10} were also shown. The day when maximum PM_{10} concentration was observed from March to April 2014 at each site was highlighted.

3.3. Spatial Distributions for Daily Concentrations of PM₁₀

Figure 7 shows the spatial distributions of daily PM_{10} concentrations and wind fields at ground level on January 3, when maximum PM_{10} concentration was observed in Bangkok. The large BB contribution area was spread out over Southern China and Cambodia. On January 3, ground-level winds were weak over Indochina. The area where simulated PM_{10} concentrations were around $80 \ \mu g \ m^{-3}$ was spread across Thailand, and the BB contributions were relatively small in the four cases; discrepancy among the four cases was small across Thailand.



Figure 7. Spatial distributions of daily mean of PM₁₀ concentrations and wind fields at ground level in (a) FNL + FINN and (b) ERA + FINN cases, and BB contributions to PM₁₀ concentrations in (c) FNL + FINN, (d) ERA + FINN, (e) FNL + GFED, and (f) ERA + GFED cases on 3 January 2014.

In March 2014, the largest number of hotspots were detected in Thailand and Myanmar from March 18 to 21 [5]. A large number of fire spots occurred in the mountainous areas of Indochina on March 21 (Figure 1). Figure 8 shows spatial distributions of daily PM_{10} concentrations and wind fields at ground level on March 21. Ground-level winds blew easterly in the eastern part of Indochina and converged at the Myanmar and Thailand border in all cases. Concentrations of 160 µg m⁻³ of PM_{10} were spread over the area along the Myanmar and Thailand border in the four cases with BB emissions; the two cases that FINN v1.5 selected for BB emissions were predicted to have higher PM_{10} concentrations in and around Northern Laos. In highly polluted areas caused by BB over Indochina,

the discrepancy of simulated PM_{10} concentrations resulting from different BB emission inventories was larger than that resulting from different atmospheric reanalyses.



Figure 8. Spatial distributions of daily mean of PM_{10} concentrations and wind fields at ground level in (a) FNL + FINN and (b) ERA + FINN cases, and BB contributions to PM_{10} concentrations in (c) FNL + FINN, (d) ERA + FINN, (e) FNL + GFED, and (f) ERA + GFED cases on 21 March 2014.

4. Conclusions

This study focused on the impacts of BB emission inventories and atmospheric reanalyses on the simulation of PM_{10} over Indochina for the year 2014. Meteorological fields to input to CMAQ were produced by using the WRF model simulation with NCEP FNL or ERA-interim. FINN v1.5 or GFED

v4.1s were selected for BB emissions. In order to evaluate the impacts, four cases of simulations (FNL + FINN; FNL + GFED; ERA + FINN; ERA + GFED) were executed.

The performance of CMAQ simulations for PM_{10} concentrations at ground-level was evaluated at Bangkok and Chiang Mai in Thailand. The FNL + FINN case performed best for both the full year and the two-month period when BB activities were intensified in 2014. To compare the impacts of input data (BB emission inventories and atmospheric reanalyses) on simulated PM_{10} , we introduced the normalized percentage difference for FNL + FINN and the other three cases (FNL + GFED; ERA + FINN; ERA + GFED) for annual mean and maximum daily mean PM_{10} concentrations in 2014 at the two observation sites. At both of the two sites, the normalized percentage difference for annual mean and maximum daily mean PM_{10} concentrations in 2014 for FNL + FINN and the two cases applying GFED v4.1s for BB emissions (FNL + GFED; ERA + GFED) was larger than that between FNL + FINN and ERA + FINN cases. In particular, the difference for maximum daily mean PM_{10} concentrations at Chiang Mai for FNL + FINN and the two cases applying GFED v4.1s (-53% to -27%) was much larger than that between the FNL + FINN and ERA + FINN cases (10%).

BB contributions were estimated by the difference between the cases with BB emissions and those without BB emissions. BB contributions to PM_{10} concentrations in the four simulation cases at Chiang Mai (75%–89%) were larger than those at Bangkok (2%–12%) on the day when the highest PM_{10} concentrations were observed in 2014 at each observation site. BB highly contributed on the particulate pollution over Southern china and Cambodia on January 3, and over the area along the Myanmar and Thailand border on March 21 in weak-wind condition. In polluted areas caused by BB, the cases applying FINN v1.5 for BB emission inventories showed higher trends of PM_{10} concentrations. Selected BB emission inventories more strongly impacted the PM_{10} simulation than selected atmospheric reanalyses in highly polluted areas by BB over Indochina in 2014.

This approach is applicable to other years and atmospheric pollutants to evaluate the impacts of selected input datasets on air quality simulations in polluted areas caused by BB. For example, GFAS can be used for one of the other BB emission inventories. However, emission factors of global BB emission inventories, such as FINN, GFAS, and GFED, were determined based on generic vegetation types of each fire pixel. BB-emission data focusing on the unique characteristics of BB in the specific region would reduce the uncertainties of BB emissions. We hope that this study will help to improve understanding about the mechanisms that degrade air quality over Indochina.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4433/11/2/160/s1, Table S1. Model performance for daily mean meteorological factors in the two simulation cases for the periods of one year and two months (from March to April) in 2014. Table S2. Model performance for daily mean PM10 concentrations in the four simulation cases for the periods of one full year (2014) and two months (from March to April 2014).

Author Contributions: Conceptualization, K.T., H.S., and A.K.; methodology, H.S. and K.U.; software, H.S. and K.U.; validation, K.T. and H.S.; formal analysis, K.T. and H.S.; data curation, H.S.; writing—original draft preparation, K.T.; writing—review and editing, H.S., K.U., and A.K.; visualization, K.T.; supervision, A.K.; project administration, H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Reid, J.S.; Hyer, E.J.; Johnson, R.S.; Holben, B.N.; Yokelson, R.J.; Zhang, J.; Campbell, J.R.; Christopher, S.A.; Girolamo, L.D.; Giglio, L.; et al. Observing and understanding the Southeast Asian aerosol system by remote sensing: An initial review and analysis for the Seven Southeast Asian Studies (7SEAS) program. *Atmos. Res.* 2013, 122, 403–468. [CrossRef]
- IPCC. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/report/ar5/wg2/ (accessed on 19 December 2019).

- 3. Pengchai, P.; Chantara, S.; Sopajaree, K.; Wangkarn, S.; Tencharoenkul, U.; Rayanakorn, M. Seasonal variation, risk assessment and source estimation of PM 10 and PM10-bound PAHs in the ambient air of Chiang Mai and Lamphun, Thailand. *Environ. Monit. Assess.* **2009**, *154*, 197–218. [CrossRef] [PubMed]
- 4. Tsai, Y.I.; Soparajee, K.; Chotruksa, A.; Wu, H.C. Source indicators of biomass burning associated with inorganic salts and carboxylates in dry season ambient aerosol in Chiang Mai basin, Thailand. *Atmos. Environ.* **2013**, *78*, 93–104. [CrossRef]
- Duc, H.N.; Bang, H.Q.; Quang, N.X. Modelling and prediction of air pollutant transport during the 2014 biomass burning and forest fires in peninsular Southeast Asia. *Environ. Monit. Assess.* 2016, *188*, 106. [CrossRef] [PubMed]
- Atwood, S.A.; Reid, J.S.; Kreidenweis, S.M.; Cliff, S.; Zhao, Y.; Lin, N.-H.; Tsay, S.-C.; Chu, Y.-C.; Westphal, D.L. Size resolved measurements of springtime aerosol particles over the northern South China Sea. *Atmos. Environ.* 2013, 78, 134–143. [CrossRef]
- Wang, S.H.; Tsay, S.-C.; Lin, N.-H.; Chang, S.-C.; Li, C.; Welton, E.J.; Holben, B.N.; Hsu, N.C.; Lau, W.K.-M.; Lolli, S.; et al. Origin, transport, and vertical distribution of atmospheric pollutants over the northern South China Sea during 7-SEAS/Dongsha experiment. *Atmos. Environ.* 2013, *78*, 124–133. [CrossRef]
- 8. Byun, D.W.; Schere, K.L. Review of the governing equations, computational algorithms, and other components of the Models-3 community multiscale air quality (CMAQ) modeling system. *Appl. Mech. Rev.* **2006**, *59*, 51–77. [CrossRef]
- Fu, J.S.; Hsu, N.C.; Gao, Y.; Huang, K.; Li, C.; Lin, N.-H.; Tsay, S.-C. Evaluating the influences of biomass burning during 2006 BASE-ASIA: A regional chemical transport modeling. *Atmos. Chem. Phys.* 2012, 12, 3837–3855. [CrossRef]
- 10. Huang, K.; Fu, J.S.; Hsu, N.C.; Gao, Y.; Dong, X.; Tsay, S.-C.; Lam, Y.F. Impact assessment of biomass burning on air quality in Southeast and East Asia during BASE-ASIA. *Atmos. Environ.* **2013**, *78*, 291–302. [CrossRef]
- 11. Amnuaylojaroen, T.; Barth, M.C.; Emmons, L.K.G.; Carmichael, R.; Kreasuwun, J.; Prasitwattanaseree, S.; Chantara, S. Effect of different emission inventories on modeled ozone and carbon monoxide in Southeast Asia. *Atmos. Environ.* **2014**, *14*, 12983–13012.
- 12. Li, J.; Zhang, Y.; Wang, Z.; Sun, Y.; Fu, P.; Yang, Y.; Huang, H.; Li, J.; Zhang, Q.; Lin, C.; et al. Regional impact of biomass burning in Southeast Asia on atmospheric aerosols during the 2013 seven South-East Asian studies project. *Aerosol Air Qual. Res.* **2017**, *17*, 2924–2941. [CrossRef]
- Wiedinmyer, C.; Akagi, S.K.; Yokelson, R.J.; Emmons, L.K.; Al-Saadi, J.A.; Orlando, J.J.; Soja, A.J. The Fire INventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning. *Geosci. Model Dev.* 2011, 4, 625–641. [CrossRef]
- 14. Kaiser, J.W.; Heil, A.; Andreae, M.O.; Benedetti, A.; Chubarova, N.; Jones, L.; Morcrette, J.-J.; Razinger, M.; Schultz, M.G.; Suttie, M.; et al. Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences* **2012**, *9*, 527–554. [CrossRef]
- Giglio, L.; Randerson, J.T.; van der Werf, G.R. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *J. Geophys. Res. Biogeosci.* 2013, 118, 317–328. [CrossRef]
- 16. Vongruang, P.; Wongwises, P.; Pimonsree, S. Assessment of fire emission inventories for simulating particulate matter in Upper Southeast Asia using WRF-CMAQ. *Atmos. Pollut. Res.* **2017**, *8*, 921–929. [CrossRef]
- 17. Dee, D.P.; Uppala, S.M.; Simmons, A.J.; Berrisford, P.; Poli, P.; Kobayashi, S.; Andrae, U.; Balmaseda, M.A.; Balsamo, G.; Bauer, P.; et al. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorolog. Soc.* **2011**, *137*, 553–597. [CrossRef]
- Kobayashi, S.; Ota, Y.; Harada, Y.; Ebita, A.; Moriya, M.; Onoda, H.; Onogi, K.; Kamahori, H.; Kobayashi, C.; Endo, H.; et al. The JRA-55 reanalysis: General specifications and basic characteristics. *J. Meteorol. Soc. Jpn. Ser. II* 2015, 93, 5–48. [CrossRef]
- Kalnay, E.; Kanamitsu, M.; Kistler, R.; Collins, W.; Deaven, D.; Gandin, L.; Iredell, M.; Saha, S.; White, G.; Woollen, J.; et al. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* 1996, 77, 437–471. [CrossRef]
- 20. Huang, D.-Q.; Zhu, J.; Zhang, Y.-C.; Huang, Y.; Kuang, X.-Y. Assessment of summer monsoon precipitation derived from five reanalysis datasets over East Asia. *Q. J. R. Meteorol. Soc.* **2016**, *142*, 108–119. [CrossRef]
- 21. Huang, B.; Cubasch, U.; Li, Y. East Asian summer monsoon representation in re-analysis datasets. *Atmosphere* **2018**, *9*, 235. [CrossRef]

- 22. Skamarock, W.C.; Klemp, J.B. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *J. Comput. Phys.* **2008**, 227, 3465–3485. [CrossRef]
- 23. Iacono, M.J.; Delamere, J.S.; Mlawer, E.J.; Shephard, M.W.; Clough, S.A.; Collins, W.D. Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *J. Geophys. Res.* **2008**, *113*, D13103. [CrossRef]
- 24. Pleim, J.E. A combined local and nonlocal closure model for the atmospheric boundary layer. Part I: Model description and testing. *J. Appl. Meteor. Climatol.* **2007**, *46*, 1383–1395. [CrossRef]
- 25. Kain, J.S. The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteorol.* **2004**, *43*, 170–181. [CrossRef]
- 26. Morrison, H.; Thompson, G.; Tatarskii, V. Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of one– and two–moment schemes. *Mon. Wea. Rev.* **2009**, *137*, 991–1007. [CrossRef]
- 27. Xiu, A.; Pleim, J.E. Development of a land surface model. Part I: Application in a mesoscale meteorological model. *J. Appl. Meteor.* **2001**, *40*, 192–209. [CrossRef]
- 28. Yarwood, G.; Rao, S.; Yocke, M.; Whitten, G.Z. Updates to the carbon bond chemical mechanism: CB05. *Final Rep. US EPA* **2005**, *8*, 13.
- Emmons, L.K.; Walters, S.; Hess, P.G.; Lamarque, J.-F.; Pfister, G.G.; Fillmore, D.; Kloster, S. Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). *Geosci. Model Dev.* 2010, 3, 43–67. [CrossRef]
- 30. van der Werf, G.R.; Randerson, J.T.; Giglio, L.; van Leeuwen, T.T.; Chen, Y.; Rogers, B.M.; Mu, M.; van Marle, M.J.E.; Morton, D.C.; Collatz, G.J.; et al. Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data* **2017**, *9*, 697–720. [CrossRef]
- 31. Randerson, J.T.; Chen, Y.; van der Werf, G.R.; Rogers, B.M.; Morton, D.C. Global burned area and biomass burning emissions from small fires. *J. Geophys. Res.* **2012**, *117*, G04012. [CrossRef]
- 32. Janssens-Maenhout, G.; Crippa, M.; Guizzardi, D.; Dentener, F.; Muntean, M.; Pouliot, G.; Li, M. HTAP-v2.2: A mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution. *Atmos. Chem. Phys.* **2015**, *15*, 11411–11432. [CrossRef]
- 33. Guenther, A.; Karl, T.; Harley, P.; Wiedinmyer, C.; Palmer, P.I.; Geron, C. Estimates of global terrestrial isoprene emissions using MEGAN (model of emissions of gases and aerosols from nature). *Atmos. Chem. Phys.* **2006**, *6*, 3181–3210. [CrossRef]
- Diehl, T.; Heil, A.; Chin, M.; Pan, X.; Streets, D.; Schultz, M.; Kinne, S. Anthropogenic, biomass burning, and volcanic emissions of black carbon, organic carbon, and SO₂ from 1980 to 2010 for hindcast model experiments. *Atmos. Chem. Phys. Discuss.* 2012, *12*, 24895–24954. [CrossRef]
- 35. University of Wyoming, Wyoming Weather Web. Available online: http://weather.uwyo.edu/ (accessed on 19 December 2019).
- 36. Network Center for EANET, EANET Data on the Acid Deposition in the East Asian Region. Available online: https://monitoring.eanet.asia/document/public/index (accessed on 14 June 2019).
- 37. Willmott, C.J. On the validation of models. Phys. Geogr. 1981, 2, 184–194. [CrossRef]



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